WADD TECHNICAL REPORT 61-106

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AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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FOREWORD

This report was prepared by Battelle Memorial Institute under USAF Contract No. AF 33(616)-5668. This contract was initiated under Project No. 7351, "Metallic Materials", Task No. 73512, "Refractory Metals". This project was administered under the direction of the Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with Lt. William Smith acting as project engineer.

This report describes the results of research conducted during the period January 1, 1960, through December 31, 1960.

ABSTRACT

The effects of alloying on the mechanical properties of tantalum have been studied. Both dispersion-strengthened and solid-solution strengthened tantalum alloys exhibit high-strength at elevated temperatures while maintaining good fabricability and excellent low-temperature ductility. Strength data to 1650 C (3000 F) are reported. The oxidation resistance of tantalum can be improved severalfold by alloying. Several alloying elements were found to be effective in reducing both scaling and contamination up to at least 1400 C (2550 F). References are included.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

I Perlmutter

I. Perlmutter
Chief, Physical Metallurgy Branch
Metals and Ceramics Laboratory
Materials Central

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INVESTIGATION OF THE PROPERTIES OF TANTALUM AND ITS ALLOYS

by

Frank F. Schmidt, William D. Klopp, Daniel J. Maykuth,
Horace R. Ogden, and Robert I. Jaffee

INTRODUCTION

This report on "Investigation of the Properties of Tantalum and Its Alloys" describes the results of work conducted on Air Force Contract 33(616)-5668 during the period January 1, 1960, through December 31, 1960. Selected results from previous studies(1)* also are included.

The objective of this research is the development of a tantalum alloy or alloys that can be used in structural applications at temperatures above 1095 C (2000 F). The major immediate applications for tantalum alloys are anticipated as leading edge and structural components in re-entry space vehicles. Other applications for tantalum in components for rocket nozzles and control devices also are contemplated. The re-entry components may be subjected to temperatures ranging from subzero in space to as high as 2205 C (4000 F) during re-entry into the earth's atmosphere. The requirements for such an alloy or alloys include good formability and useful strength in the contemplated service-temperature range; good oxidation resistance is also desired.

Tantalum has a high melting point [2996 C (5425 F)], excellent room-temperature fabricability, and ductility at subzero temperatures, a combination of properties not found in many refractory metals. Tantalum has only moderate strength properties and poor oxidation resistance at elevated temperatures. However, the high melting point of tantalum and its large capacity for both interstitial and substitutional solutes makes it an attractive base metal for the development of high-temperature alloys.

Early studies in the long-range alloy-development program established base-line data on the mechanical properties (at both room and elevated temperatures), recrystallization behavior, and oxidation behavior of high-purity tantalum.(1) Since this time, the work has been extended to a study of the effects of alloying elements on the base-line mechanical properties and oxidation behavior. These latter investigations are described in this report.

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* References are given on page 149.

SUMMARY

Mechanical-Property Studies

The binary and ternary tantalum-alloy fabricability limits were determined. The limits for binary and ternary combinations of hafnium, molybdenum, vanadium, and tungsten were extended when fabrication temperature was increased from 980 to 1600 C (1800 to 2910 F). It was shown that relatively large amounts of both substitutional and interstitial solutes may be added to tantalum and still maintain reasonable fabricability.

Binary alloy additions of columbium, hafnium, molybdenum, rhenium, and tungsten raised the recrystallization temperature of unalloyed tantalum from 1200 C (2190 F) to as high as 1600 and 1650 C (2910 and 3000 F) for the Ta-10Mo and Ta-10W alloys. These binary additions also show the greatest effect in raising the recrystallization temperature in ternary combination. Ternary alloys of Ta-Cb-W, Ta-Hf-W, Ta-Mo-Hf, and Ta-Mo-W have recrystallization temperatures 250 to 500 C (480 to 930 F) higher than those of unalloyed tantalum. Conversely, binary alloy additions of titanium, vanadium, and zirconium have little effect on the recrystallization temperature of tantalum, while ternary combinations of these metals with aluminum and chromium appear to decrease the recrystallization temperature of tantalum.

The known low ductile-to-brittle transition temperature characteristic for unalloyed tantalum is retained to a considerable extent in many of its alloys. Binary alloys containing up to 50 per cent columbium, 20 per cent hafnium, 5 per cent rhenium, 40 per cent titanium, 15 per cent vanadium, 10 per cent tungsten, and 1 and 10 per cent zirconium were ductile in bending at both 25 and -196 C (75 and -320 F). Binary alloy additions of up to 7.5 per cent molybdenum, 15 per cent tungsten, and 5 and 20 to 40 per cent zirconium were ductile at 25 C (75 F), but brittle at -196 C (-320 F). In general, ternary alloys had good ductility at 25 C (75 F) except those containing aluminum, beryllium, chromium, molybdenum, and silicon. Many of the other ternary alloys, particularly those containing either columbium or titanium, were ductile at -196 C (-320 F).

All binary and ternary alloys of tantalum exhibited strength improvements over pure tantalum at room temperature. Binary additions of vanadium and hafnium were found to be the most potent strengtheners, increasing the strength from 30,600 psi for unalloyed tantalum to as high as 177,600 psi for the Ta-20V alloy. This was the highest room-temperature strength found. Several of the ternary alloys, particularly those containing 5 to 10 per cent vanadium with 30 per cent columbium or 5 to 10 per cent tungsten

show an excellent combination of strength, approximately 140,000 to 150,000 psi, and ductility. Small additions of the Group IVA metals, titanium, zirconium, and hafnium, with and without supplemental carbon and oxygen additions increased the strength of unalloyed tantalum significantly through dispersion hardening.

At 1200 C (2190 F), a four-to-eightfold strengthening improvement over unalloyed tantalum is obtained with binary additions of 5 to 30 per cent hafnium, 5 to 10 per cent molybdenum, 5 to 20 per cent vanadium, 10 to 20 per cent tungsten, and 1 to 10 per cent zirconium. Strength peaks of 83,100, 66,400, and 60,200 psi are exhibited for the Ta-15V, Ta-10Mo, and Ta-20Hf alloys, respectively. Several of the ternary alloys tested show strength improvements at 1200 C (2190 F) ranging from six-to-ninefold. The Ta-Cb-V, Ta-Hf-W, Ta-Mo-Hf, Ta-Mo-V, Ta-Mo-W, and Ta-V-W alloys exhibited tensile strengths in excess of 60,000 psi at 1200 C (2190 F). A strength of 87,400 psi measured for the Ta-10V-5W alloy represents the highest strength level attained at 1200 C (2190 F). Dispersion-hardening effects appear to be greater in the Ta-1Zr alloy than in either the Ta-1Hf or Ta-1Ti alloys at these temperatures. Carbon was found to have a more potent hot-strengthening effect than oxygen. Generally, as expected, wrought structures exhibited higher 1200 C (2190 F) tensile strengths than the recrystallized structures.

The binary Ta-5 to 15V and Ta-1Zr and ternary Ta-30Cb-5 to 10V alloys exhibit good strengthening over the high-purity base at 1200 to 1690 C (2190 to 3075 F). These alloys show approximately the same tensile strength above 1425 C (2600 F), although considerable difference in tensile strength is observed at lower temperatures. The Ta-10Hf-5W, Ta-5V-5W, and Ta-5V-7.5W alloys represent a still higher strength level above 1425 C (2600 F). At 1650 C (3000 F), these alloys show about a fivefold strengthening improvement over pure tantalum and about a twofold strengthening improvement over the binary Ta-V and Ta-Zr and ternary Ta-Cb-V alloys.

Most of the alloys exhibiting high tensile strength at 1200 C (2190 F) show even greater improvements when corrected for density, particularly when the 16.6 g/cm^3 for pure tantalum is considered. The highest strength-to-weight ratios were found for the Ta-15V and Ta-10V-5W alloys; these values at 1200 C are 174,000 and 169,000 psi/lb/in.^{3}, respectively.

Several tantalum alloys exhibited higher strength levels in the temperature range 1000 to 1690 C (1830 to 3075 F) as compared with several other refractory metals and alloys. Many of these tantalum alloys also showed excellent strength-to-weight ratios up to at least 1650 C (3000 F).

A metallographic study was made on the effects of binary and ternary additions on the structure of tantalum. Approximate minimum solid-solubility limits of columbium, hafnium, molybdenum, rhenium, titanium, vanadium, tungsten, and zirconium in tantalum were established. Grain-size measurements were made following vacuum annealing for these binary additions and the Ta-10Hf-5W alloy.

Oxidation Behavior

Screening tests were conducted at 1200 C (2190 F) on several binary and a larger number of ternary alloys which were designed primarily for high temperature strength. The behavior of these alloys correlated well with previous studies on binary tantalum alloys. Small additions of carbon were observed to reduce, by about 15 per cent, the oxidation rates of binary tantalum alloys with titanium, zirconium, or hafnium. This effect was also observed with Ta-10Hf-5W, but not with a binary vanadium alloy.

A number of Ta-Hf-W alloys were included in the screening study. The Ta-10Hf-5W alloy oxidizes about two-thirds as rapidly as unalloyed tantalum at 1200 C (2190 F).

Detailed oxidation and contamination studies were conducted on nine complex tantalum-titanium-base alloys which may find application as high-temperature cladding materials. Superior oxidation and contamination resistance were found for Ta-40Ti-10Al and Ta-30Ti-5Al-5Cr. These alloys are about 300 times more oxidation resistant than unalloyed tantalum at 1400 C (2550 F). The oxidation behavior of these alloys is correlated qualitatively with the properties of complex oxides of the minor additions.

MECHANICAL-PROPERTY STUDIES

This phase of the project is concerned with the investigation of the mechanical properties of tantalum and tantalum alloys. Properties evaluated and studied included the effect of both substitutional and interstitial alloying additions on the fabricability, recrystallization behavior, bend ductility, tensile properties at both low and elevated temperatures, and metallography.

Background Information

Hardness measurements(1-10), recrystallization behavior(1,2,8,11-13), tensile properties(1,2,4,11,14-29), and other metallurgical properties(1,2,4,8,16,21,29-54) of unalloyed tantalum at various levels of impurity content have been reported extensively in the literature. Tantalum has a high melting point [2996 C (5425 F)], excellent room-temperature fabricability (i.e., can be rolled to >95 per cent reduction without intermediate annealing), no ductile-to-brittle transition temperature (ductile behavior reported down to 4 K), high density [16.6 g/cm^3 (0.600 lb/in.^{3})], high solubility for both interstitial and substitutional solutes, and moderate room-temperature strength (30,000-psi ultimate strength, as annealed). Although strength is retained reasonably well at elevated temperature [ultimate strength, as annealed, 10,000 and 5,000 psi at 1200 and 1650 C (2190 and 3000 F), respectively], alloying is needed to provide a useful and competitive structural material for use at high temperatures.

However, studies of hardness(1,15,55-59), recrystallization behavior(1,55,59), tensile properties(1,15,55,59,60), and other metallurgical properties(1,39,55,56,61-64) of tantalum alloys have been much less extensive. These studies have, in general, been limited to specific alloys or alloy systems rather than the general effects of alloy additions on base-line properties. In addition to the present tantalum-alloy development program at Battelle Memorial Institute(1), both National Research Corporation(59) and Westinghouse Research Laboratories(58) are conducting studies on Ta-W alloys, particularly at the 10 to 30 per cent tungsten level, and Ta-Hf-W alloys, particularly the Ta-8Hf-8W alloy, respectively. Two alloys, the Ta-10Hf-5W and Ta-30Cb-7.5V alloys, developed at Battelle and described in this report are being scaled-up to 40 to 50-pound ingots for further evaluation under a companion program at Battelle(65). These investigations, along with available data from the producers of the commercially available Ta-10W alloy, have resulted in increased interest in tantalum alloys as possible candidates for high-temperature structural applications.

Two literature surveys covering the state of the art for tantalum and tantalum alloys have recently been reported.(3,66) In addition, Bechtold, Wessel, and France(67) recently published an excellent report covering the mechanical properties of the refractory metals in Groups VA (V, Cb, Ta) and VIA (Cr, Mo, W) from very low to ultrahigh temperatures. The present status in the development of refractory metal and alloy sheet in the United States has also been well summarized by Jaffee, Harris, and Promisel.(68)

Experimental Procedures

Preparation of Materials

High-purity tantalum prepared by the electron-beam-melting process was used as base material for these studies. Typical chemical analyses and microstructure are given in Table 1 and Figure 1, respectively. As-received cast hardness ranged from about 75 to 90 VHN.

Interstitial additions of carbon and oxygen were added to the melt as graphite rod and Ta_2O_5 powder (which was wrapped in tantalum foil), respectively. Chemical analyses showed the recovery of carbon in tantalum alloys was essentially complete, whereas the recovery of oxygen was approximately 50 per cent.

Substitutional alloying additions to tantalum were made using highest available purity alloying elements. Additions were usually in thin sheet form.

Melting

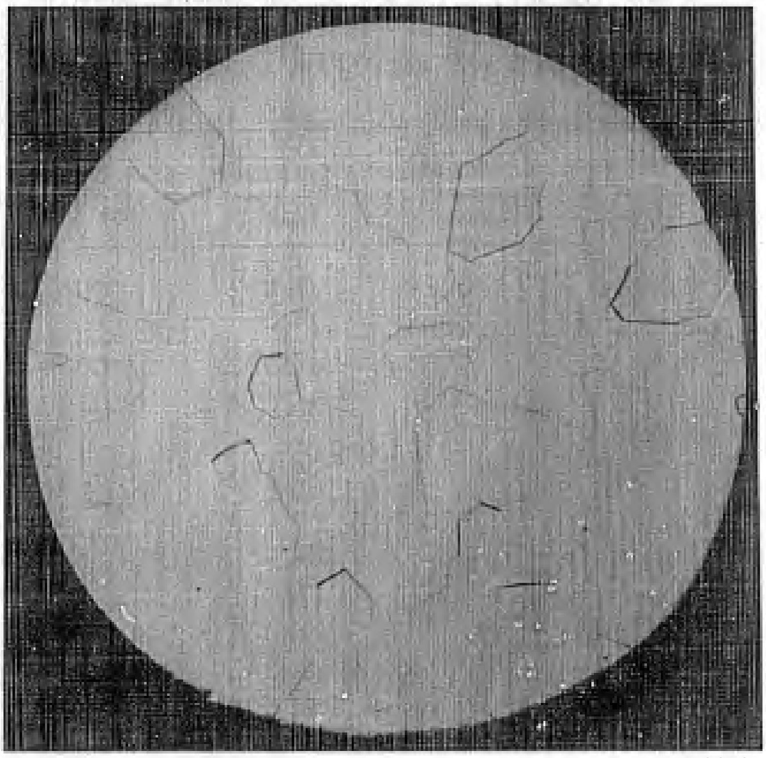
All alloys were prepared as 150-gram ingots by inert electrode-arc melting under a partial atmosphere of helium. Each alloy button was melted 6 to 10 times using 400 to 800 amp at 30 to 32 v dc to insure homogeneity.

Alloy buttons measured about 1-1/2 to 1-3/4 inches in diameter by about 0.35 to 0.40 inch thick.

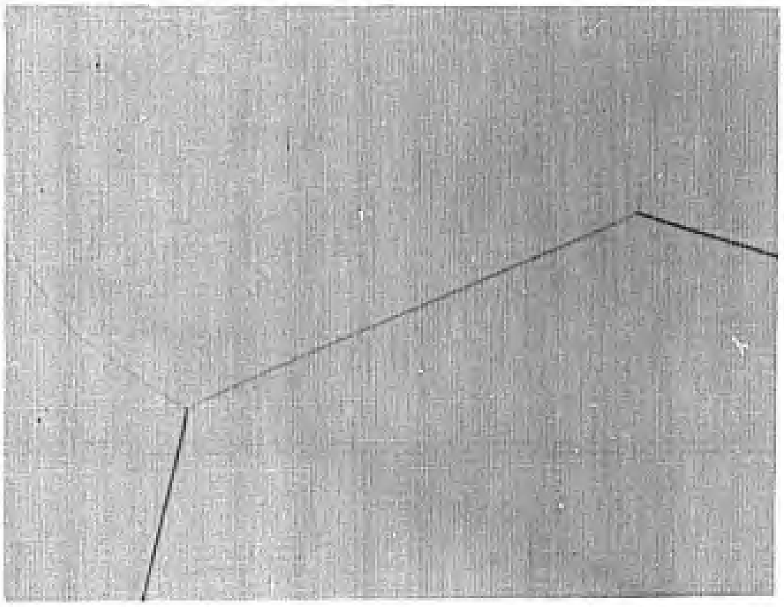
Nominal alloy compositions were checked on each alloy button by weighing after arc melting. In almost all instances, weight losses were less than 3 per cent. Check chemical analyses on several alloys showed weight-loss measurements were a good indication of final alloy composition. For example, weight-loss measurements for three tantalum ternary alloys containing 5 to 15 per cent vanadium were less than 1 per cent. Subsequent chemical analyses showed vanadium contents all within 0.15 per cent of the

TABLE 1. ANALYSES OF ELECTRON-BEAM-MELTED TANTALUM

Element	Amount Present, weight per cent					
	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6
C	0.0030	0.0020	0.003	0.006	0.004	<0.003
H	0.00014	0.00032				
N	0.0010	0.0030	<0.002	0.003	<0.002	0.0015
O	0.0016	<0.0006	0.004	0.013		<0.005
Al			<0.002	<0.002	<0.002	<0.002
B						<0.001
Cb	0.02		<0.05	<0.05	0.11	<0.05
Cd						<0.005
Co			<0.002	<0.002	<0.002	
Cr	0.0003		<0.002	<0.002	0.002	<0.002
Cu	0.003		<0.004	<0.004	0.004	<0.004
Fe	0.0008		<0.005	<0.005	0.032	<0.01
Mg			<0.002	<0.002	<0.002	<0.002
Mn			<0.002	<0.002	<0.002	<0.002
Mo			0.03	0.004	0.03	<0.002
Ni	0.0003		<0.002	<0.002	<0.002	<0.002
Pb			<0.002	<0.002	<0.002	<0.002
Si			<0.01	<0.002	<0.01	<0.01
Sn			0.002	0.002	0.002	<0.002
Ti			<0.005	<0.005	<0.002	<0.015
V			<0.002	<0.002	<0.002	<0.002
W			0.19	<0.05	0.10	<0.030
Zn						<0.002
Zr						<0.050



2-1/2X N56102



100X N56103

FIGURE 1. PHOTOMICROGRAPHS OF CAST ELECTRON-BEAM-MELTED TANTALUM (LOT 2)

intended values. However, certain additions are difficult to retain when arc melting under reduced pressures. These elemental additions, particularly aluminum and chromium, were found to best be retained by master alloying before being added to tantalum.

Fabrication

After the cast hardness was measured, each alloy ingot was prepared for fabrication at room temperature, 980 C (1800 F), or 1600 C (2910 F).

Room Temperature. Ingots were rolled directly from the cast ingot, using kerosene as a lubricant, to 0.035 to 0.045-inch strip. The strip was annealed in vacuum for 1 hour at 1300 C (2370 F) at 0.090 to 0.110 inch, thus providing final cold reductions of 50 to 75 per cent.

980 C (1800 F). The following procedures were used to prepare alloys for fabrication at 980 C (1800 F).

(1) Machine ingots to 1.250 x 1.250 x 0.300-inch rectangular slabs.

(2) Press-fit ingots into stainless steel frame (see Figure 2).

(3) Apply parting compound (Cr_2O_3 mixed with a small amount of water to give a consistency which is suitable for applying with a brush) between stainless steel frame, buttons, and cover plates.

(4) Weld all eight edges and evacuation tubing in air.

(5) Evacuate at room temperature to 1×10^{-4} mm Hg. Heat to 980 C (1800 F) and evacuate to 2×10^{-4} mm Hg. Seal off evacuation tube.

Alloys were then rolled in the stainless steel packs at 980 C (1800 F), using an argon preheating atmosphere to minimize the possibility of contamination, to 0.040 to 0.100-inch strip. The alloys were then stripped from the packs, surface conditioned by pickling (mixed H_2SO_4-HNO_3-HF acids) and grinding, and evaluated for fabricability.

A number of alloys showed a high capacity for subsequent reduction by cold rolling. In particular, cold reductions of 5 to 75 per cent were affected on a number of alloys and were usually beneficial in improving surface quality.

1600 C (2910 F). The following procedures were used to prepare alloys for fabrication at 1600 C (2910 F) (see Figure 3):

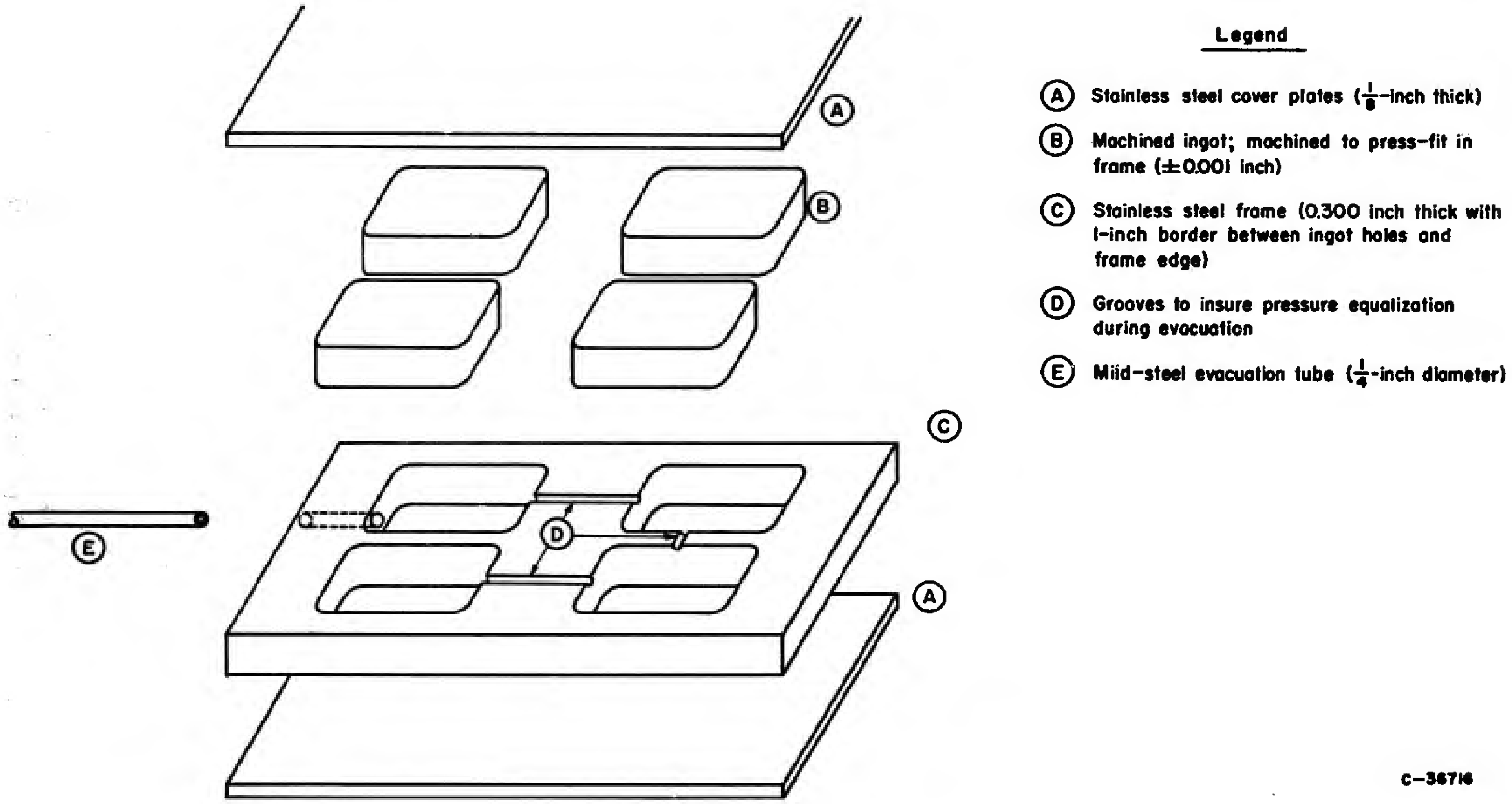
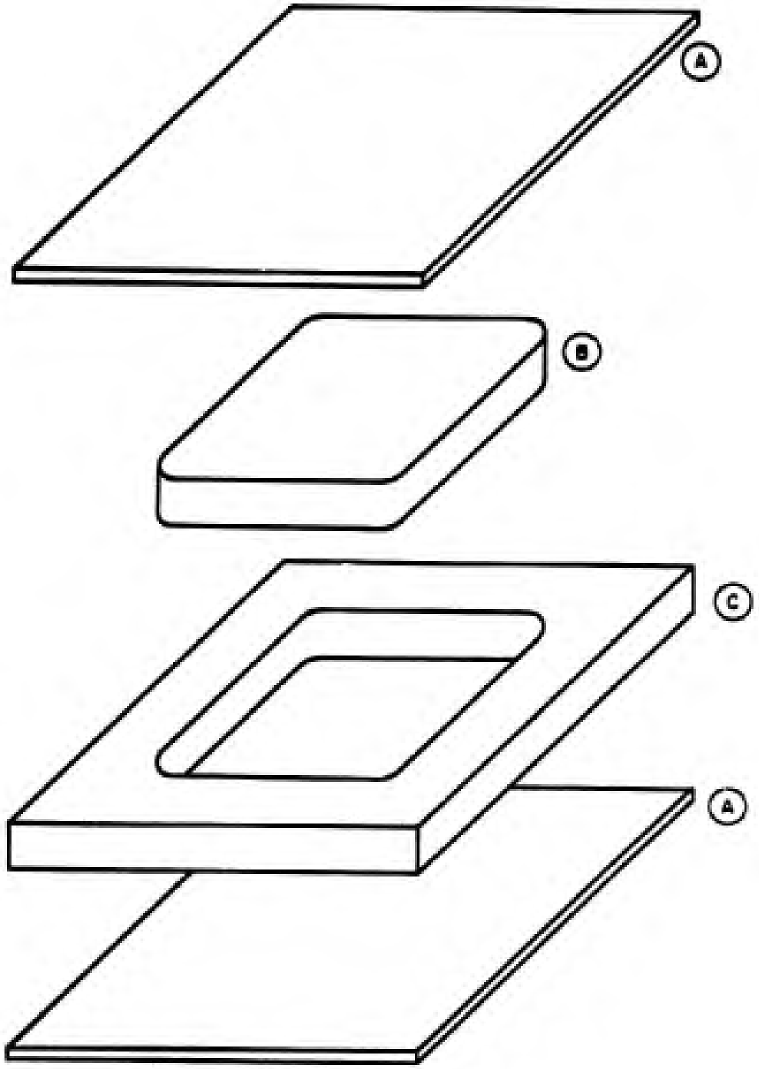


FIGURE 2. SCHEMATIC REPRESENTATION OF STAINLESS STEEL PACK



Legend

Ⓐ	Molybdenum cover plates (0.050 inch thick)
Ⓑ	Machined ingot; press-fit in frame (±0.001 inch)
Ⓒ	Molybdenum frame (0.300 inch thick with $\frac{3}{8}$-inch border between ingot hole and frame edge)

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FIGURE 3. SCHEMATIC REPRESENTATION OF MOLYBDENUM PACK

(1) Machine ingots to 1.250 x 1.250 x 0.300-inch rectangular slabs.

(2) Press-fit ingots into molybdenum frame.

(3) Weld 7 edges under argon. Weld final edge by electron-beam-welding, thus insuring a vacuum of less than 5 x 10^{-4} mm Hg within the molybdenum pack.

The molybdenum packs were rolled at 1600 C (2910 F), using a hydrogen preheating atmosphere, to 0.040 to 0.080-inch strip. The alloy strips were then leached from the molybdenum packs using 2 parts HNO_3 and 1 part HCl and evaluated for fabricability. A few alloys fabricated in this manner were cold rolled to final sheet thickness.

Most recent fabricability studies show that a stainless steel pack configuration similar to the molybdenum pack, Figure 3, proves superior. This is attributed to a more positive vacuum seal when the final edge is welded by the electron-beam technique.

Heat Treatments

Test specimens were annealed in vacuum at 900 to 1800 C (1650 to 3270 F) for 1 hour. Pressures were always below 1 x 10^{-4} mm Hg. Specimens were heated by a resistance tantalum heater element with manual temperature control. An optical pyrometer was used to measure the specimen temperature with an estimated accuracy of about ±5 C (10 F).

Metallography

Specimens for metallographic study were mounted in Bakelite, ground through 600X paper, and mechanically polished, finishing on a high-speed wheel with a mixture of alumina and chromic acid. The specimens were etched chemically with 50 to 70 per cent lactic – 20 to 40 per cent nitric – 1 to 10 per cent hydrofluoric acid etchant.

Grain-size measurements were made by visual comparison at 100X with the standard ASTM grain-size chart.

Hardness Measurements

Hardness values were measured using the Vickers hardness test and a 10-kilogram load. The values reported are the average of 5 impressions on each specimen.

Cast hardness was measured directly from the cast ingot which was mounted in Wood's metal and ground through 600X paper. Other hardness measurements were made on specimens mounted in Bakelite and ground through 600X paper.

Test Specimens

Bend Specimens. Specimens were cut to a 1 x 1/4-inch size from 0.035 to 0.045-inch strip parallel to the rolling direction. Surfaces were ground through 600X paper.

Tensile Specimens. Specimens were cut from 0.035 to 0.045-inch strip parallel to the rolling direction. Specifications are shown in Figure 4. The 4-inch specimen used early in this program was later replaced by the 3-1/8-inch specimen, also shown in Figure 4. This allowed a higher specimen yield per alloy strip.

Bend Tests

Duplicate specimens were tested for bend ductility at room temperature and -196 C (-320 F) in the recrystallized condition. Each specimen was bent through a progressively sharper die until evidence of cracking appeared. Die radii used are listed below:

Die Radius, in.	Decimal Equivalent, in.	Die Radius, in.	Decimal Equivalent, in.
1-1/2	1.5	3/32	0.0937
3/4	0.75	1/16	0.0625
3/8	0.375	3/64	0.0468
1/4	0.25	1/32	0.0312
3/16	0.1875	1/64	0.0156
1/8	0.125	Sharp	--

The bend ductility value, T, was calculated from

$$T = \frac{D}{t},$$

where

T = bend ductility

D = radius of last good die before evidence of cracking appears, in.

t = specimen thickness, in.

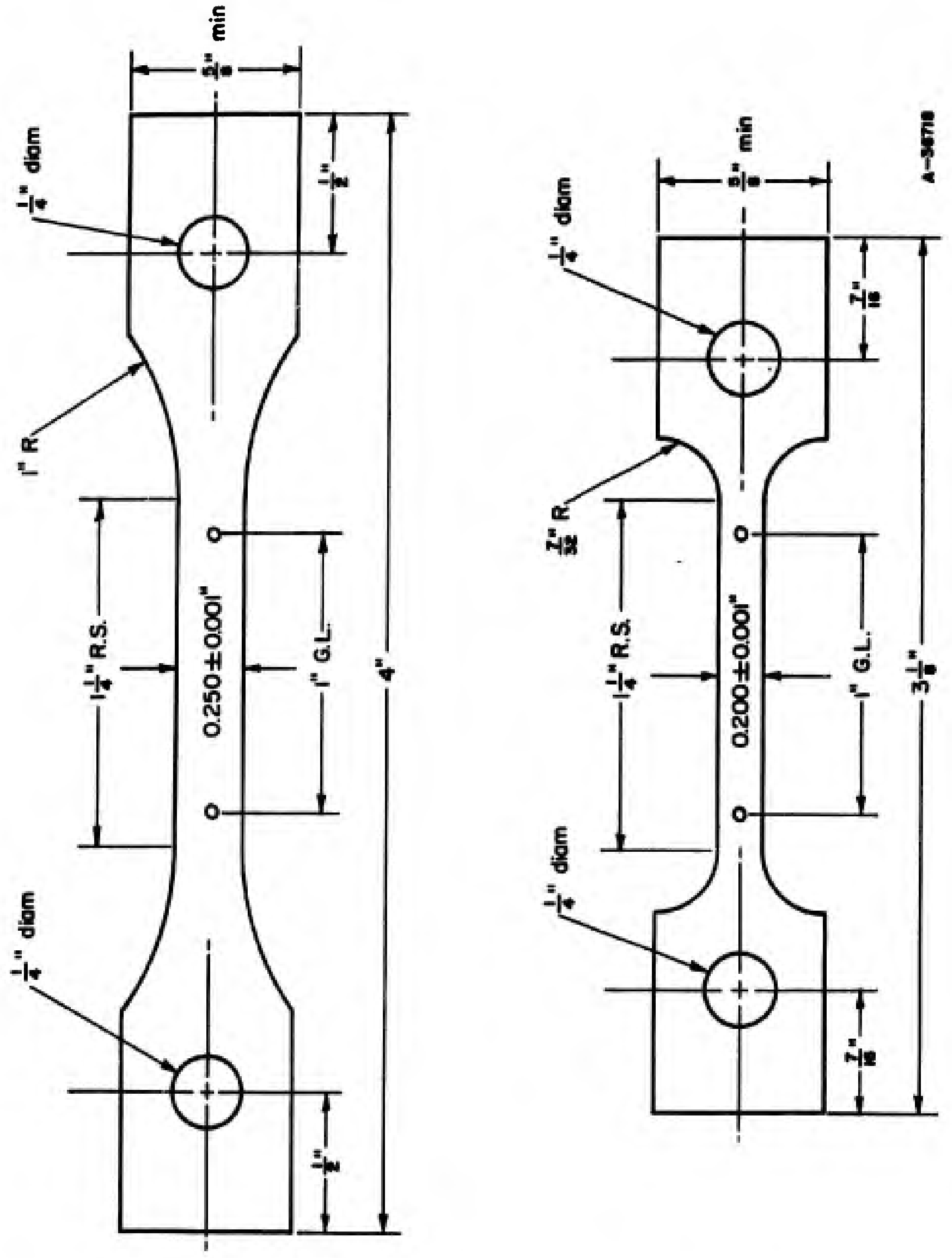


FIGURE 4. SPECIFICATIONS FOR TENSILE SPECIMENS

Tensile Tests

Room Temperature and -196 C (-320 F). All tests were conducted using conventional hydraulic testing machines. Load-strain curves were recorded autographically from a strain gage attached to the specimen (room-temperature tests) or a wide-range extensometer attached to the crosshead [-196 C (-320 F) tests]. A crosshead speed of 0.02 inch per minute was used up to the point of yielding, and a speed of 0.05 inch per minute was then used for the rest of the test.

All test specimens were in the recrystallized condition.

135 to 490 C (275 to 915 F). All tests were conducted using conventional hydraulic testing machines. Load-strain curves were recorded autographically from a wide-range extensometer attached to the specimen. Because oxidation tests showed only a surface tarnish at 500 C (930 F), the specimens were heated in a resistance furnace with no protective atmosphere. To minimize possible oxidation effects, a moderately high crosshead speed of 0.05 inch per minute was used for the entire test.

Only unalloyed recrystallized tantalum was tested over this temperature range.

1175 C (2150 F) and Above. Two test units were used for elevated temperature tensile testing.

The first unit, used early in this program, was a conventional creep-rupture rack equipped with a vacuum furnace and with a lever-magnified dead-weight loading system. The specimen was loaded by adding lead shot until the ultimate tensile strength was reached. Typical vacuum system pressures at temperature were about 3×10^{-3} to 6×10^{-3} mm Hg. Temperature was measured by a platinum – platinum-rhodium thermocouple to ±2 C (±4 F) with all specimens wrapped in tantalum foil to minimize contamination.

The second unit (see Figure 5), which replaced the first, has the following distinct advantages:

(1) Hydraulic loading (controlled crosshead speed of approximately 0.01 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture, versus a lever-magnified dead-weight loading system)

(2) Higher operating temperature [1700 C (3090 F) versus 1370 C (2500 F)]

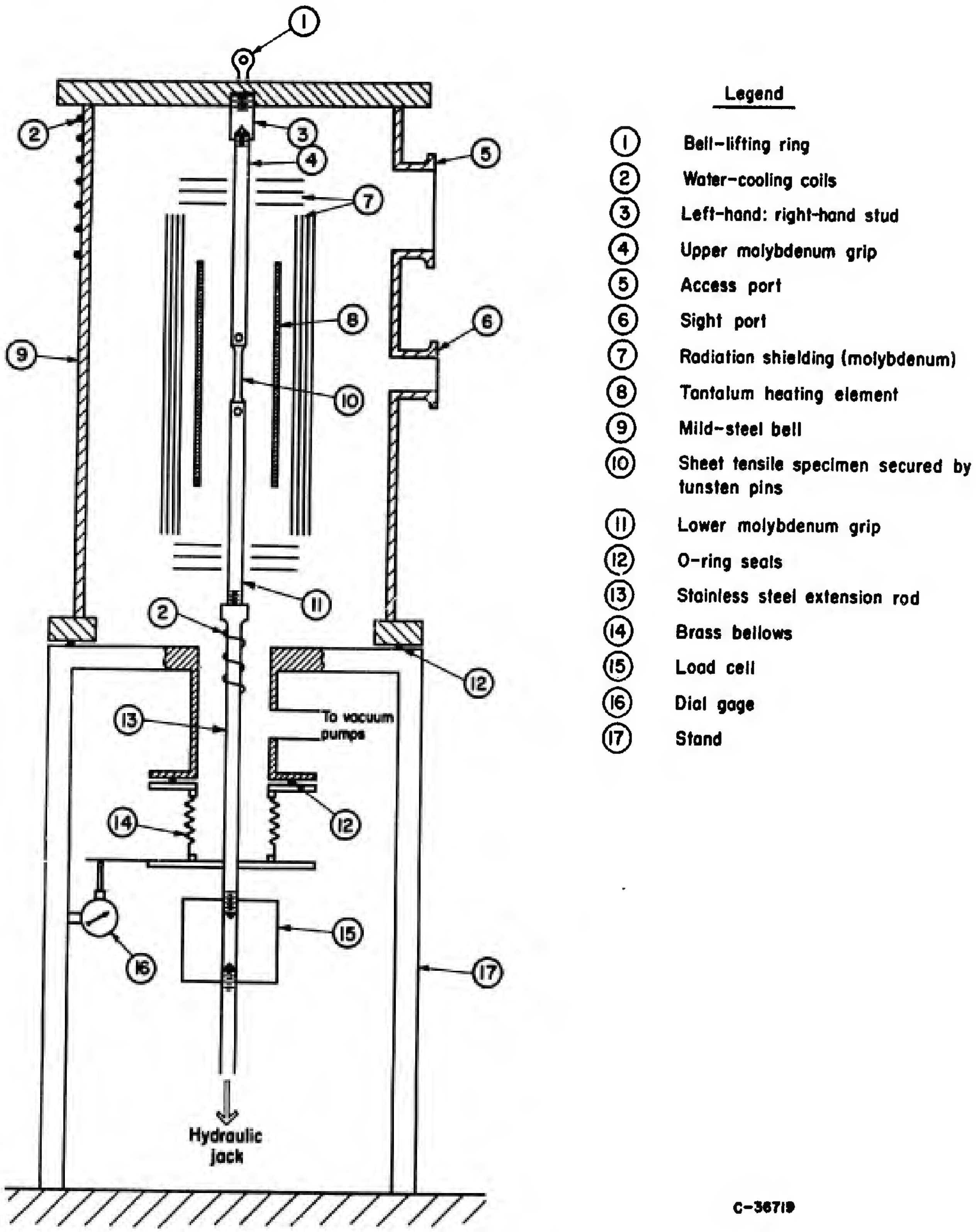


FIGURE 5. SCHEMATIC REPRESENTATION OF ELEVATED-TEMPERATURE TENSILE EQUIPMENT

(3) Higher vacuum (less than 1×10^{-4} mm Hg versus 3×10^{-3} to 6×10^{-3} mm Hg)

(4) Shorter time-to-temperature (5 to 10 minutes versus 1 to 2 hours).

Fabrication

Table 2 presents data on the fabrication of tantalum and tantalum alloys.

The binary fabricability limits based on these fabrication studies are given below:

Alloy Addition	Limiting Alloy Content for Satisfactory Strip[a], weight per cent, at Indicated Temperature			Maximum Fabricability Limit
	25 C (75 F)	980 C (1800 F)	1600 C (2910 F)	
Cb	>50	--	--	None
Hf	>5	>35, <40	--	37.5
Mo	<5	7.5	>10, <20	15
Re	>5	--	--	>5
Ti	>80	--	--	None
V	<10	>20, <30	>30	35
W	>5	15	>20, <30	25
Zr	>1, <5	>40	--	None

(a) Fair quality or better; see Table 2.

It can be seen that, as fabrication temperature is increased, the binary fabricability limits for Ta-Mo, Ta-V, and Ta-W alloys are extended.

Many of the alloys which failed at 980 C (1800 F) fabricated to good-quality strip when the higher fabrication temperature was used. However, as noted below, fabrication difficulties were experienced with many of the alloys containing 10 per cent vanadium.

Alloy Composition, weight per cent	Number of Fabrication Attempts	Number of Fabrication Failures at Indicated Temperature	
		980 C (1800 F)	1600 C (2910 F)
Ta-10V	3	1 of 2	0 of 1
Ta-10V-30Cb	2	1 of 1	0 of 1
Ta-10V-5Hf	1	--	1 of 1
Ta-10V-10Hf	1	1 of 1	--

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS

Alloy Composition, weight per cent	Cast Hardness(a), VHN	Rolling Temperature(b), C	Quality of Strip(c)
100Ta	88	RT	Excellent
Ta-5Cb	--	RT	Excellent
Ta-10Cb	89	RT	Excellent
Ta-20Cb	91	RT	Excellent
Ta-30Cb	104	RT	Excellent
Ta-40Cb	93	RT	Excellent
Ta-50Cb	--	RT	Excellent
Ta-1Hf	116	RT	Excellent
Ta-1Hf + C (700 ppm)	156	RT	Excellent
Ta-1Hf + O (170 ppm)	128	RT	Excellent
Ta-5Hf	146	RT	Excellent
Ta-10Hf	235	980	Good
Ta-10Hf	260	980/RT	Excellent
Ta-10Hf + C (630 ppm)	251	980/RT	Good
Ta-20Hf	287	980	Good
Ta-20Hf	268	980/RT	Excellent
Ta-30Hf	330	980	Fair
Ta-30Hf	322	980/RT	Excellent
Ta-35Hf	306	980/RT	Excellent
Ta-40Hf	342	980	Very poor
Ta-40Hf	405	980	Very poor
Ta-5Mo	--	RT	Very poor
Ta-5Mo	345	980/RT	Good
Ta-7.5Mo	260	RT	Very poor
Ta-7.5Mo	260	980/RT	Fair
Ta-10Mo	314	980	Poor
Ta-10Mo	360	1600	Good
Ta-20Mo	442	980	Very poor
Ta-20Mo	413	1600	Very poor
Ta-30Mo	442	(d)	--
Ta-5Re	253	RT	Excellent
Ta-1Ti	100	RT	Excellent
Ta-1Ti + C (2300 ppm)	146	980/RT	Excellent
Ta-1Ti + O (280 ppm)	124	RT	Excellent
Ta-5Ti	94	RT	Excellent
Ta-10Ti	168	RT	Excellent

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness[(a)], VHN	Rolling Temperature[(b)], C	Quality of Strip[(c)]
Ta-20Ti	185	RT	Excellent
Ta-30Ti	170	RT	Excellent
Ta-40Ti	168	RT	Excellent
Ta-50Ti	176	RT	Poor[(e)]
Ta-60Ti	181	RT	Excellent
Ta-80Ti	162	RT	Excellent
Ta-5V	245	980/RT	Excellent
Ta-5V	268	980/RT	Excellent
Ta-5V + C (580 ppm)	357	980/RT	Excellent
Ta-7.5V	325	980/RT	Excellent
Ta-10V	363	RT	Very poor
Ta-10V	363	980	Fair
Ta-10V	342	980/RT	Excellent
Ta-10V	345	980/RT	Poor
Ta-10V	376	1600/RT	Good
Ta-15V	383	980/RT	Excellent
Ta-20V	421	980/RT	Good
Ta-20V	455	980/RT	Good
Ta-30V	397	980	Very poor
Ta-30V	429	1600/RT	Excellent
Ta-5W	196	RT	Excellent
Ta-5W	207	980	Good
Ta-10W	225	980	Good
Ta-10W	283	980	Fair
Ta-10W + C (590 ppm)	253	RT	Very poor
Ta-10W + C (590 ppm)	253	980/RT	Fair
Ta-15W	268	980/RT	Fair
Ta-20W	328	980	Poor
Ta-20W	339	1600	Good
Ta-30W	376	980	Poor
Ta-30W	455	1600	Poor
Ta-1Zr	133	RT	Excellent
Ta-1Zr	146	RT	Excellent
Ta-1Zr + C (1400 ppm)	192	980/RT	Excellent
Ta-1Zr + O (400 ppm)	147	RT	Excellent
Ta-5Zr	256	RT	Very poor
Ta-5Zr	240	980	Good

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness(a), VHN	Rolling Temperature(b), C	Quality of Strip(c)
Ta-5Zr	256	980/RT	Good
Ta-10Zr	330	980/RT	Good
Ta-20Zr	357	980/RT	Excellent
Ta-30Zr	373	980	Excellent
Ta-40Zr	297	980	Excellent
Ta-5Cb-10Ti	179	RT	Excellent
Ta-5Cb-20Ti	179	RT	Excellent
Ta-10Cb-20Ti	178	RT	Excellent
Ta-20Cb-10Ti	173	RT	Excellent
Ta-30Cb-10Ti	172	RT	Excellent
Ta-30Cb-10Cr	143	980	Fair
Ta-30Cb-10Hf	193	980	Excellent
Ta-30Cb-20Hf	251	980/RT	Good
Ta-30Cb-10Mo	277	980	Fair
Ta-30Cb-10W	214	980	Good
Ta-30Cb-5V	244	980	Excellent
Ta-30Cb-5V	247	980/RT	Excellent
Ta-30Cb-5V	247	980/RT	Excellent
Ta-30Cb-5V	272	980/RT	Excellent
Ta-30Cb-5V-1Zr	247	980/RT	Good
Ta-30Cb-7.5V	312	980/RT	Excellent
Ta-30Cb-7.5V	336	980/RT	Excellent
Ta-30Cb-10V	327	980	Poor
Ta-30Cb-10V	292	980/RT	Excellent
Ta-30Cb-10V	322	980/RT	Excellent
Ta-30Cb-10V	314	1600/RT	Excellent
Ta-30Cb-1Zr	159	RT	Excellent
Ta-30Cb-5Zr	221	980	Fair
Ta-10Hf-5V	319	980	Poor
Ta-10Hf-5V	325	1600	Fair
Ta-10Hf-10V	417	980	Very poor
Ta-10Hf-5W	270	980/RT	Excellent
Ta-10Hf-5W	292	980/RT	Good
Ta-10Hf-5W + C (540 ppm)	333	980/RT	Excellent
Ta-10Hf-5W-1Zr	292	980	Poor

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness[a], VHN	Rolling Temperature[b], C	Quality of Strip[c]
Ta-10Hf-10W	360	980	Poor
Ta-10Hf-10W	348	1600	Good
Ta-10Hf-15W	373	980	Very poor
Ta-10Hf-15W	401	1600	Fair
Ta-10Hf-1Zr	227	980/RT	Excellent
Ta-10Hf-1Zr	228	980/RT	Excellent
Ta-10Hf-10Zr	417	980/RT	Excellent
Ta-20Hf-1Zr	302	980/RT	Good
Ta-20Hf-2Al	343	980	Excellent
Ta-20Hf-5Al	292	980/RT	Fair
Ta-20Hf-2Al-2Cr	368	980	Good
Ta-20Hf-4Al-4Cr	660	980	Very poor
Ta-20Hf-8Al-1B	--	(f)	--
Ta-20Hf-3Al-1Si	468	980	Very poor
Ta-20Hf-5Al-3Si	--	(f)	--
Ta-20Hf-2Cr	293	980	Excellent
Ta-20Hf-5Cr	325	980/RT	Poor
Ta-20Hf-5Fe	508	980	Very poor
Ta-20Hf-5Ni	339	980	Very poor
Ta-20Hf-10W	401	980	Very poor
Ta-20Hf-10W	405	1600	Fair
Ta-30Hf-10W	442	980	Very poor
Ta-30Hf-10W	464	1600	Poor
Ta-5Mo-5Hf	287	980	Fair
Ta-5Mo-10Hf	312	980	Poor
Ta-5Mo-10Hf	339	1600	Good
Ta-5Mo-15Hf	409	1600	Poor
Ta-10Mo-5Hf	433	1600	Very poor
Ta-10Mo-10Hf	394	980	Very poor
Ta-5Mo-5V	342	980/RT	Good
Ta-5Mo-10V	503	980	Very poor
Ta-5Mo-10V	417	1600	Good

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness(a), VHN	Rolling Temperature(b), C	Quality of Strip(c)
Ta-5Mo-10V	437	1600	Poor
Ta-5Mo-10V	468	1600	Very poor
Ta-10Mo-10V	503	980	Very poor
Ta-5Mo-5W	289	980	Good
Ta-5Mo-7.5W	327	980	Fair
Ta-5Mo-10W	302	980	Poor
Ta-5Mo-10W	325	1600	Good
Ta-10Mo-5W	397	980	Poor
Ta-5Mo-1Zr	266	980	Excellent
Ta-5Mo-5Zr	351	980	Very poor
Ta-5Mo-10Zr	397	980	Very poor
Ta-10Mo-5Zr	413	1600	Very poor
Ta-10Mo-10Zr	483	980	Very poor
Ta-10Ti-5Mo	287	980	Very poor
Ta-10Ti-5V	281	980	Poor
Ta-10Ti-5W	233	RT	Excellent
Ta-10Ti-10Hf	245	RT	Excellent
Ta-10Ti-10W	306	980	Very poor
Ta-10Ti-10Zr	455	980/RT	Excellent
Ta-20Ti-5Al	266	RT	Excellent
Ta-20Ti-5Cr	266	RT	Good
Ta-20Ti-5Al-5Cr	383	980	Very poor
Ta-20Ti-3Al-5Cr	367	980	Excellent
Ta-20Ti-3Al-3Cr-1Si	461	980	Excellent
Ta-20Ti-4Al-1Be	522	980	Poor
Ta-20Ti-4Al-2Si	--	(f)	--
Ta-20Ti-5Al-1La	339	980	Poor
Ta-20Ti-5Al-1Y	248	980	Excellent
Ta-20Ti-6Cr-2Si	608	980	Very poor
Ta-20Ti-8Cr-1Y	352	980	Good

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness(a), VHN	Rolling Temperature(b), C	Quality of Strip(c)
Ta-20Ti-5Fe	421	980	Very poor
Ta-20Ti-5Mo	263	980/RT	Good
Ta-20Ti-5Ni	322	980	Poor
Ta-20Ti-5V	235	RT	Excellent
Ta-20Ti-5W	262	980/RT	Good
Ta-20Ti-10W	294	980/RT	Excellent
Ta-30Ti-1Be	309	980	Excellent
Ta-30Ti-1.5Si	373	980	Good
Ta-30Ti-5Al	264	980	Excellent
Ta-30Ti-5Al-1.5Si	458	980	Good
Ta-30Ti-5Al-5Cr	343	980	Excellent
Ta-30Ti-5Al-5Cr-1.5Si	--	(d)	--
Ta-30Ti-10Al	403	980	Very poor
Ta-30Ti-5Cr	264	980	Excellent
Ta-30Ti-10Cr	236	980	Excellent
Ta-30Ti-5Fe	353	980	Very poor
Ta-30Ti-5Ni	373	980	Fair
Ta-40Ti-5Al	251	980	Excellent
Ta-40Ti-10Al	383	980	Excellent
Ta-5V-5Hf	319	980/RT	Good
Ta-10V-5Hf	383	1600	Poor
Ta-5V-5W	339	980/RT	Excellent
Ta-5V-7.5W	317	980/RT	Excellent
Ta-5V-10W	579	980	Very poor
Ta-5V-10W	373	1600	Good
Ta-5V-1Zr	322	980/RT	Good
Ta-5V-5Zr	237	980	Poor
Ta-10V-10Zr	413	980	Very poor
Ta-10V-5W	455	980	Very poor
Ta-10V-5W	421	980/RT	Good
Ta-10V-5W	405	1600	Poor
Ta-10V-5W	417	1600	Poor

TABLE 2. FABRICATION OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition, weight per cent	Cast Hardness[(a)], VHN	Rolling Temperature[(b)], C	Quality of Strip[(c)]
Ta-10W-1Zr	264	980/RT	Good
Ta-10W-1Zr + C (1400 ppm)	376	980	Very poor
Ta-10W-5Hf	276	980/RT	Excellent
Ta-10Zr-5W	493	980	Very poor
Ta-20Zr-5Al	425	980	Very poor
Ta-20Zr-5Cr	425	980	Fair
Ta-20Zr-5Fe	473	980	Very poor
Ta-20Zr-5Ni	272	980	Poor

(a) Hardness values are the average of five impressions using a 10-kg load.

(b) Where two temperatures are shown [980/RT or 1600/RT], initial rolling conducted at 980 C (1800 F) or 1600 C (2910 F), followed by rolling at room temperature. Alloys rolled at 980 C (1800 F) in evacuated stainless steel packs. Alloys rolled at 1600 C (2910 F) in evacuated molybdenum packs.

(c) Excellent - no cracking of edges or surface
Good - slight cracking of edges and surface
Fair - considerable cracking of edges and surface
Poor - extensive cracking throughout specimen
Very poor - nonfabricable.

(d) Cracked upon machining.

(e) Fabrication failure attributed to contamination during arc melting.

(f) Broke upon cooling after arc melting.

Alloy Composition, weight per cent	Number of Fabrication Attempts	Number of Fabrication Failures at Indicated Temperature	
		980 C (1800 F)	1600 C (2910 F)
Ta-10V-5Mo	2	1 of 1	1 of 1
Ta-10V-10Mo	1	1 of 1	--
Ta-10V-5W	4	1 of 2	2 of 2
Ta-10V-10Zr	1	1 of 1	--

The reason for the inconsistent and poor fabricability of alloy composition containing 10 per cent vanadium is in part associated with interstitial contaminants contained in the vanadium. Typical interstitial analyses of the vanadium used in preparation of alloys are given below:

	Interstitial Contaminant, ppm				Total Interstitial Contaminants, ppm
	C	O	H	N	
Lot 1	800	187	9	760	1756
Lot 2	600	830	26	740	2196
Lot 3	400	830	6	280	1516

Material from Lots 1 and 2 were used in the preparation of the above alloys, while material from Lot 3 was used in the following alloys:

Alloy Composition, weight per cent	Number of Fabrication Attempts	Number of Fabrication Failures at Indicated Temperature	
		980 C (1800 F)	1600 C (2910 F)
Ta-10V	1	0 of 1	--
Ta-10V-30Cb	2	0 of 2	--
Ta-10V-5Mo	2	--	2 of 2

These results have shown that better fabricability is attained by using Lot 3 vanadium. This is attributed mainly to the lower nitrogen content of Lot 3 material as compared with either Lots 1 or 2. These findings are in general agreement with the recent studies of Savitskii, Baron, and Efimov(69) on the effects of impurities on the fabricability of unalloyed vanadium.

Cast hardnesses and fabricability data on the binary and ternary tantalum alloys are summarized graphically in Figure 6. On the basis of these data, the approximate fabricability limit for each ternary system has been established. The fabricability limits for solid-solution-strengthening

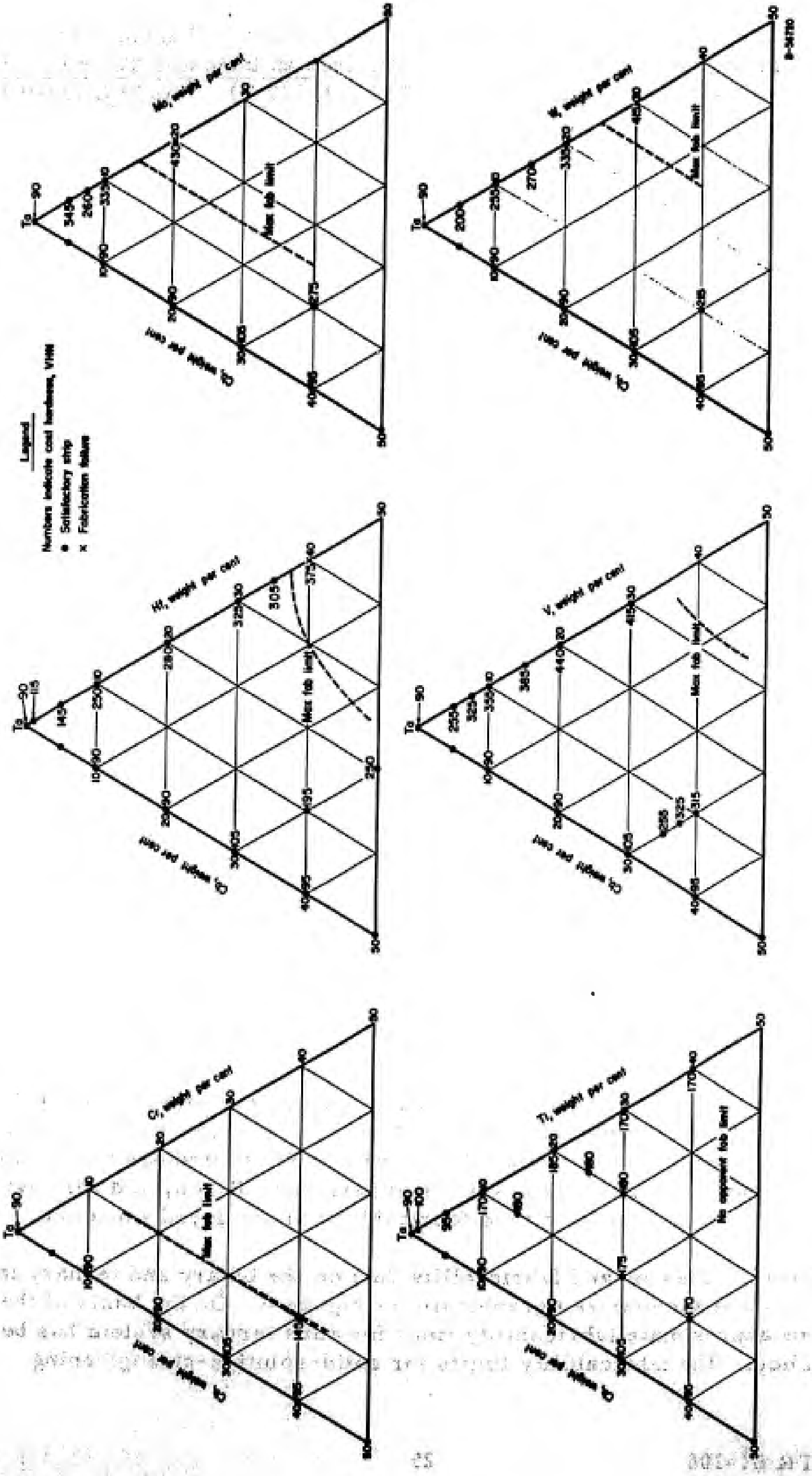


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS

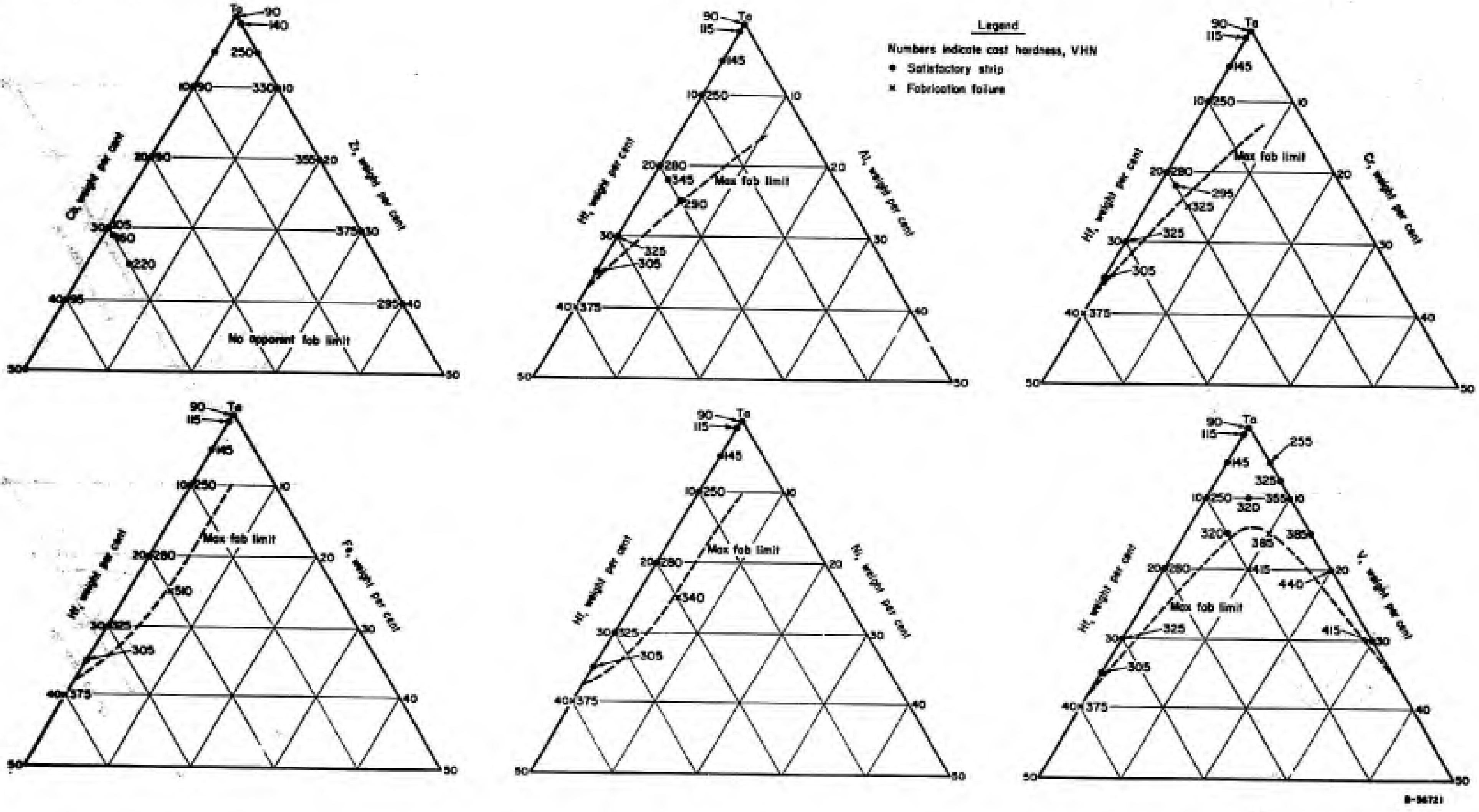


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS (Continued)

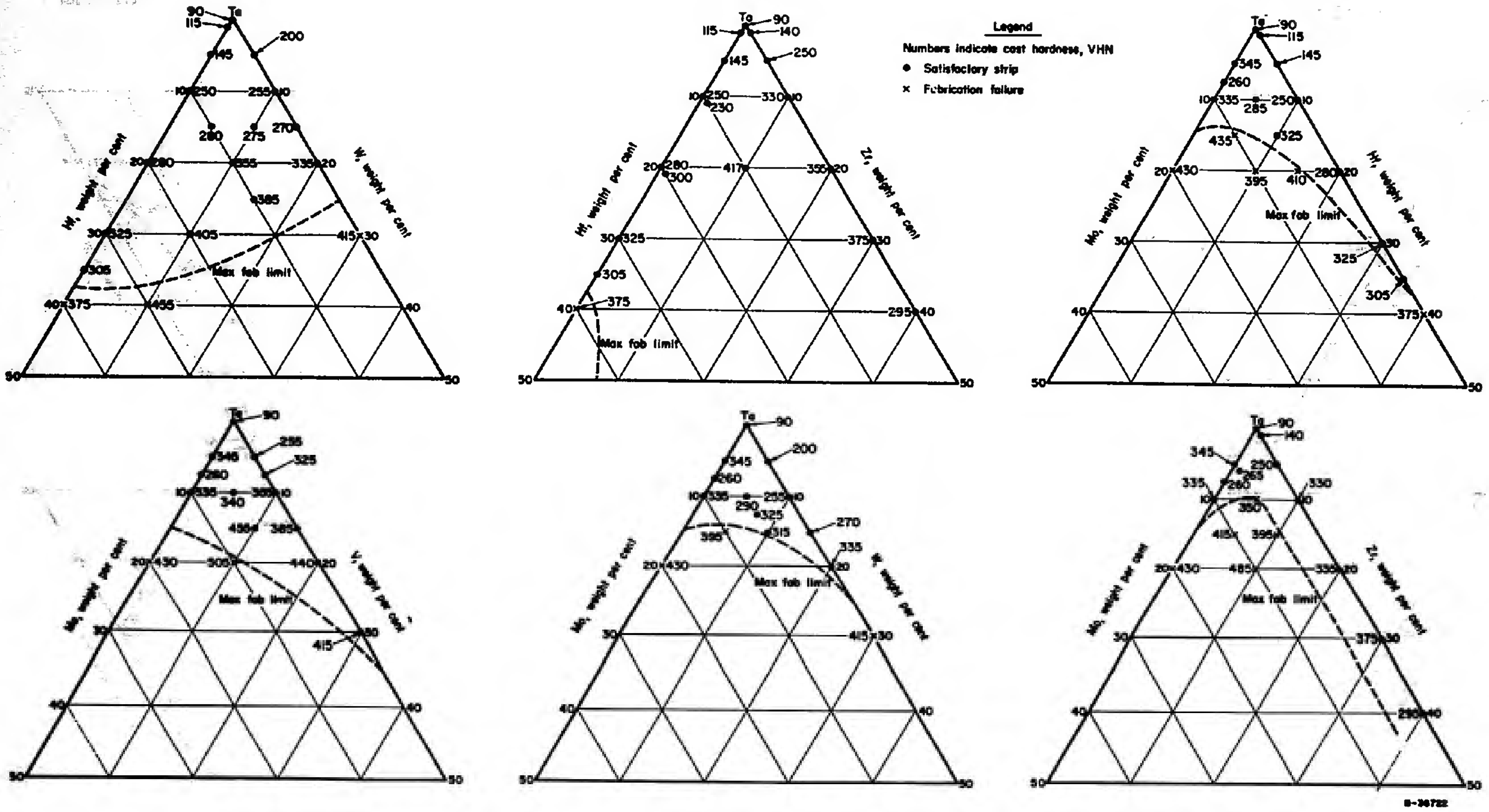


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS (Continued)

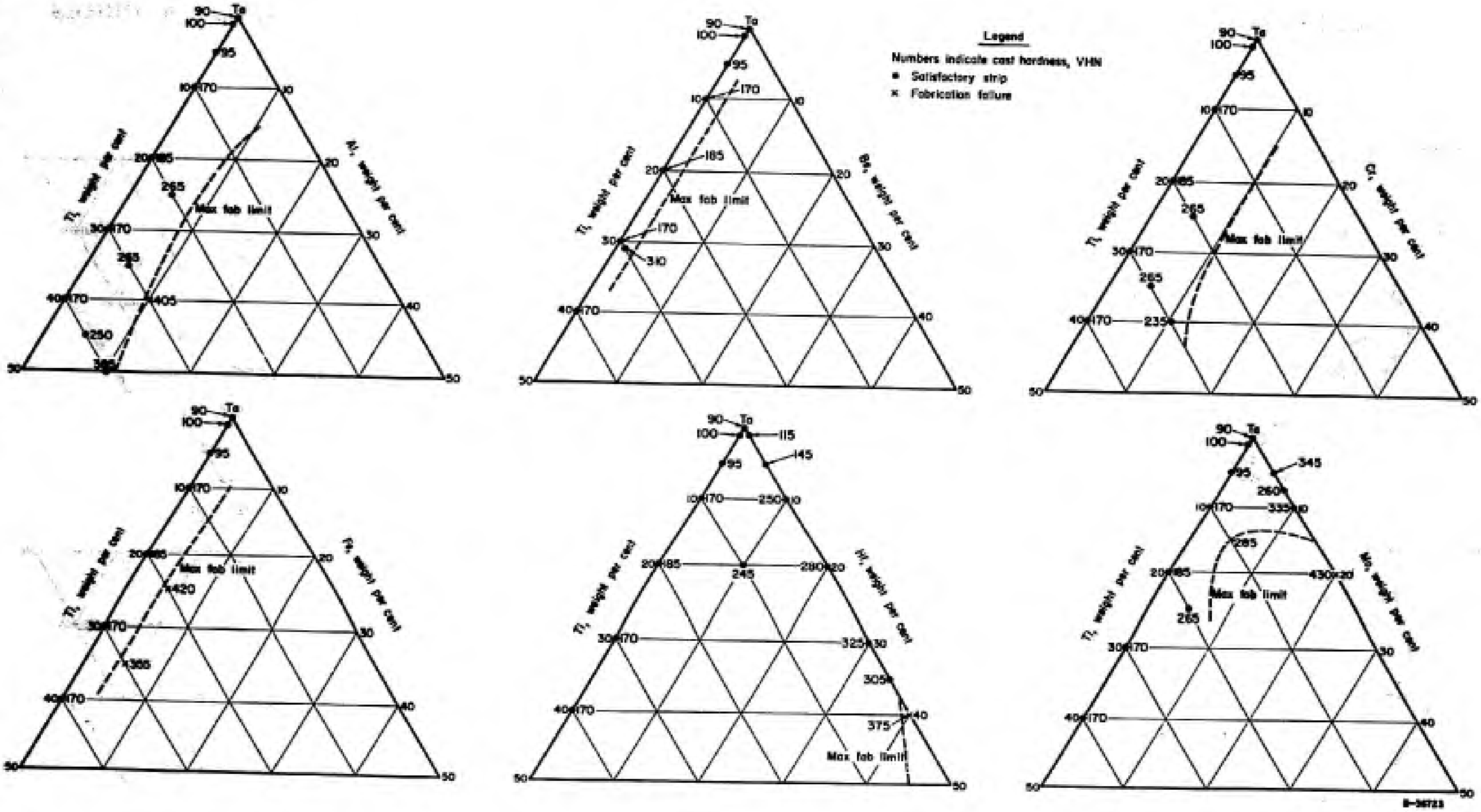


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS (Continued)

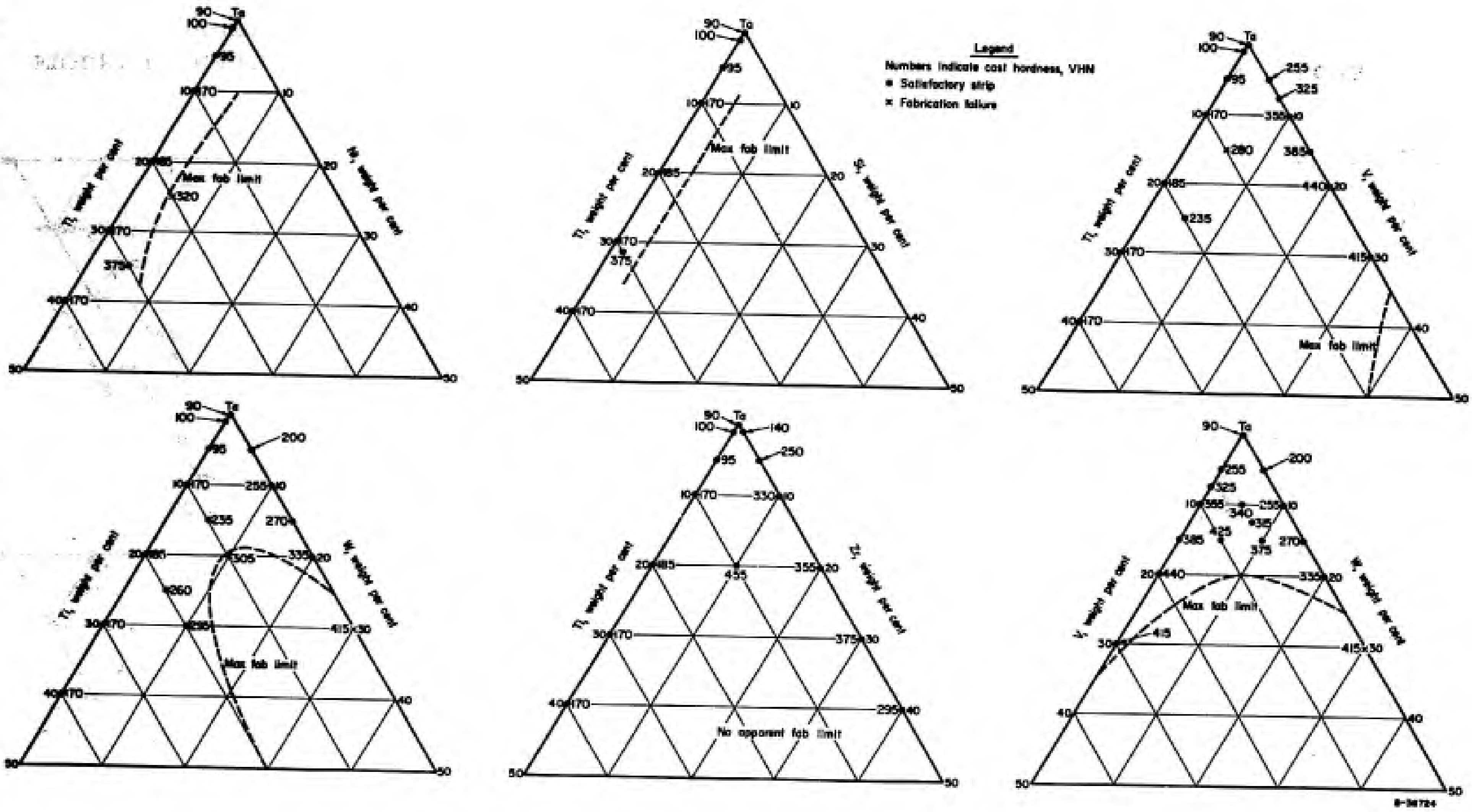


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS (Continued)

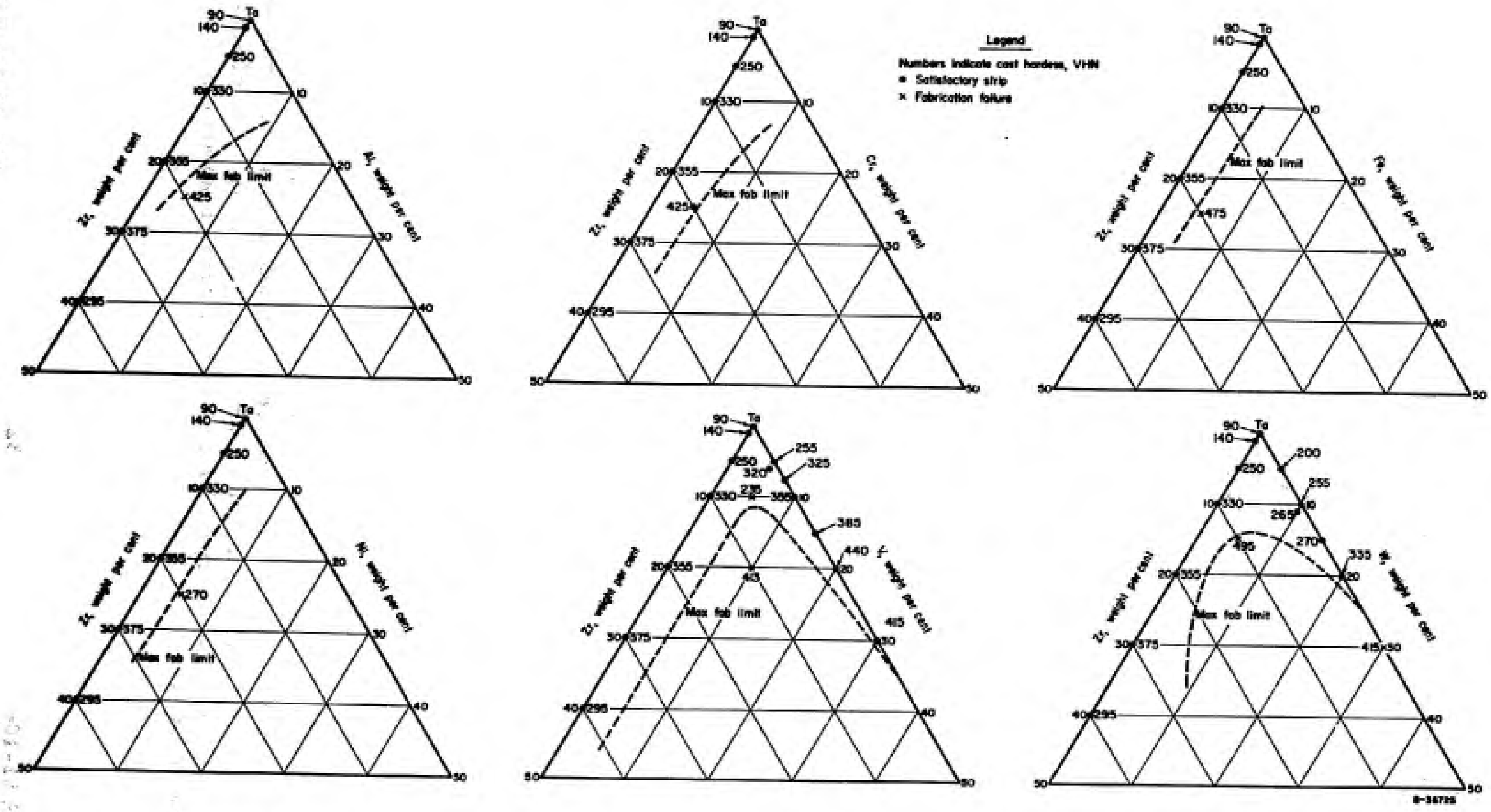


FIGURE 6. CAST HARDNESS AND FABRICABILITY OF BINARY AND TERNARY TANTALUM ALLOYS (Continued)

additions of columbium, hafnium, molybdenum, titanium, vanadium, tungsten, and zirconium were replotted to show the composite fabricability curves in Figures 7 through 13.

Each of the Ta-Cb-Ti, Ta-Cb-Zr, and Ta-Ti-Zr alloys investigated was fabricated to good-quality strip. However, definite limits to the region of alloy content for good fabricability were observed in the ternary alloys containing additions of hafnium, molybdenum, vanadium, and/or tungsten. Generally, these limits were less than those found for the same elements as binary-alloy additions. For example, the binary fabricability limits for hafnium and molybdenum are approximately 37.5 and 15 per cent, respectively, while the ternary Ta-Hf-Mo alloy fabricability limit continuously decreases below the 37.5 per cent for hafnium and the 15 per cent for molybdenum, Figure 8.

The fabricability of many of the Ta-20 to 40Ti-base alloys designed primarily for oxidation resistance was quite good, particularly when considering the complexity of many of the alloys. Increasing the titanium content improved the fabricability of a number of alloys. For example, the Ta-20Ti-5Al-5Cr alloy failed during fabrication; however, when the titanium content was increased to 30 per cent, the alloy fabricated to excellent-quality strip.

This behavior was also noted for alloy additions of hafnium, molybdenum, vanadium, and tungsten to the Ta-Ti base, Figure 10. These alloy additions to the Ta-Cb base remained at the approximate binary fabricability limits established, Figure 7. Therefore columbium can be added to high-strength, binary Ta-Mo and Ta-W alloys to reduce density without decreasing the fabricability.

Interstitial additions of carbon and oxygen ranging from 540 to 2300 ppm and 170 to 400 ppm, respectively, to binary and ternary tantalum alloys had little measurable effect on the fabricability.

Recrystallization Behavior

Test specimens were cut from the wrought strip and annealed in vacuum for 1 hour at temperatures from 1000 to 1500 C (1830 to 2730 F). Table 3 gives the recrystallization temperatures for tantalum and tantalum alloys, based on the results of microstructural examinations and hardness measurements as presented in Tables 4 and 5, respectively. The effects of alloy additions on the recrystallization temperature of tantalum are shown in Figures 14 and 15.

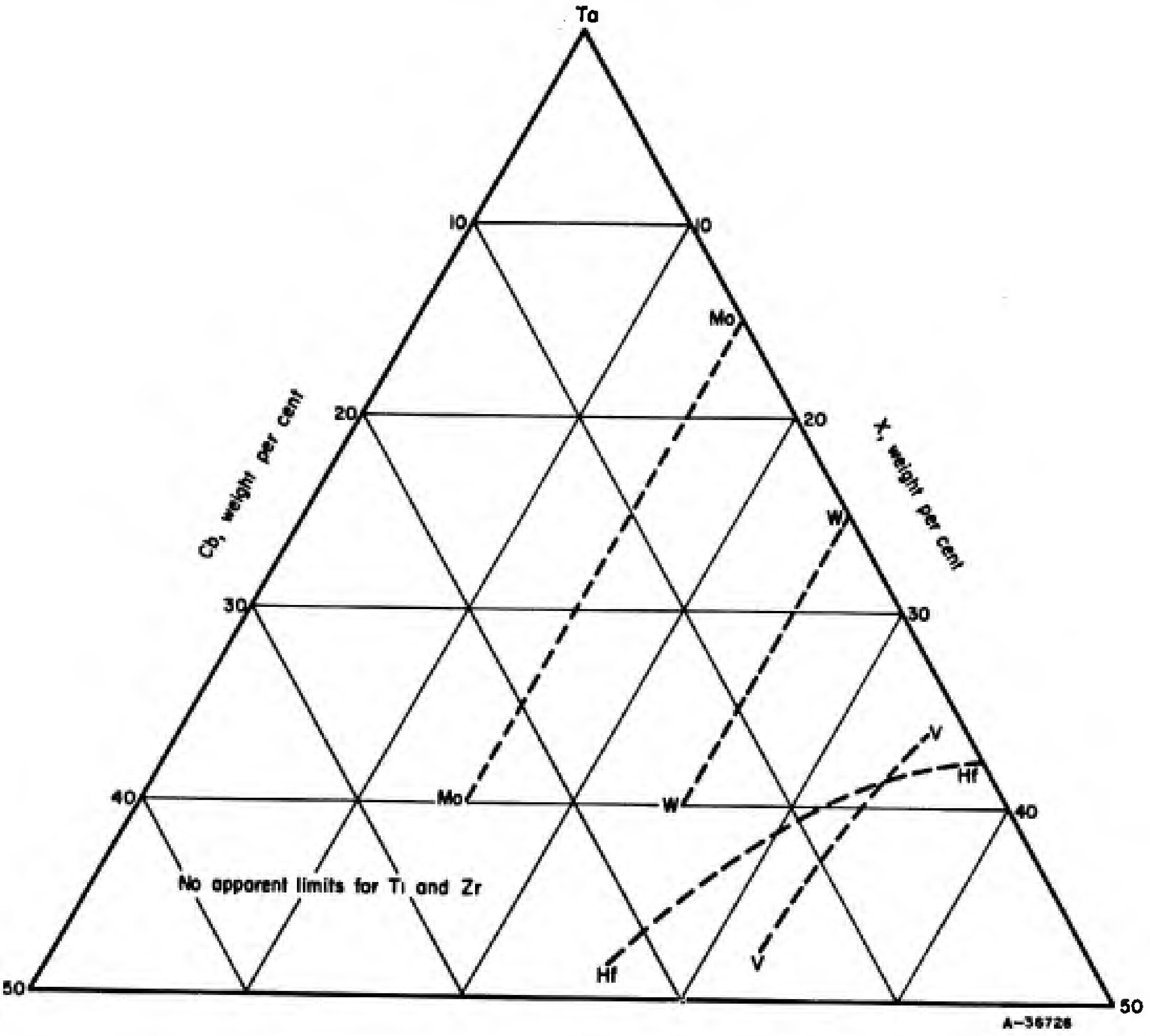


FIGURE 7. EFFECT OF Hf, Mo, Ti, V, W, AND Zr ON THE FABRICABILITY OF Ta-Cb ALLOYS

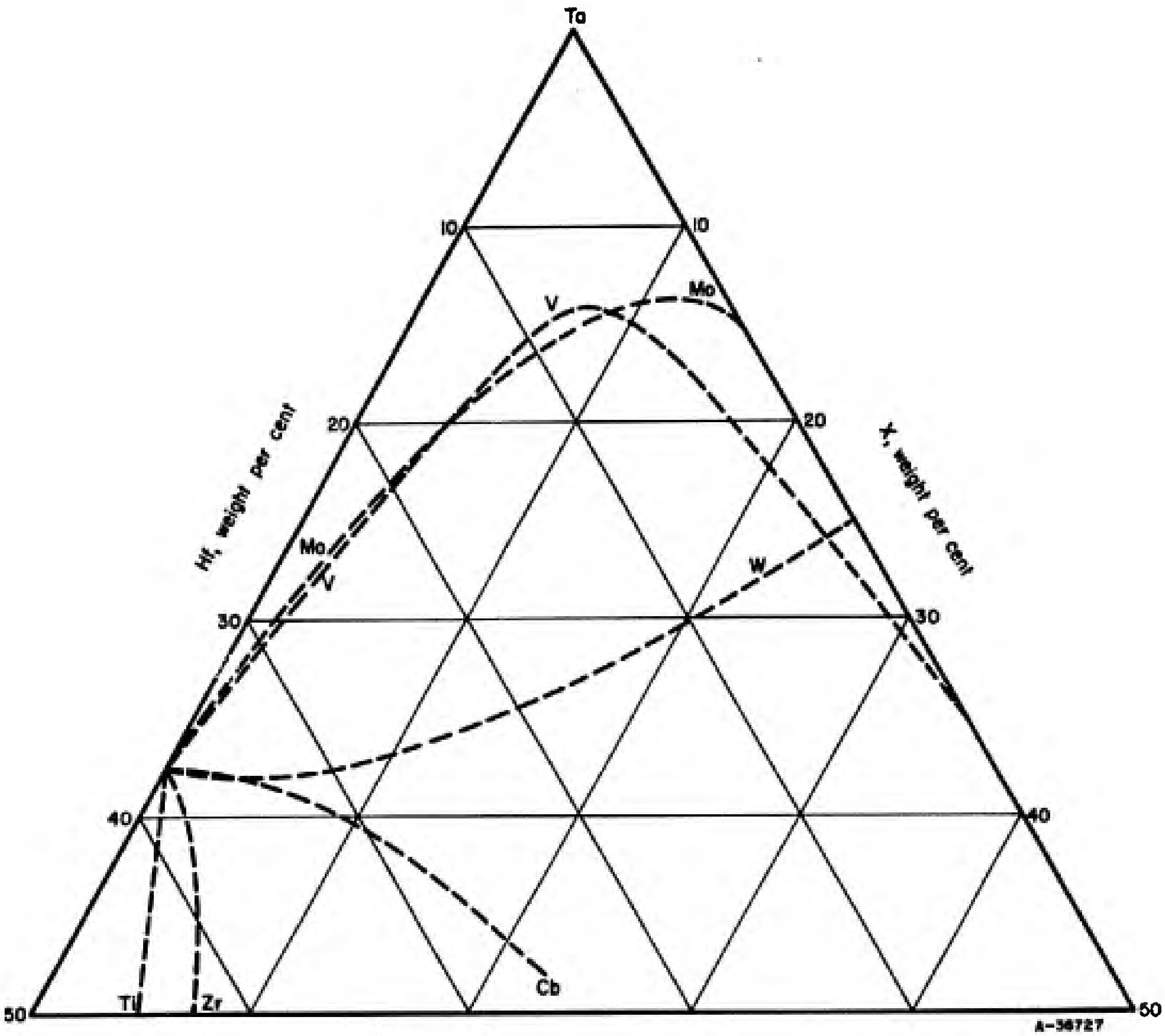


FIGURE 8. EFFECT OF Cb, Mo, Ti, V, W, AND Zr ON THE FABRICABILITY OF Ta-Hf ALLOYS

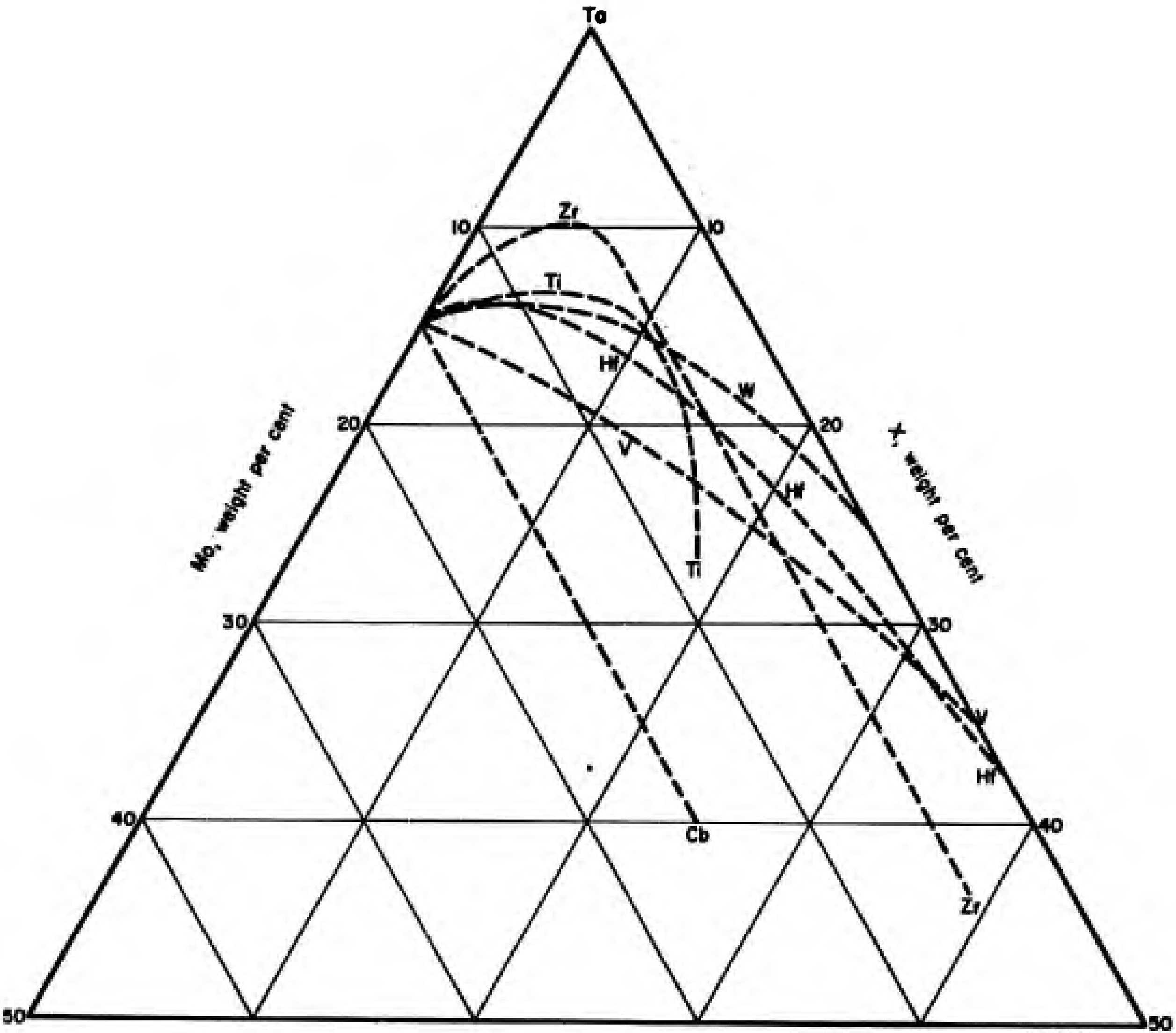


FIGURE 9. EFFECT OF Cb, Hf, Ti, V, W, AND Zr ON THE FABRICABILITY OF Ta-Mo ALLOYS

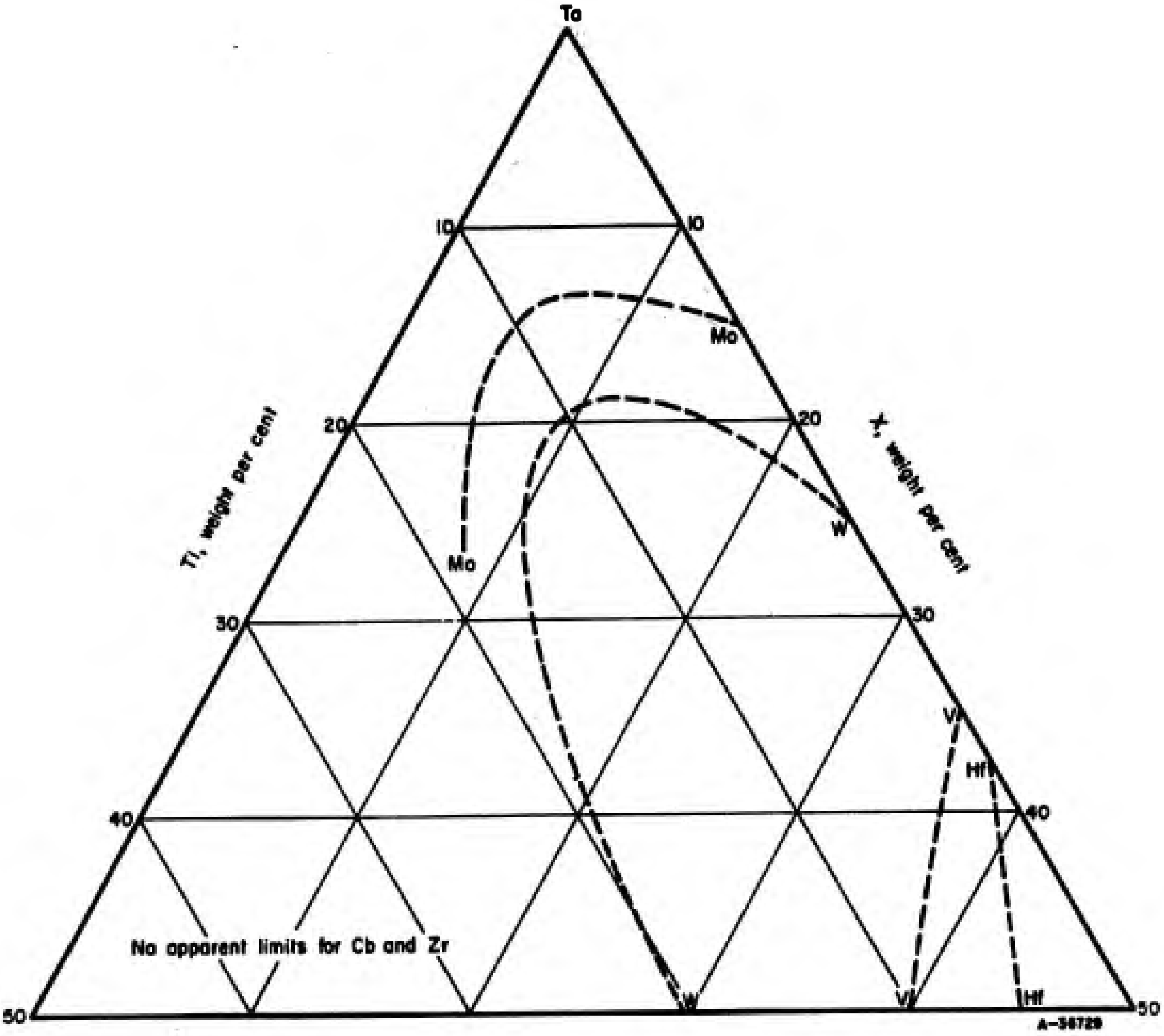


FIGURE 10. EFFECT OF Cb, Hf, Mo, V, W, AND Zr ON THE FABRICABILITY OF Ta-Ti ALLOYS

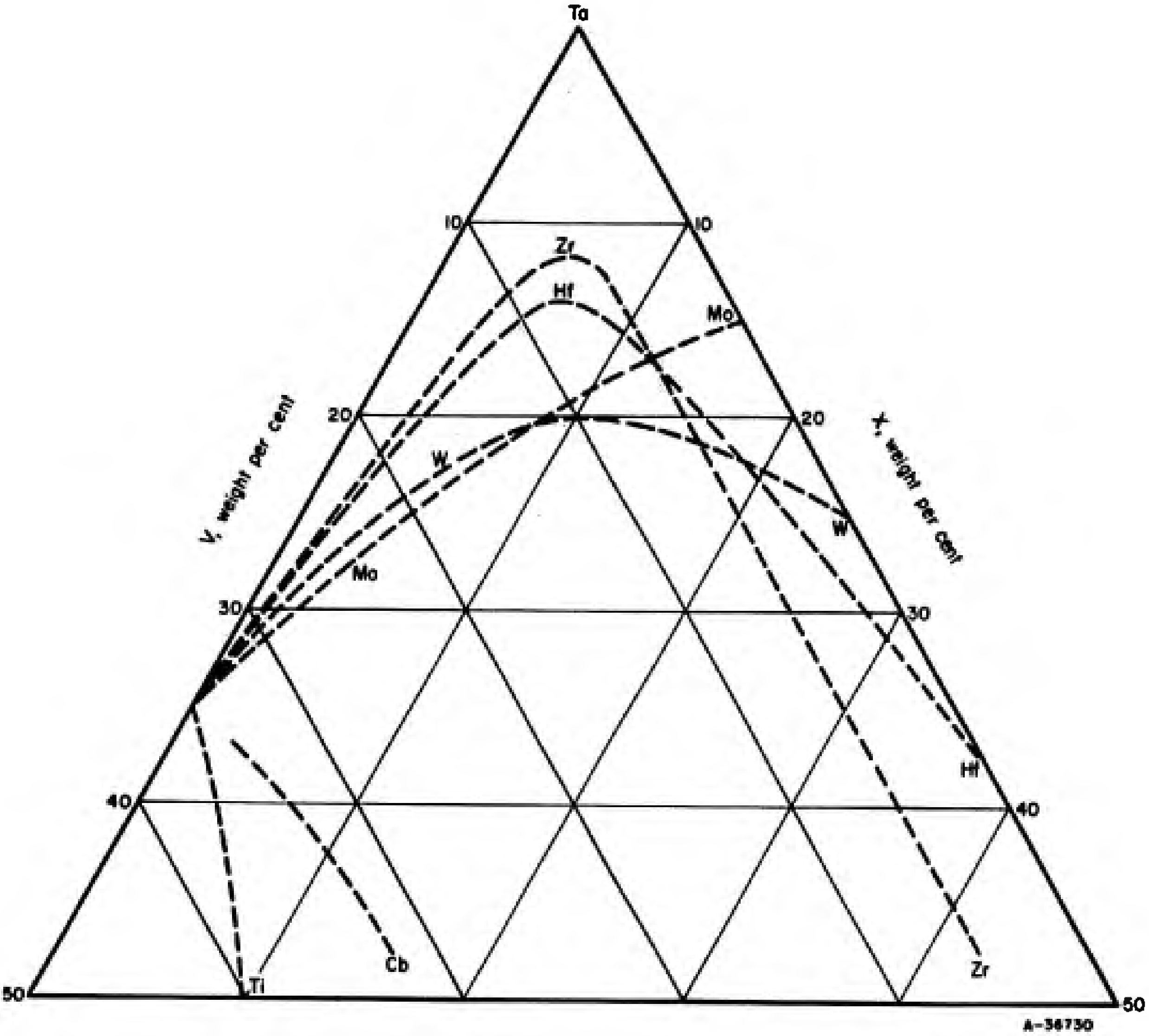


FIGURE 11. EFFECT OF Cb, Hf, Mo, Ti, W, AND Zr ON THE FABRICABILITY OF Ta-V ALLOYS

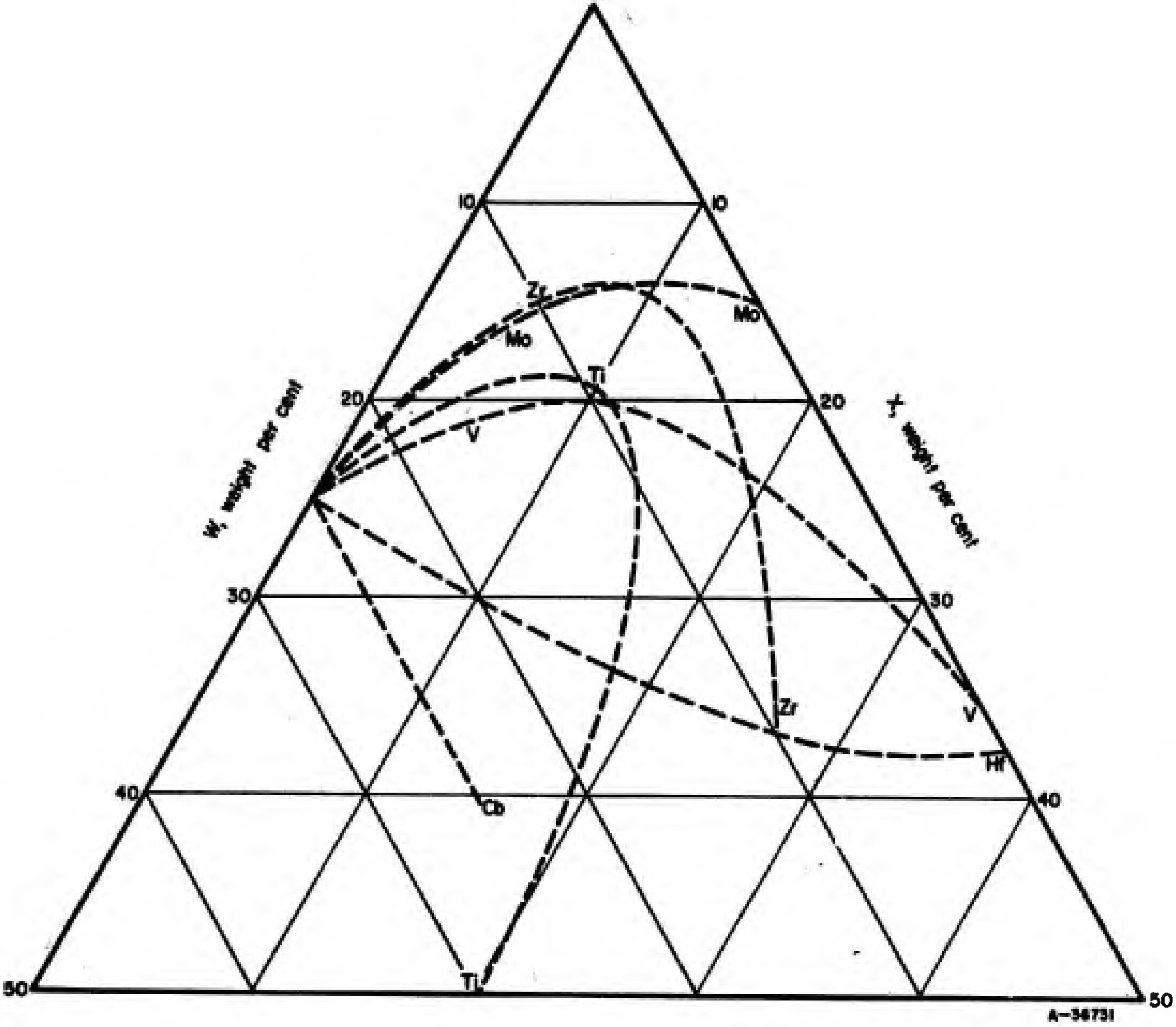


FIGURE 12. EFFECT OF Cb, Hf, Mo, Ti, V, AND Zr ON THE FABRICABILITY OF Ta-W ALLOYS

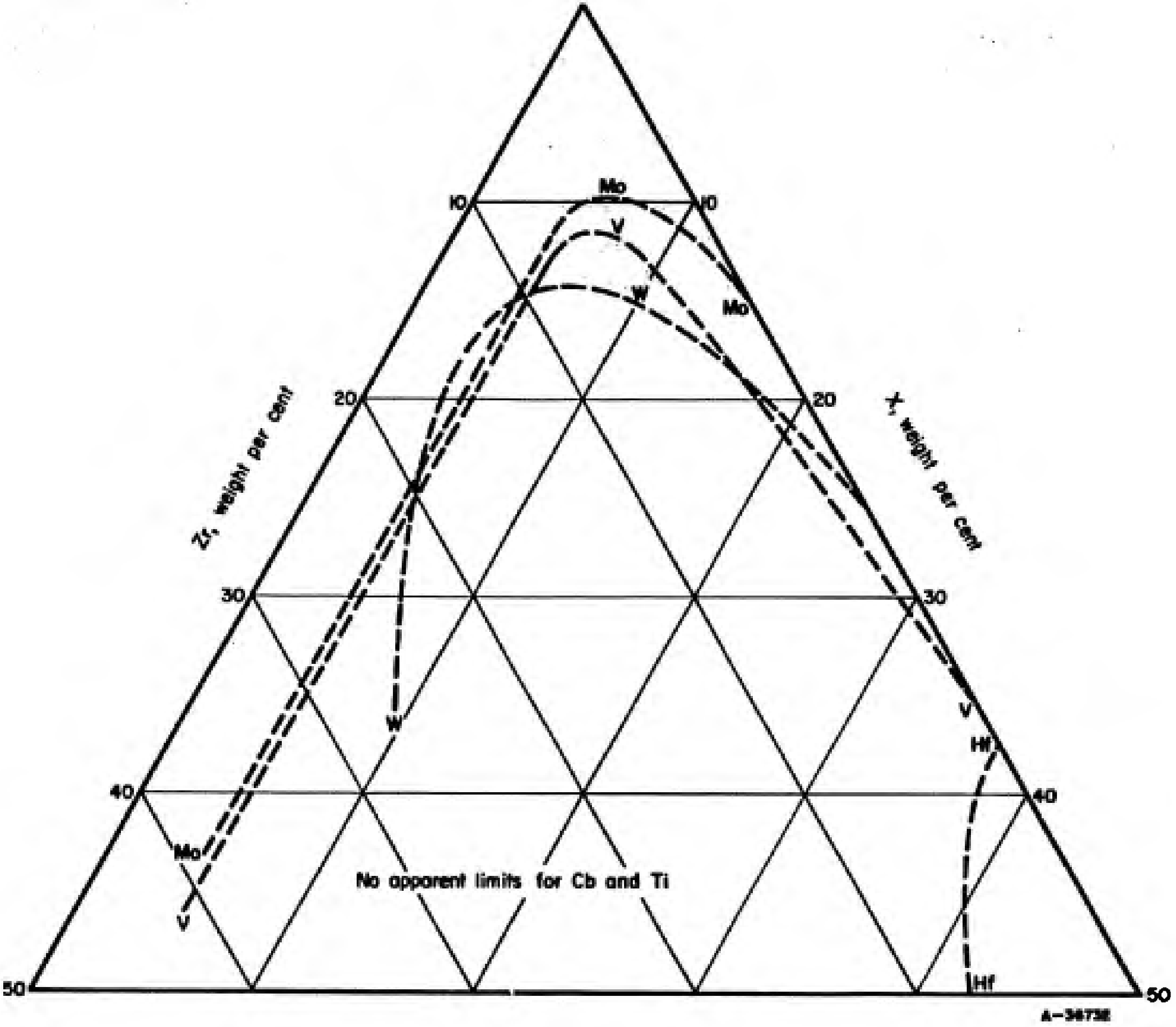


FIGURE 13. EFFECT OF Cb, Hf, Mo, Ti, V, AND W ON THE FABRICABILITY OF Ta-Zr ALLOYS

TABLE 3. RECRYSTALLIZATION TEMPERATURES FOR TANTALUM AND TANTALUM ALLOYS[(a)]

Alloy Composition, weight per cent	Condition[(b)]	Recrystallization Temperature C	Recrystallization Temperature F
100Ta	CW 50 per cent	1200	2190
Ta-5Cb	CW 50 per cent	1300	2370
Ta-10Cb	CW 50 per cent	1300	2370
Ta-20Cb	CW 50 per cent	1300	2370
Ta-30Cb	CW 50 per cent	1400	2550
Ta-40Cb	CW 50 per cent	1400	2550
Ta-50Cb	CW 50 per cent	1300	2370
Ta-1Hf	CW 50 per cent	1300	2370
Ta-1Hf + C (700 ppm)	CW 65 per cent	1300	2370
Ta-1Hf + O (170 ppm)	CW 65 per cent	1300	2370
Ta-5Hf	CW 50 per cent	1300	2370
Ta-10Hf	PR 980 C/CW 30 per cent	1300	2370
Ta-10Hf + C (630 ppm)	PR 980 C/CW 60 per cent	1500	2730
Ta-20Hf	PR 980 C/CW 75 per cent	1400	2550
Ta-30Hf	PR 980 C/CW 15 per cent	1400	2550
Ta-35Hf	PR 980 C/CW 50 per cent	1300	2370
Ta-5Mo	PR 980 C/CW 35 per cent	1400	2550
Ta-7.5Mo	PR 980 C/CW 60 per cent	1400	2550
Ta-10Mo	PR 1600 C	(1600)[(c)]	(2910)
Ta-5Re	CW 65 per cent	1400	2550
Ta-1Ti	CW 50 per cent	1300	2370
Ta-1Ti + C (2300 ppm)	PR 980 C/CW 10 per cent	1300	2370
Ta-1Ti + O (280 ppm)	CW 65 per cent	1300	2370
Ta-5Ti	CW 50 per cent	1200	2190
Ta-10Ti	CW 50 per cent	1200	2190
Ta-20Ti	CW 50 per cent	1200	2190
Ta-30Ti	CW 50 per cent	1100	2010
Ta-40Ti	CW 50 per cent	1000	1830
Ta-5V	PR 980 C/CW 30 per cent	1300	2370
Ta-5V	PR 980 C/CW 50 per cent	1300	2370
Ta-5V + C (580 ppm)	PR 980 C/CW 40 per cent	1300	2370
Ta-7.5V	PR 980 C/CW 50 per cent	1300	2370
Ta-10V	PR 980 C/CW 50 per cent	1300	2370
Ta-10V	PR 980 C/CW 75 per cent	1200	2190

TABLE 3. RECRYSTALLIZATION TEMPERATURES FOR TANTALUM AND TANTALUM ALLOYS[(a)] (Continued)

Alloy Composition, weight per cent	Condition[(b)]	Recrystallization Temperature C	Recrystallization Temperature F
Ta-10V	PR 1600 C/CW 15 per cent	(d)	(d)
Ta-15V	PR 980 C/CW 50 per cent	1300	2370
Ta-20V	PR 980 C/CW 10 per cent	1300	2370
Ta-20V	PR 980 C/CW 75 per cent	1300	2370
Ta-30V	PR 1600 C/CW 5 per cent	(d)	(d)
Ta-5W	CW 65 per cent	1400	2550
Ta-10W	PR 980 C	1400	2550
Ta-10W + C (590 ppm)	PR 980 C/CW 60 per cent	1400	2550
Ta-15W	PR 980 C/CW 65 per cent	1500	2730
Ta-20W	PR 980 C	(1600)	(2910)
Ta-20W	PR 1600 C	(1700)	(3090)
Ta-1Zr	CW 50 per cent	1300	2370
Ta-1Zr + C (1400 ppm)	PR 980C/CW 20 per cent	1300	2370
Ta-1Zr + O (400 ppm)	CW 65 per cent	1300	2370
Ta-5Zr	PR 980 C/CW 50 per cent	1400	2550
Ta-10Zr	PR 980 C/CW 30 per cent	1300	2370
Ta-20Zr	PR 980 C/CW 20 per cent	1300	2370
Ta-40Zr	PR 980 C	1300	2370
Ta-5Cb-10Ti	CW 75 per cent	1200	2190
Ta-5Cb-20Ti	CW 65 per cent	1200	2190
Ta-10Cb-20Ti	CW 50 per cent	1200	2190
Ta-20Cb-10Ti	CW 50 per cent	(1300)	(2370)
Ta-30Cb-10Ti	CW 50 per cent	1300	2370
Ta-30Cb-10Cr	PR 980 C	1300	2370
Ta-30Cb-10Hf	PR 980 C	1300	2370
Ta-30Cb-20Hf	PR 980 C/CW 60 per cent	1400	2550
Ta-30Cb-10Mo	PR 980 C	1400	2550
Ta-30Cb-10W	PR 980 C	(1500)	(2730)
Ta-30Cb-5V	PR 980 C	1200	2190
Ta-30Cb-5V	PR 980 C/CW 50 per cent	1300	2370
Ta-30Cb-5V	PR 980 C/CW 55 per cent	1200	2190
Ta-30Cb-5V-1Zr	PR 980 C/CW 60 per cent	1200	2190
Ta-30Cb-7.5V	PR 980 C/CW 50 per cent	1300	2370
Ta-30Cb-10V	PR 980 C/CW 50 per cent	1500	2730
Ta-30Cb-10V	PR 1600 C/CW 45 per cent	1200	2190

TABLE 3. RECRYSTALLIZATION TEMPERATURES FOR TANTALUM AND TANTALUM ALLOYS[(a)] (Continued)

Alloy Composition, weight per cent	Condition[(b)]	Recrystallization Temperature	
		C	F
Ta-30Cb-1Zr	CW 65 per cent	1400	2550
Ta-30Cb-5Zr	PR 980 C	1400	2550
Ta-10Hf-5V	PR 1600 C	1300	2370
Ta-10Hf-5W	PR 980 C/CW 30 per cent	1500	2730
Ta-10Hf-5W	PR 980 C/CW 60 per cent	1400	2550
Ta-10Hf-5W + C (540 ppm)	PR 980 C/CW 60 per cent	1500	2730
Ta-10Hf-10W	PR 1600 C	1500	2730
Ta-10Hf-15W	PR 1600 C	(1600)	(2910)
Ta-10Hf-1Zr	PR 980 C/CW 50 per cent	1400	2550
Ta-10Hf-1Zr	PR 980 C/CW 50 per cent	1400	2550
Ta-10Hf-10Zr	PR 980 C/CW 70 per cent	1300	2370
Ta-20Hf-5Al	PR 980 C/CW 75 per cent	1300	2370
Ta-20Hf-5Cr	PR 980 C/CW 75 per cent	1300	2370
Ta-20Hf-10W	PR 1600 C	1500	2730
Ta-5Mo-10Hf	PR 1600 C	1500	2730
Ta-5Mo-5V	PR 980 C/CW 65 per cent	1300	2370
Ta-5Mo-10V	PR 1600 C	(d)	(d)
Ta-5Mo-10W	PR 1600 C	(1700)	(3090)
Ta-10Ti-5W	CW 65 per cent	1300	2370
Ta-10Ti-10Hf	CW 65 per cent	1200	2190
Ta-10Ti-10Zr	PR 980 C/CW 70 per cent	1300	2370
Ta-20Ti-5Al	CW 70 per cent	1100	2010
Ta-20Ti-5Cr	CW 65 per cent	1100	2010
Ta-20Ti-5Mo	PR 980 C/CW 70 per cent	1200	2190
Ta-20Ti-5V	CW 65 per cent	1000	1830
Ta-20Ti-5W	PR 980 C/CW 70 per cent	1300	2370
Ta-20Ti-10W	PR 980 C/CW 70 per cent	1300	2370

TABLE 3. RECRYSTALLIZATION TEMPERATURES FOR TANTALUM AND TANTALUM ALLOYS[a] (Continued)

Alloy Composition, weight per cent	Condition[b]	Recrystallization Temperature C	Recrystallization Temperature F
Ta-5V-5W	PR 980 C/CW 50 per cent	1400	2550
Ta-5V-7.5W	PR 980 C/CW 50 per cent	1500	2730
Ta-5V-10W	PR 1600 C	1500	2730
Ta-5V-1Zr	PR 980 C/CW 65 per cent	1300	2370
Ta-10V-5W	PR 980 C/CW 5 per cent	1400	2550
Ta-10W-1Zr	PR 980 C/CW 60 per cent	1400	2550
Ta-10W-5Hf	PR 980 C/CW 60 per cent	1400	2550

(a) Complete recrystallization after 1-hour exposure in vacuum.

(b) PR = pack rolled
CW = cold worked.

(c) Values in parentheses are estimated.

(d) Wrought material showed a completely recrystallized microstructure.

TABLE 4. MICROSTRUCTURES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS[(a)]

Alloy Composition, weight per cent	Microstructure[(b)] After Annealing 1 Hour at Indicated Temperature					
	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
100Ta	R_p	R_p	$\underline{R}$	R	R	--
Ta-5Cb	W	R_b	R_p	$\underline{R}$	R	--
Ta-10Cb	W	R_p	R_p	$\underline{R}$	R	--
Ta-20Cb	W	R_p	R_p	$\underline{R}$	R	--
Ta-30Cb	W	W	R_p	R_p	$\underline{R}$	--
Ta-40Cb	W	W	R_p	R_p	$\underline{R}$	--
Ta-50Cb	--	W	R_p	$\underline{R}$	R	R
Ta-1Hf	W	R_b	R_p	$\underline{R}$	R	R
Ta-1Hf + C (700 ppm)	W	R_b	R_p	$\underline{R}$	R	R
Ta-1Hf + O (170 ppm)	W	R_b	R_p	$\underline{R}$	R	R
Ta-5Hf	W	R_b	R_p	$\underline{R}$	R	--
Ta-10Hf	W	W	R_p	$\underline{R}$	R	R
Ta-10Hf + C (630 ppm)	W	W	R_b	R_p	R_p	$\underline{R}$
Ta-20Hf	W	W	W	R_p	$\underline{R}$	R
Ta-30Hf	W	W	R_b	R_p	$\underline{R}$	R
Ta-35Hf	W	W	R_b	$\underline{R}$	R	R
Ta-5Mo	W	W	W	R_b	$\underline{R}$	R
Ta-7.5Mo	W	W	W	R_p	$\underline{R}$	R
Ta-10Mo	W	W	W	W	W	R_b
Ta-5Re	W	W	R_b	R_p	$\underline{R}$	R
Ta-1Ti	W	R_b	R_p	$\underline{R}$	R	R
Ta-1Ti + C (2300 ppm)	W	R_b	R_p	$\underline{R}$	R	R
Ta-1Ti + O (280 ppm)	W	R_b	R_p	$\underline{R}$	R	R
Ta-5Ti	R_b	R_p	$\underline{R}$	R	--	--
Ta-10Ti	W	R_b	$\underline{R}$	--	--	--
Ta-20Ti	W	R_p	$\underline{R}$	--	--	--
Ta-30Ti	R_p	$\underline{R}$	R			
Ta-40Ti	$\underline{R}$	R	R	R		
Ta-5V	W	W	R_p	$\underline{R}$	R	R
Ta-5V	W	W	R_p	$\underline{R}$	R	R
Ta-5V + C (580 ppm)	W	W	R_b	$\underline{R}$	R	R
Ta-7.5V	W	W	R_p	$\underline{R}$	R	R
Ta-10V	W	R_b	R_p	$\underline{R}$	R	R
Ta-10V	W	R_p	$\underline{R}$	R	R	R
Ta-10V[(c)]	R	R	R	R	R	R
Ta-15V	W	W	W	$\underline{R}$	R	R
Ta-20V	W	R_b	R_p	$\underline{R}$	R	R
Ta-20V	W	W	W	$\underline{R}$	R	R
Ta-30V[(c)]	--	--	--	R	R	R

TABLE 4. MICROSTRUCTURES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS(a) (Continued)

Alloy Composition, weight per cent	Microstructure(b) After Annealing 1 Hour at Indicated Temperature					
	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
Ta-5W	W	W	R_b	R_p	$\underline{R}$	R
Ta-10W	--	W	W	R_b	$\underline{R}$	R
Ta-10W + C (590 ppm)	W	W	R_b	R_p	$\underline{R}$	R
Ta-15W	W	W	W	W	R_b	$\underline{R}$
Ta-20W	--	W	W	W	W	R_b
Ta-20W	W	W	W	W	W	W
Ta-1Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-1Zr + C (1400 ppm)	W	W	R_b	$\underline{R}$	R	R
Ta-1Zr + O (400 ppm)	W	R_b	R_p	$\underline{R}$	R	R
Ta-5Zr	W	W	W	R_b	$\underline{R}$	R
Ta-10Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-20Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-40Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-5Cb-10Ti	W	R_p	$\underline{R}$	R	R	R
Ta-5Cb-20Ti	R_b	R_p	$\underline{R}$	R	R	R
Ta-10Cb-20Ti	W	R_p	$\underline{R}$	--	--	--
Ta-20Cb-10Ti	W	R_p	R_p	$(\underline{R})$(d)	--	--
Ta-30Cb-10Ti	W	R_b	R_p	$\underline{R}$	R	--
Ta-30Cb-10Cr	W	R_b	R_p	$\underline{R}$	R	--
Ta-30Cb-10Hf	W	R_b	R_p	$\underline{R}$	R	--
Ta-30Cb-20Hf	W	W	R_b	R_p	$\underline{R}$	R
Ta-30Cb-10Mo	W	W	W	R_p	$\underline{R}$	--
Ta-30Cb-10W	W	W	W	R_b	R_p	$(\underline{R})$
Ta-30Cb-5V	W	R_p	$\underline{R}$	R	R	--
Ta-30Cb-5V	W	W	R_p	$\underline{R}$	R	R
Ta-30Cb-5V	--	--	$\underline{R}$	R	R	--
Ta-30Cb-5V-1Zr	W	R_b	$\underline{R}$	R	R	R
Ta-30Cb-7.5V	W	W	R_p	$\underline{R}$	R	R
Ta-30Cb-10V	W	W	R_p	R_p	R_p	$\underline{R}$
Ta-30Cb-10V	R_p	R_p	$\underline{R}$	R	R	R
Ta-30Cb-1Zr	W	W	R_b	R_p	$\underline{R}$	R
Ta-30Cb-5Zr	W	R_b	R_p	R_p	$\underline{R}$	--
Ta-10Hf-5V	R_p	R_p	R_p	$\underline{R}$	R	R
Ta-10Hf-5W	W	W	W	R_b	R_p	$\underline{R}$
Ta-10Hf-5W	--	--	--	R_p	$\underline{R}$	R
Ta-10Hf-5W + C (540 ppm)	W	W	W	R_b	R_p	$\underline{R}$
Ta-10Hf-10W	W	W	W	W	R_b	$\underline{R}$
Ta-10Hf-15W	W	W	W	W	W	R_p

TABLE 4. MICROSTRUCTURES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS[(a)] (Continued)

Alloy Composition, weight per cent	Microstructure[(b)] After Annealing 1 Hour Indicated Temperature					
	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
Ta-10Hf-1Zr	W	W	W	R_p	$\underline{R}$	R
Ta-10Hf-1Zr	W	W	R_b	R_p	$\underline{R}$	R
Ta-10Hf-10Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-20Hf-5Al	W	W	R_p	$\underline{R}$	R	R
Ta-30Hf-5Cr	W	W	R_b	$\underline{R}$	R	R
Ta-20Hf-10W	W	W	R_p	R_p	R_p	$\underline{R}$
Ta-5Mo-10Hf	W	W	W	W	R_p	$\underline{R}$
Ta-5Mo-5V	W	W	R_p	$\underline{R}$	R	R
Ta-5Mo-10V[(c)]	R	R	R	R	R	R
Ta-5Mo-10W	W	W	W	W	W	W
Ta-10Ti-5W	W	W	R_p	$\underline{R}$	R	R
Ta-10Ti-10Hf	W	R_p	$\underline{R}$	R	R	R
Ta-10Ti-10Zr	W	R_b	R_p	$\underline{R}$	R	R
Ta-20Ti-5Al	R_p	$\underline{R}$	R	R	R	R
Ta-20Ti-5Cr	R_p	$\underline{R}$	R	R	R	R
Ta-20Ti-5Mo	W	R_p	$\underline{R}$	R	R	R
Ta-20Ti-5V	$\underline{R}$	R	R	R	R	R
Ta-20Ti-5W	W	R_b	R_p	$\underline{R}$	R	R
Ta-20Ti-10W	W	R_b	R_p	$\underline{R}$	R	R
Ta-5V-5W	W	W	W	R_p	$\underline{R}$	R
Ta-5V-7.5W	W	W	W	R_p	R_p	$\underline{R}$
Ta-5V-10W	W	W	W	R_b	R_p	$\underline{R}$
Ta-5V-1Zr	W	W	R_b	$\underline{R}$	R	R
Ta-10V-5W	W	W	W	R_b	$\underline{R}$	R
Ta-10W-1Zr	W	W	R_b	R_p	$\underline{R}$	R
Ta-10W-5Hf	W	W	W	R_p	$\underline{R}$	R

(a) Specimens annealed in vacuum.

(b) W = Wrought; R_p = Recrystallization partially complete; R_b = Recrystallization beginning; R = Recrystallization completed. Minimum temperature for complete recrystallization is underlined.

(c) Wrought material showed a completely recrystallized microstructure.

(d) Values in parentheses are estimated.

TABLE 5. HARDNESSES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS[(a)]

Alloy Composition, weight per cent	Hardness[(b)], VHN, After Annealing 1-Hour At Indicated Temperature							
	Cast, RT	Wrought, RT	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
100Ta	88	161	128	132	108[(c)]	88	91	--
Ta-5Cb	--	157	150	136	93	98	93	--
Ta-10Cb	89	178	146	132	104	87	93	--
Ta-20Cb	91	175	147	135	104	91	103	--
Ta-30Cb	104	178	158	144	133	112	107	--
Ta-40Cb	93	167	140	135	104	98	95	--
Ta-50Cb	--	156	--	110	105	97	113	114
Ta-1Hf	116	189	175	167	148	136	113	118
Ta-1Hf + C (700 ppm)	156	242	216	202	176	126	121	131
Ta-1Hf + O (170 ppm)	128	285	274	266	258	245	232	218
Ta-5Hf	146	249	190	193	195	157	145	--
Ta-10Hf	260	325	268	260	215	206	215	222
Ta-10Hf + C (630 ppm)	251	351	330	285	251	218	215	212
Ta-20Hf	268	366	363	276	270	270	274	294
Ta-30Hf	322	390	357	336	330	322	336	342
Ta-35Hf	306	387	383	325	327	314	327	333
Ta-5Mo	345	363	351	360	333	327	302	292
Ta-7.5Mo	260	380	348	351	360	330	317	281
Ta-10Mo	360	413	394	366	345	339	330	330
Ta-5Re	253	373	327	330	309	279	247	243
Ta-1Ti	100	222	197	199	185	171	167	154
Ta-1Ti + C (2300 ppm)	146	203	183	157	157	160	197	197
Ta-1Ti + O (280 ppm)	124	180	147	150	126	121	123	135
Ta-5Ti	94	--	167	156	108	103	--	--
Ta-10Ti	168	229	195	192	182	--	--	--
Ta-20Ti	185	229	212	208	204	--	--	--
Ta-30Ti	170	225	197	190	192	--	--	--
Ta-40Ti	168	265	177	185	188	192	--	--
Ta-5V	245	302	287	297	299	--	281	283
Ta-5V	268	373	325	322	302	264	254	262
Ta-5V + C (580 ppm)	357	417	394	373	366	322	333	351
Ta-7.5V	325	421	383	363	342	327	327	333
Ta-10V	342	459	405	387	363	339	342	360
Ta-10V	345	446	397	357	345	360	373	339
Ta-10V[(d)]	376	425	366	357	354	351	351	366
Ta-15V	383	459	421	433	437	387	387	390
Ta-20V	421	488	483	488	503	446	383	413
Ta-20V	455	525	519	548	525	437	437	450
Ta-30V[(d)]	429	464	--	--	--	437	433	442

TABLE 5. HARDNESSES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS[(a)] (Continued)

Alloy Compositions, weight per cent	Hardness[(b)], VHN, After Annealing 1-Hour At Indicated Temperature							
	Cast, RT	Wrought, RT	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
Ta-5W	196	299	274	283	272	240	206	206
Ta-10W	225	299	--	302	342	304	272	304
Ta-10W + C (590 ppm)	253	370	380	387	360	325	279	249
Ta-15W	268	425	413	390	373	373	370	292
Ta-20W	328	366	--	390	394	366	394	394
Ta-20W	339	437	401	390	376	363	357	351
Ta-1Zr	146	212	213	196	149	139	126	140
Ta-1Zr + C (1400 ppm)	192	274	247	230	171	160	156	173
Ta-1Zr + O (400 ppm)	147	213	215	196	179	142	136	152
Ta-5Zr	256	302	256	242	225	225	232	230
Ta-10Zr	330	289	249	238	232	230	268	285
Ta-20Zr	357	285	251	247	264	276	339	336
Ta-40Zr	297	267	253	259	273	289	312	332
Ta-5Cb-10Ti	179	236	210	188	179	178	173	187
Ta-5Cb-20Ti	179	227	206	201	209	210	213	225
Ta-10Cb-20Ti	178	227	199	193	195	--	--	--
Ta-20Cb-10Ti	173	234	199	192	183	--	--	--
Ta-30Cb-10Ti	172	234	195	180	174	187	223	--
Ta-30Cb-10Cr	143	268	251	232	225	241	233	--
Ta-30Cb-10Hf	193	262	236	208	188	174	178	--
Ta-30Cb-20Hf	251	299	276	245	225	227	230	240
Ta-30Cb-10Mo	277	336	336	339	327	319	309	--
Ta-30Cb-10W	214	281	279	268	236	236	243	--
Ta-30Cb-5V	244	329	289	241	254	288	300	--
Ta-30Cb-5V	247	357	327	312	287	264	260	268
Ta-30Cb-5V	272	--	--	--	287	294	292	--
Ta-30Cb-5V-1Zr	247	376	312	287	262	251	256	254
Ta-30Cb-7.5V	336	442	394	363	351	345	339	348
Ta-30Cb-10V	292	405	354	339	322	314	317	317
Ta-30Cb-10V	314	405	339	330	317	317	317	327
Ta-30Cb-1Zr	159	203	187	181	162	156	156	153
Ta-30Cb-5Zr	221	245	224	197	201	189	175	--
Ta-10Hf-5V	325	370	314	299	292	289	304	299
Ta-10Hf-5W	292	370	333	322	272	254	262	264
Ta-10Hf-5W	270	--	--	--	--	264	270	274
Ta-10Hf-5W + C (540 ppm)	333	413	409	348	319	285	270	268
Ta-10Hf-10W	348	370	345	326	317	342	327	317
Ta-10Hf-15W	401	455	394	409	370	348	322	299

TABLE 5. HARDNESSES OF TANTALUM AND TANTALUM ALLOYS AFTER VARIOUS ANNEALING TREATMENTS[(a)] (Continued)

Alloy Compositions, weight per cent	Hardness[(b)], VHN, After Annealing 1-Hour At Indicated Temperature							
	Cast, RT	Wrought, RT	1000 C (1830 F)	1100 C (2010 F)	1200 C (2190 F)	1300 C (2370 F)	1400 C (2550 F)	1500 C (2730 F)
Ta-10Hf-1Zr	228	317	287	281	254	224	219	219
Ta-10Hf-1Zr	227	312	294	258	232	218	219	227
Ta-10Hf-10Zr	417	254	264	243	245	319	322	360
Ta-20Hf-5Al	292	409	387	360	360	387	360	376
Ta-20Hf-5Cr	325	413	348	322	319	309	325	336
Ta-20Hf-10W	405	421	446	405	401	401	390	376
Ta-5Mo-10Hf	339	354	333	322	306	309	306	299
Ta-5Mo-5V	342	446	417	405	373	348	348	345
Ta-5Mo-10V[(d)]	417	442	425	442	421	421	417	413
Ta-5Mo-10W	325	433	401	383	360	366	357	357
Ta-10Ti-5W	233	302	274	270	253	235	228	233
Ta-10Ti-10Hf	245	299	274	253	251	253	253	254
Ta-10Ti-10Zr	455	281	272	268	253	281	276	--
Ta-20Ti-5Al	266	373	289	287	283	287	285	289
Ta-20Ti-5Cr	266	289	251	236	242	254	272	294
Ta-20Ti-5Mo	263	306	287	283	287	309	292	336
Ta-20Ti-5V	235	283	243	240	243	243	245	279
Ta-20Ti-5W	262	319	297	371	462	488	490	495
Ta-20Ti-10W	294	327	325	319	317	336	327	333
Ta-5V-5W	339	429	401	409	405	366	354	339
Ta-5V-7.5W	317	478	464	450	429	397	363	360
Ta-5V-10W	373	425	394	376	380	370	354	363
Ta-5V-1Zr	322	380	351	345	285	251	294	279
Ta-10V-5W	421	--	446	397	390	380	383	373
Ta-10W-1Zr	264	421	380	360	312	258	253	247
Ta-10W-5Hf	276	397	383	339	345	297	270	268

(a) Specimens annealed in vacuum.

(b) Hardness values reported are the average of five impressions on each specimen using a 10-kg load.

(c) Minimum temperature for complete recrystallization is underlined.

(d) Wrought material showed a completely recrystallized microstructure.

Binary alloy additions of columbium, hafnium, molybdenum, rhenium, and tungsten are most effective in raising the recrystallization temperature from 1200 C (2190 F), for unalloyed tantalum, to as high as 1600 and 1650 C (2910 and 3000 F) for the Ta-10Mo and Ta-20W alloys. Binary alloy additions of titanium, vanadium, and zirconium are seen to have little effect on the recrystallization temperature of the high-purity base metal. The Ta-30Ti and Ta-40Ti alloys, by virtue of their titanium content, act as titanium-base alloys and thus exhibit a lower recrystallization temperature than observed for pure tantalum.

As expected, binary alloy additions showing the greatest effect in raising the recrystallization temperature are also most effective in tantalum ternary alloys. Ternary alloys of Ta-Cb-W, Ta-Hf-W, Ta-Mo-Hf, and Ta-Mo-W were found to have recrystallization temperatures 250 to 500 C (480 to 930 F) higher than unalloyed tantalum. The 1-hour 1700 C (3090 F) recrystallization temperature observed for the Ta-5Mo-10W alloy was the highest recrystallization temperature found.

Conversely, the use of aluminum, chromium, titanium, or vanadium as ternary additions tends to reduce recrystallization temperature. For example, the Ta-30Cb and Ta-5Mo alloys recrystallize at 1400 C (2550 F), while the Ta-30Cb-10Cr and Ta-5Mo-5V alloys recrystallize at 1300 C (2370 F).

Carbon additions of 700 to 2300 ppm and oxygen additions of 170 to 400 ppm to the Ta-1Hf, Ta-1Ti, and Ta-1Zr alloys had little or no effect on the recrystallization temperature. However, considerable grain refinement was observed for the alloys containing carbon additions. Similar behavior was noted for the Ta-5V and Ta-10W alloys with carbon additions. The addition of 540-ppm carbon to the Ta-10Hf-5W alloy resulted in an increase in recrystallization temperature and a finer grain size.

Bend Ductility

The results of duplicate bend tests on tantalum and tantalum alloys at room temperature and -196 C (-320 F) are given in Table 6.

Binary alloy additions of 5 to 50 per cent columbium, 1 to 20 per cent hafnium, 5 per cent rhenium, 1 to 40 per cent titanium, 5 to 15 per cent vanadium, 5 to 10 per cent tungsten, and 1 and 10 per cent zirconium show excellent bend ductility at both room temperature and -196 C (-320 F). Binary alloy additions of 5 to 7.5 molybdenum, 15 per cent tungsten, and 5 and 20 to 40 per cent zirconium show ductile behavior at room temperature but are brittle at -196 C (-320 F). However binary alloy additions of 30 to 35 per cent hafnium, 10 per cent molybdenum, 60 to 80 per cent

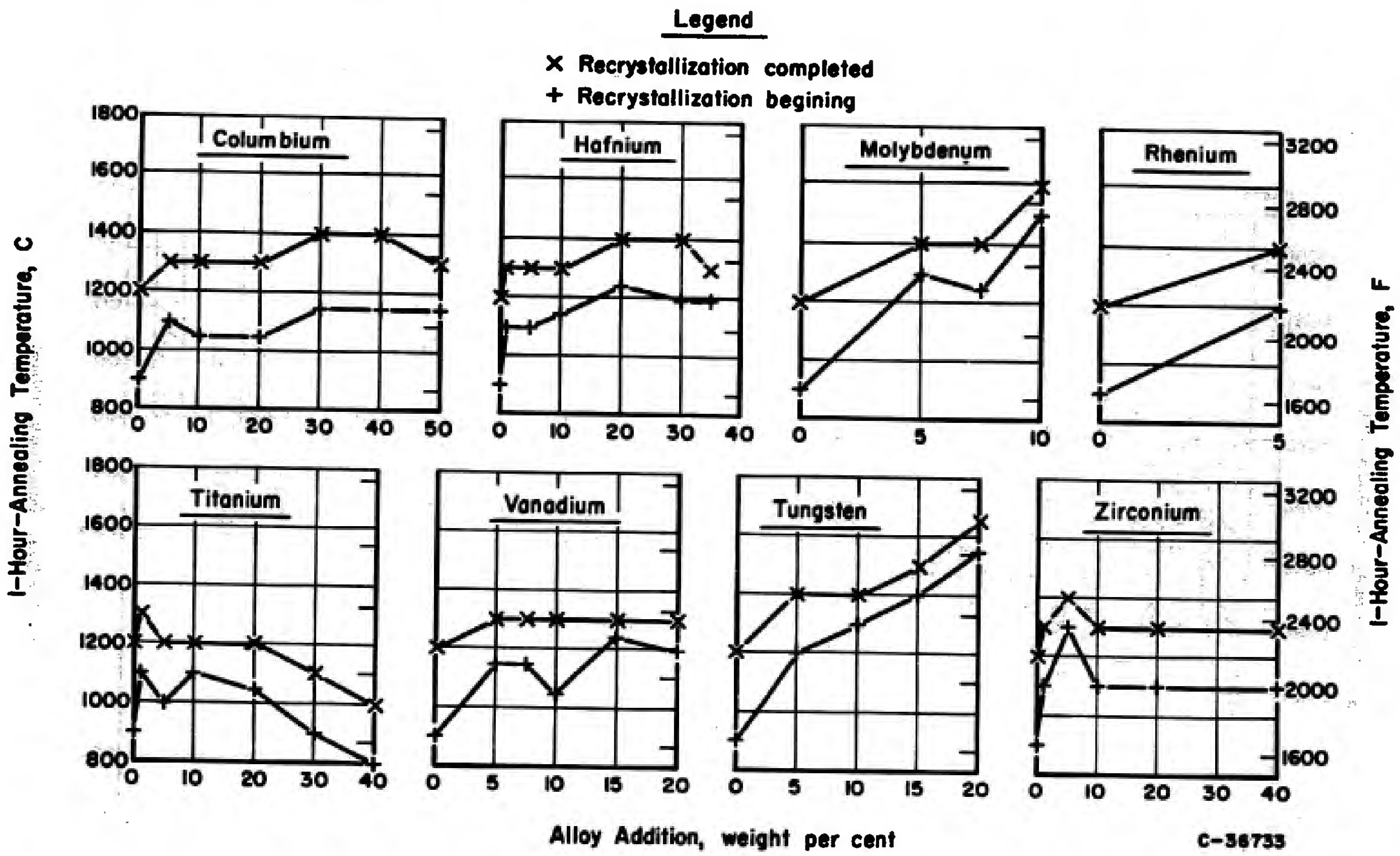


FIGURE 14. EFFECT OF BINARY ALLOY ADDITIONS ON THE RECRYSTALLIZATION TEMPERATURE OF TANTALUM

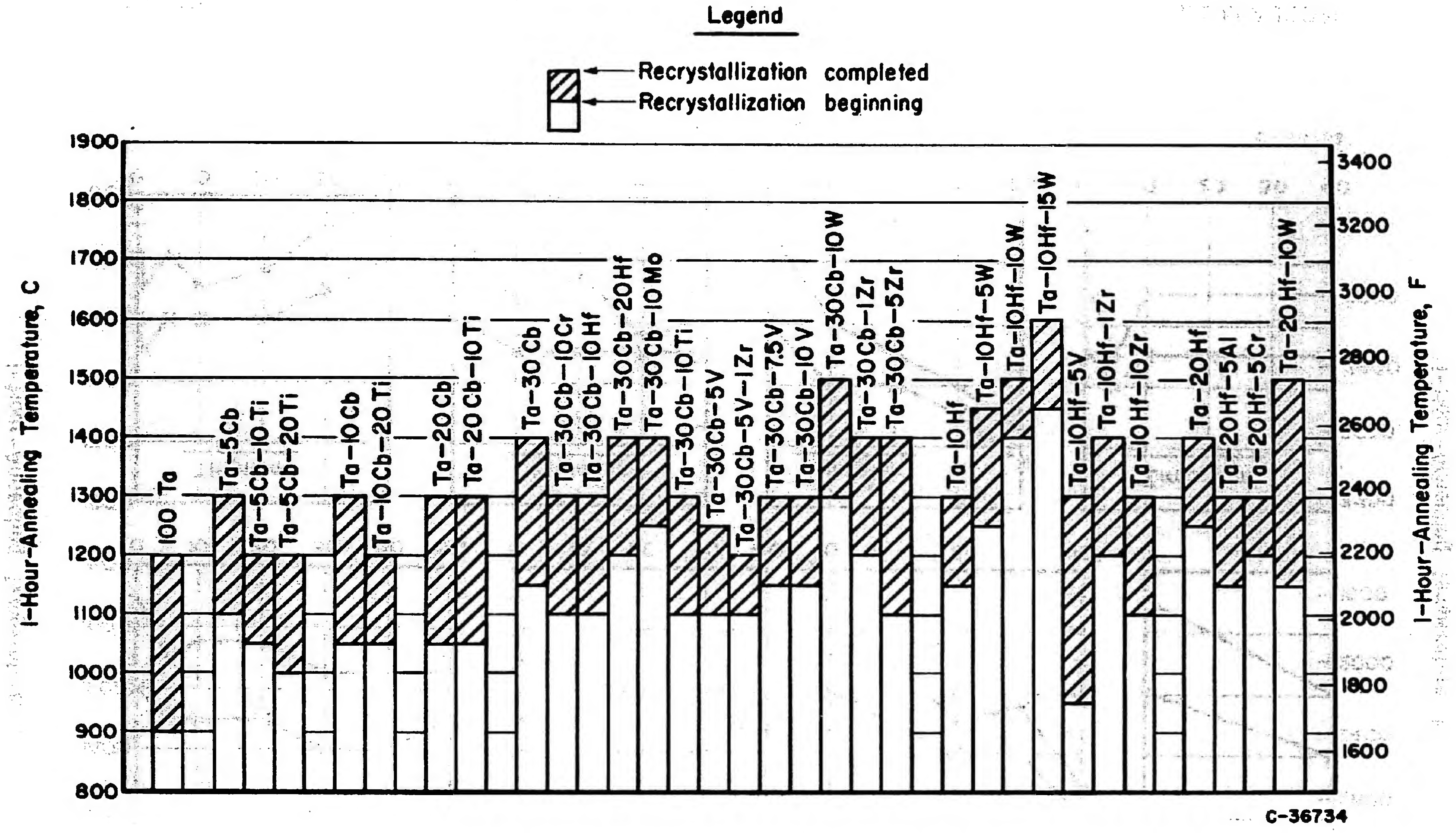


FIGURE 15. EFFECT OF ALLOY ADDITIONS ON THE RECRYSTALLIZATION TEMPERATURE OF TANTALUM AND TANTALUM ALLOYS

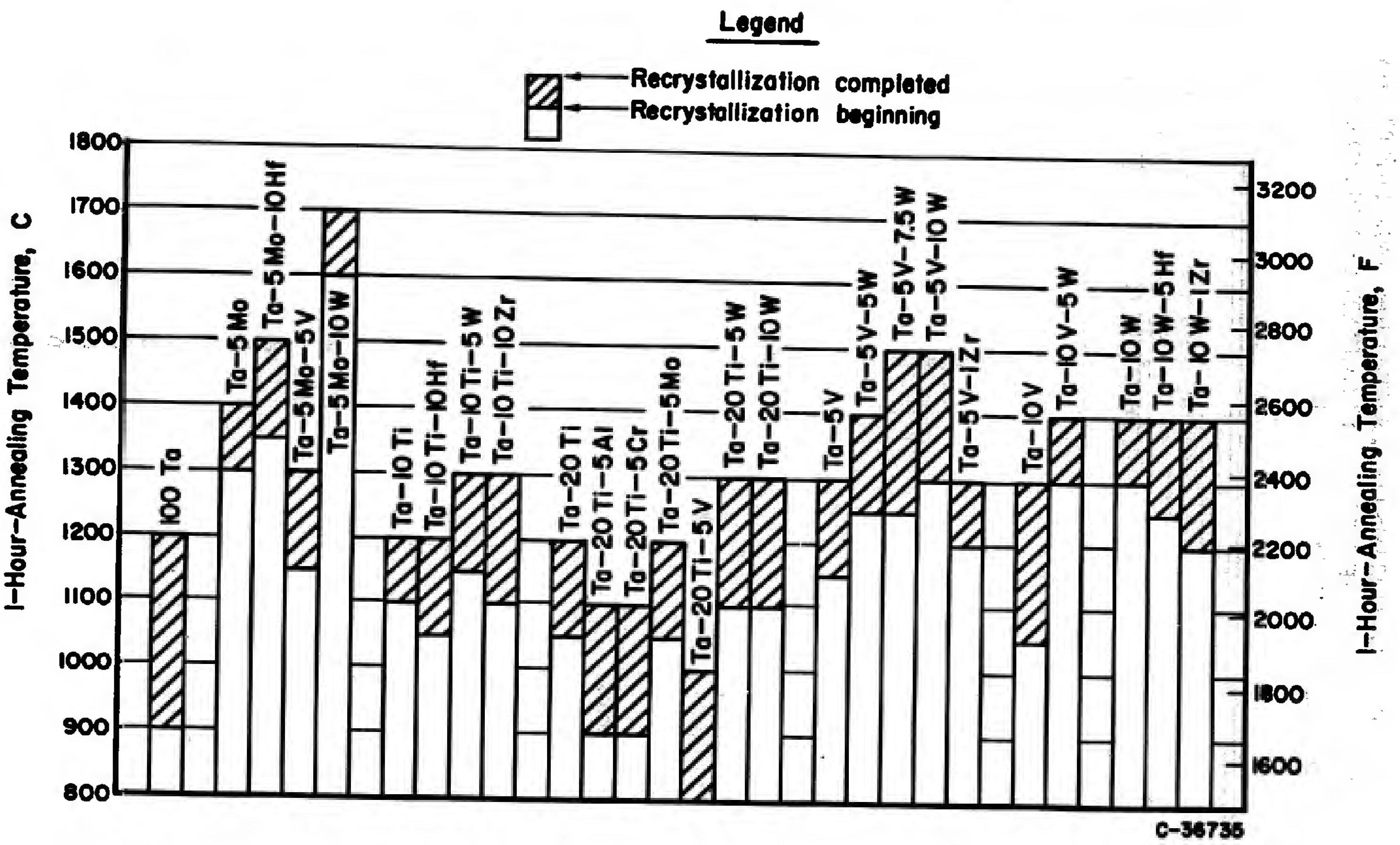


FIGURE 15. EFFECT OF ALLOY ADDITIONS ON THE RECRYSTALLIZATION TEMPERATURE OF TANTALUM AND TANTALUM ALLOYS (Continued)

TABLE 6. BEND DUCTILITIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION AT 25 AND -196 C (75 AND -320 F)

Alloy Composition, weight per cent	Minimum Bend Radius Value[(a)], T, at Indicated Temperature 25 C (75 F)	-196 C (-320 F)
100Ta	0	0
Ta-5Cb	0	0
Ta-10Cb	0	0
Ta-20Cb	0	0
Ta-30Cb	0	0
Ta-40Cb	0	0
Ta-50Cb	0	0
Ta-1Hf	0	0
Ta-1Hf + C (700 ppm)	0	0
Ta-1Hf + O (170 ppm)	0	0
Ta-5Hf	0	0
Ta-10Hf	0	0
Ta-10Hf + C (630 ppm)	0	0
Ta-20Hf	0	1
Ta-30Hf	15	>16
Ta-35Hf	21	>21
Ta-5Mo	0	11
Ta-7.5Mo	0	32
Ta-10Mo	7	>24
Ta-5Re	0	0
Ta-1Ti	0	0
Ta-1Ti + C (2300 ppm)	3	15
Ta-1Ti + O (280 ppm)	0	0
Ta-5Ti	0	0
Ta-10Ti	0	0
Ta-20Ti	0	0
Ta-30Ti	0	0
Ta-40Ti	0	0
Ta-60Ti	5	15
Ta-80Ti	8	2

TABLE 6. BEND DUCTILITIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION AT 25 AND -196 C (75 AND -320 F) (Continued)

Alloy Composition, weight per cent	Minimum Bend Radius Value[(a)], T, at Indicated Temperature	
	25 C (75 F)	-196 C (-320 F)
Ta-5V	0	0
Ta-5V + C (580 ppm)	0	0
Ta-7.5V	0	0
Ta-10V	0	0
Ta-15V	0	0
Ta-20V	4	>18
Ta-30V	>43	--
Ta-5W	0	0
Ta-10W	0	0
Ta-10W + C (590 ppm)	(b)	--
Ta-15W	0	>24
Ta-20W	44	--
Ta-1Zr	0	0
Ta-1Zr + C (1400 ppm)	0	0
Ta-1Zr + O (400 ppm)	0	0
Ta-5Zr	0	>28
Ta-10Zr	0	1
Ta-20Zr	2	8
Ta-40Zr	3	6
Ta-5Cb-10Ti	0	0
Ta-5Cb-20Ti	0	0
Ta-10Cb-20Ti	0	0
Ta-20Cb-10Ti	0	0
Ta-30Cb-10Ti	0	0
Ta-30Cb-10Cr	0	0
Ta-30Cb-10Hf	0	0
Ta-30Cb-20Hf	0	0
Ta-30Cb-10Mo	50	--
Ta-30Cb-10W	0	>31
Ta-30Cb-5V	0	0
Ta-30Cb-5V-1Zr	0	0
Ta-30Cb-7.5V	0	0
Ta-30Cb-10V	0	0

TABLE 6. BEND DUCTILITIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION AT 25 AND -196 C (75 AND -320 F) (Continued)

Alloy Composition, weight per cent	Minimum Bend Radius Value(a), T, at Indicated Temperature	
	25 C (75 F)	-196 C (-320 F)
Ta-30Cb-1Zr	0	0
Ta-30Cb-5Zr	0	>22
Ta-10Hf-5V	2	24
Ta-10Hf-5W	3	4
Ta-10Hf-5W + C (540 ppm)	5	>20
Ta-10Hf-10W	3	5
Ta-10Hf-15W	>57	--
Ta-10Hf-1Zr	0	0
Ta-10Hf-10Zr	7	7
Ta-20Hf-2Al	>19	--
Ta-20Hf-5Al	>27	--
Ta-20Hf-2Cr	1	2
Ta-20Hf-5Cr	6	6
Ta-20Hf-10W	>49	--
Ta-10Hf-5Mo	0	6
Ta-5Mo-5V	0	12
Ta-5Mo-10V	>41	--
Ta-5Mo-10W	>46	--
Ta-10Ti-5W	0	0
Ta-10Ti-10Hf	0	0
Ta-10Ti-10Zr	0	0
Ta-20Ti-5Al	0	0
Ta-20Ti-5Cr	0	0

TABLE 6. BEND DUCTILITIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION AT 25 AND -196 C (75 AND -320 F) (Continued)

Alloy Composition, weight per cent	Minimum Bend Radius Value[a], T, at Indicated Temperature 25 C (75 F)	-196 C (-320 F)
Ta-20Ti-5Mo	0	1
Ta-20Ti-5V	0	0
Ta-20Ti-5W	20	--
Ta-20Ti-10W	0	0
Ta-30Ti-1Be	7	20
Ta-30Ti-1.5Si	31	--
Ta-30Ti-5Al	0	17
Ta-30Ti-5Al-1.5Si	18	--
Ta-30Ti-5Al-5Cr	>18	--
Ta-30Ti-5Cr	0	1
Ta-30Ti-10Cr	1	>16
Ta-40Ti-5Al	0	17
Ta-40Ti-10Al	>19	--
Ta-5V-5W	0	12
Ta-5V-7.5W	>24	--
Ta-5V-10W	2	>22
Ta-5V-1Zr	0	0
Ta-10V-5W	13	--
Ta-10W-1Zr	0	6
Ta-10W-5Hf	0	0

(a) T-value is radius of last good die before evidence of cracking appears, divided by specimen thickness.
(b) Failed along grain-boundary cracks.

titanium, 20 to 30 per cent vanadium, and 20 per cent tungsten exhibit brittle behavior at both room temperature and -196 C (-320 F).

Generally, the bend ductility in binary alloys with hafnium, molybdenum, vanadium, and tungsten decreases with increasing alloy content.

Most of the ternary alloys exhibited good ductility at room temperature. The exceptions include the alloys containing aluminum, beryllium, chromium, molybdenum, and silicon. Many of the other ternary alloys, particularly those containing columbium or titanium, were ductile at -196 C (-320 F).

The poor ductility for the Ta-20Ti-5W and Ta-5V-7.5W alloys is ascribed to segregation and surface cracks from fabrication, respectively.

These bend data show good agreement with tensile ductility values (Tables 6 and 12) at both 25 and -196 C (75 and -320 F). For example, the Ta-30Cb-5 to 10V alloys exhibited 0T bends at 25 and -196 C (75 and -320 F) while measured tensile elongation at both temperatures was high.

Interstitial additions of carbon and oxygen to several of the tantalum alloys appear to have little effect on the bend ductility. These data indicate a high tolerance of tantalum for interstitial solutes without marked decreasing ductility.

These results show that the low ductile-to-brittle transition characteristic of tantalum is retained to a considerable degree in many of its alloys.

Tensile Properties

Room Temperature

Room-temperature tensile properties of tantalum and tantalum alloys in the recrystallized condition are given in Table 7 and illustrated in Figures 16 and 17.

On the basis of these room-temperature tensile properties, the maximum solid-solution strengthening for various binary alloy additions are given below:

TABLE 7. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION(a)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent
100Ta	29.4	26.3	36
100Ta	31.8	20.0	47
Ta-5Cb	38.2	28.6	(17)(b)
Ta-10Cb	39.5	27.6	(22)
Ta-20Cb	41.8	29.0	29
Ta-30Cb	46.9	39.4	33
Ta-40Cb	50.5	29.6	39
Ta-50Cb	42.7	31.4	27
Ta-1Hf	52.6	35.6	29
Ta-1Hf + C (700 ppm)	61.9	30.8	32
Ta-1Hf + O (170 ppm)	87.6	82.5	11
Ta-5Hf	45.4	34.3	27
Ta-10Hf	86.3	72.8	26
Ta-10Hf + C (630 ppm)	>52.0(c)	--	2
Ta-20Hf	120.0	109.5	19
Ta-30Hf	146.8	141.0	2
Ta-35Hf	138.0	131.0	13
Ta-5Mo	110.3	108.0	4
Ta-7.5Mo	>27.7(c)	--	2
Ta-10Mo	72.4	--	0
Ta-5Re	98.0	86.0	23
Ta-1Ti	71.5	63.8	12
Ta-1Ti + C (2300 ppm)	99.5	46.8	17
Ta-1Ti + O (280 ppm)	48.6	44.0	18
Ta-5Ti	52.8	37.9	27
Ta-10Ti	66.9	59.4	26
Ta-20Ti	82.8	80.0	(20)
Ta-30Ti	91.9	18.5	12
Ta-40Ti	106.0	21.7	21

TABLE 7. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION[(a)] (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in Inch, per cent
Ta-5V	87.0	70.0	27
Ta-5V + C (580 ppm)	133.9	115.6	21
Ta-10V	161.2	144.0	16
Ta-20V	177.6	170.0	8
Ta-5W	84.0	78.5	19
Ta-10W	79.6	69.7	16
Ta-10W + C (590 ppm)	>91.8[(c)]	79.2	9
Ta-15W	89.0	--	(2)
Ta-1Zr	57.6	43.9	27
Ta-1Zr + C (1400 ppm)	80.5	45.5	17
Ta-1Zr + O (400 ppm)	60.3	44.1	20
Ta-5Zr	94.5	85.4	8
Ta-10Zr	109.5	100.3	9
Ta-20Zr	112.5	99.1	23
Ta-40Zr	102.4	93.7	23
Ta-5Cb-10Ti	78.6	71.6	19
Ta-5Cb-20Ti	87.3	86.5	15
Ta-10Cb-20Ti	78.5	75.9	15
Ta-20Cb-10Ti	75.3	68.3	24
Ta-30Cb-10Ti	69.4	61.5	25
Ta-30Cb-10Hf	65.1	53.0	(8)
Ta-30Cb-20Hf	85.9	77.0	3
Ta-30Cb-10W	65.0	64.8	2
Ta-30Cb-5V	95.8	78.0	22
Ta-30Cb-5V-1Zr	111.0	94.0	(9)
Ta-30Cb-7.5V	139.1	125.2	27
Ta-30Cb-10V	147.5	126.5	21
Ta-30Cb-1Zr	61.3	51.0	23
Ta-30Cb-5Zr	73.8	60.2	(11)
Ta-10Hf-5V	61.8	--	0

TABLE 7. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION[(a)] (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in Inch, per cent
Ta-10Hf-5W	115.3	105.0	23
Ta-10Hf-5W + C (540 ppm)	96.8	96.4	4
Ta-10Hf-10W	122.8	120.0	4
Ta-10Hf-1Zr	98.6	84.6	28
Ta-10Hf-10Zr	132.0	124.0	14
Ta-5Mo-10Hf	106.0	103.7	(3)
Ta-5Mo-5V	133.2	125.0	3
Ta-10Ti-5W	97.1	91.1	18
Ta-10Ti-10Hf	104.6	99.2	26
Ta-10Ti-10Zr	120.7	108.7	3
Ta-20Ti-5Al	133.9	125.9	14
Ta-20Ti-5Cr	109.4	108.2	12
Ta-20Ti-5Mo	92.0	--	0
Ta-20Ti-5V	107.6	106.2	20
Ta-20Ti-5W	47.5	--	0
Ta-20Ti-10W	129.0	--	0
Ta-30Ti-1Be	105.0	--	(0)
Ta-30Ti-5Al	113.5	109.0	27
Ta-30Ti-5Cr	114.1	109.0	9
Ta-30Ti-5Al-5Cr	72.0	--	(0)
Ta-40Ti-5Al	105.2	101.0	33
Ta-40Ti-10Al	101.0	--	0
Ta-5V-5W	141.3	131.6	21
Ta-5V-7.5W	>118.0[(c)]	--	0
Ta-5V-10W	152.9	137.1	19

TABLE 7. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION[a] (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in Inch, per cent
Ta-5V-1Zr	108.2	91.9	(11)
Ta-10W-1Zr	87.5	87.0	1
Ta-10W-5Hf	105.0	96.3	(9)

(a) Tested using conventional hydraulic loading and a crosshead speed of approximately 0.02 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture.

(b) Values in parentheses are estimated.

(c) Failed along grain-boundary cracks.

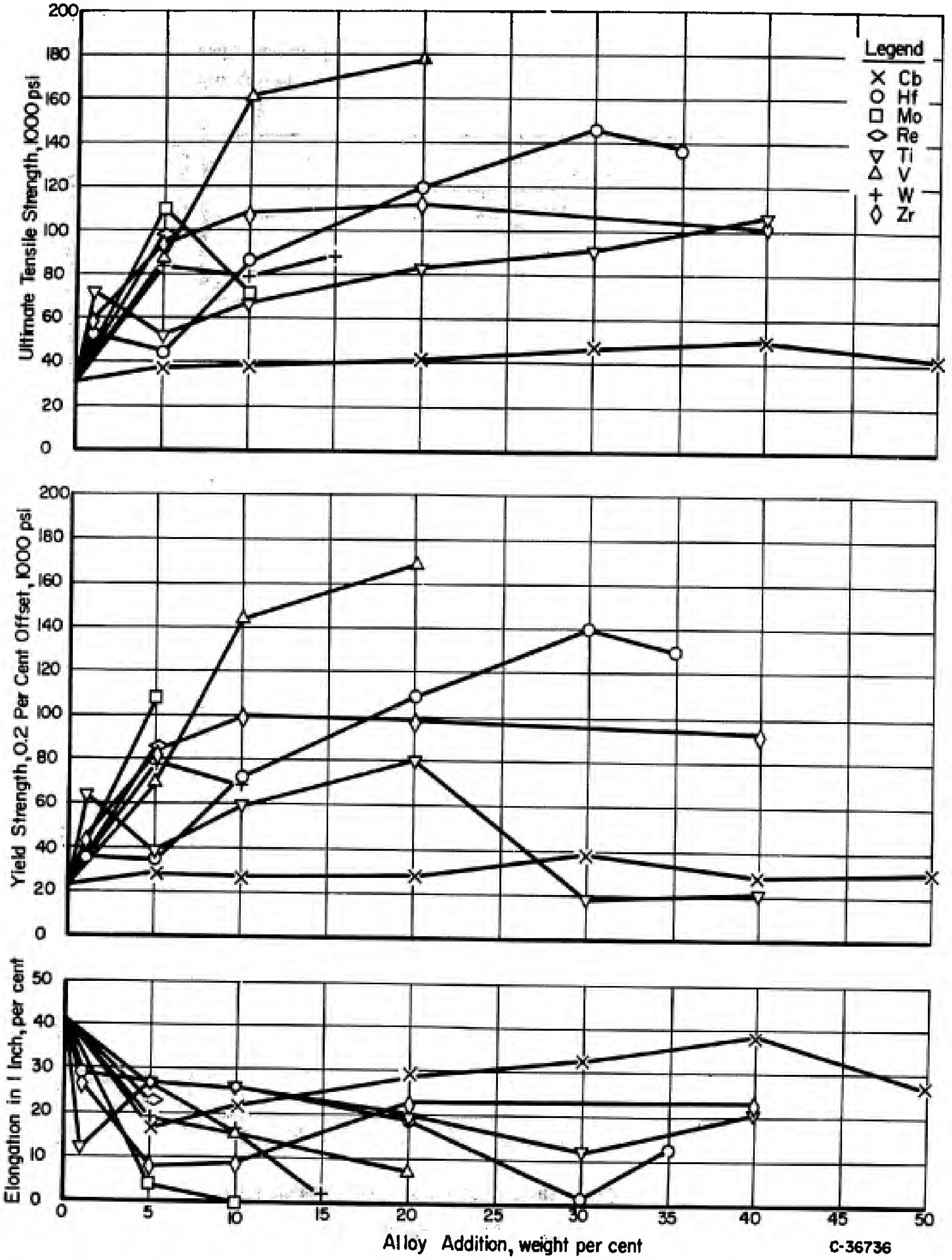


FIGURE 16. ROOM-TEMPERATURE TENSILE PROPERTIES OF BINARY TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

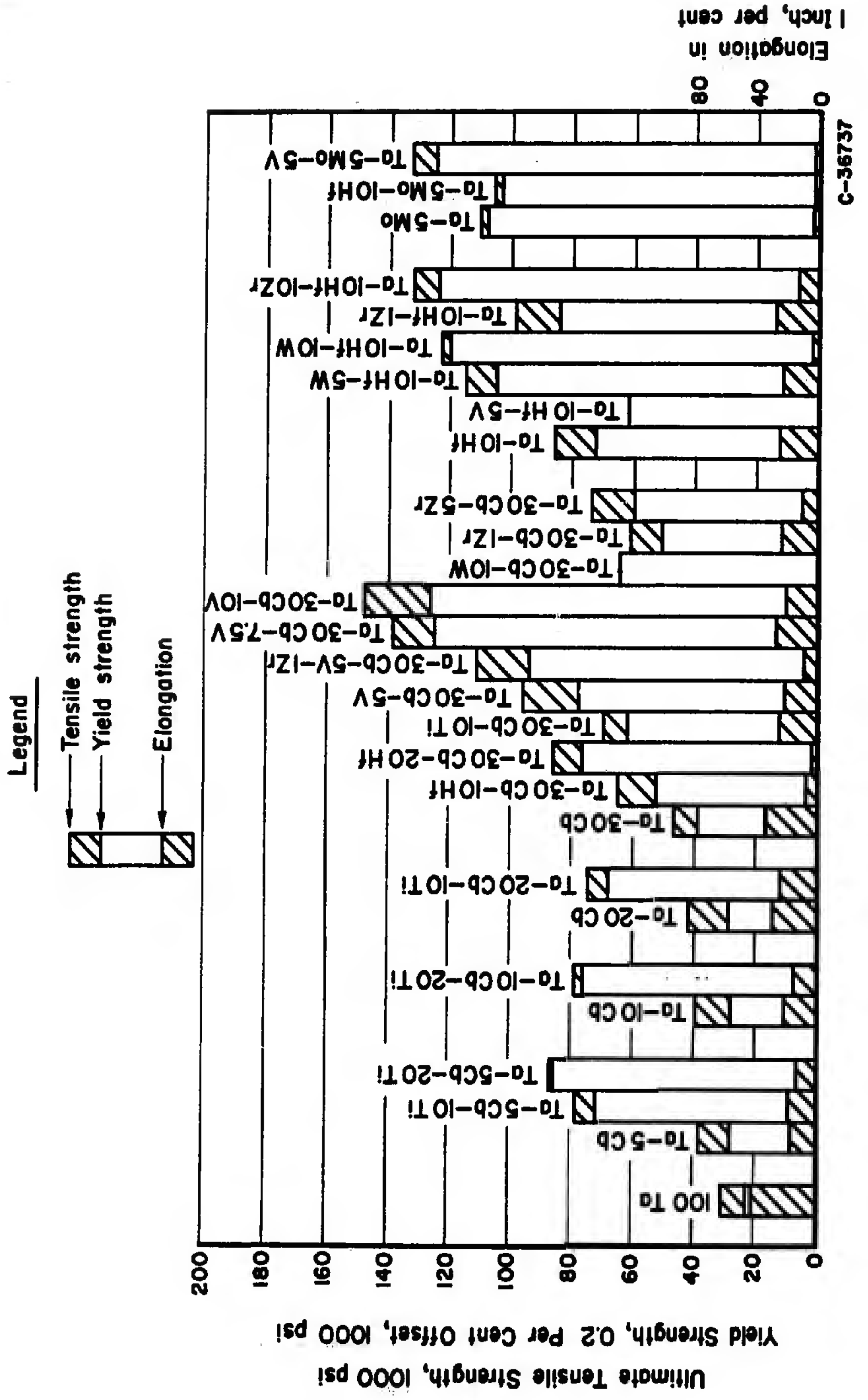


FIGURE 17. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

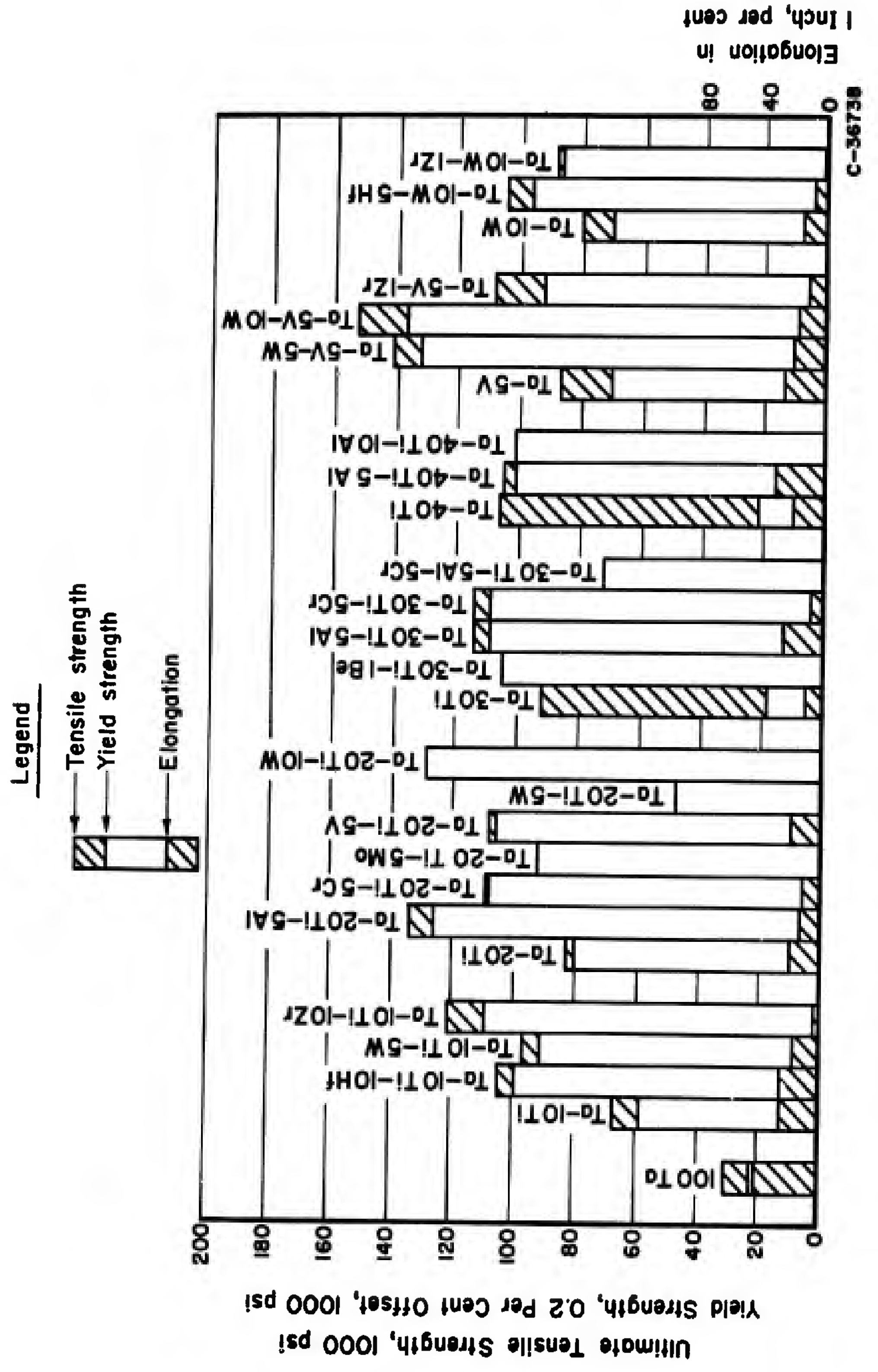


FIGURE 17. ROOM-TEMPERATURE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Addition	Binary Alloy Addition, weight per cent, for Maximum Strengthening
Cb	40
Hf	30
Mo	>5
Re	>5
Ti	20
V	>20
W	>20
Zr	>20, <40

These strength maxima are seen to correlate well with cast hardnesses, Figure 18. Generally, as shown in Table 6, the increased strength was accompanied by a decrease in the elongation and bend ductility of the alloys.

Although the Ta-30Ti and Ta-40Ti alloys show higher ultimate strengths than the Ta-20Ti alloy, the yield strength drops sharply in the region 20 to 30 per cent titanium. The low yield strengths in the Ta-30Ti and Ta-40Ti alloys apparently results from the strain-induced transformation of the tantalum-rich matrix into a martensitic structure containing needles of the titanium-rich (alpha prime) phase.(1) A photomicrograph of the strained portion of the Ta-40Ti tensile sample illustrating this transformation is shown in Figure 19.

Binary additions of vanadium and hafnium appear to be the most effective room-temperature strengtheners. Thus, the ultimate strength of 177,600 psi shown by the Ta-20V alloy represents about a sixfold improvement over unalloyed tantalum. Small binary additions (1 per cent) of the Group IVA metals, titanium, zirconium, and hafnium, also increase the strength of pure tantalum significantly. This strengthening probably results from dispersion hardening.

Several of the ternary tantalum alloys showed four- to fivefold strengthening improvements over pure tantalum. In particular, tantalum alloys containing 5 to 10 per cent vanadium with 30 per cent columbium or 5 to 10 per cent tungsten were found to have an excellent combination of tensile strength (approximately 140,000 to 150,000 psi) and ductility (approximately 20 per cent elongation and a 0 to 2T minimum bend radius, Table 6). However the strength measured for these ternary alloys is below that of the strongest binary alloy, Ta-20V (177,600 psi).

The tensile samples of the Ta-20Ti-5Mo, Ta-20Ti-5W, and Ta-20Ti-10W alloys were examined visually and metallographically to determine the possible cause of the brittle behavior observed in tensile testing of these alloys. In the case of the Ta-20Ti-5Mo and Ta-20Ti-10W alloys,

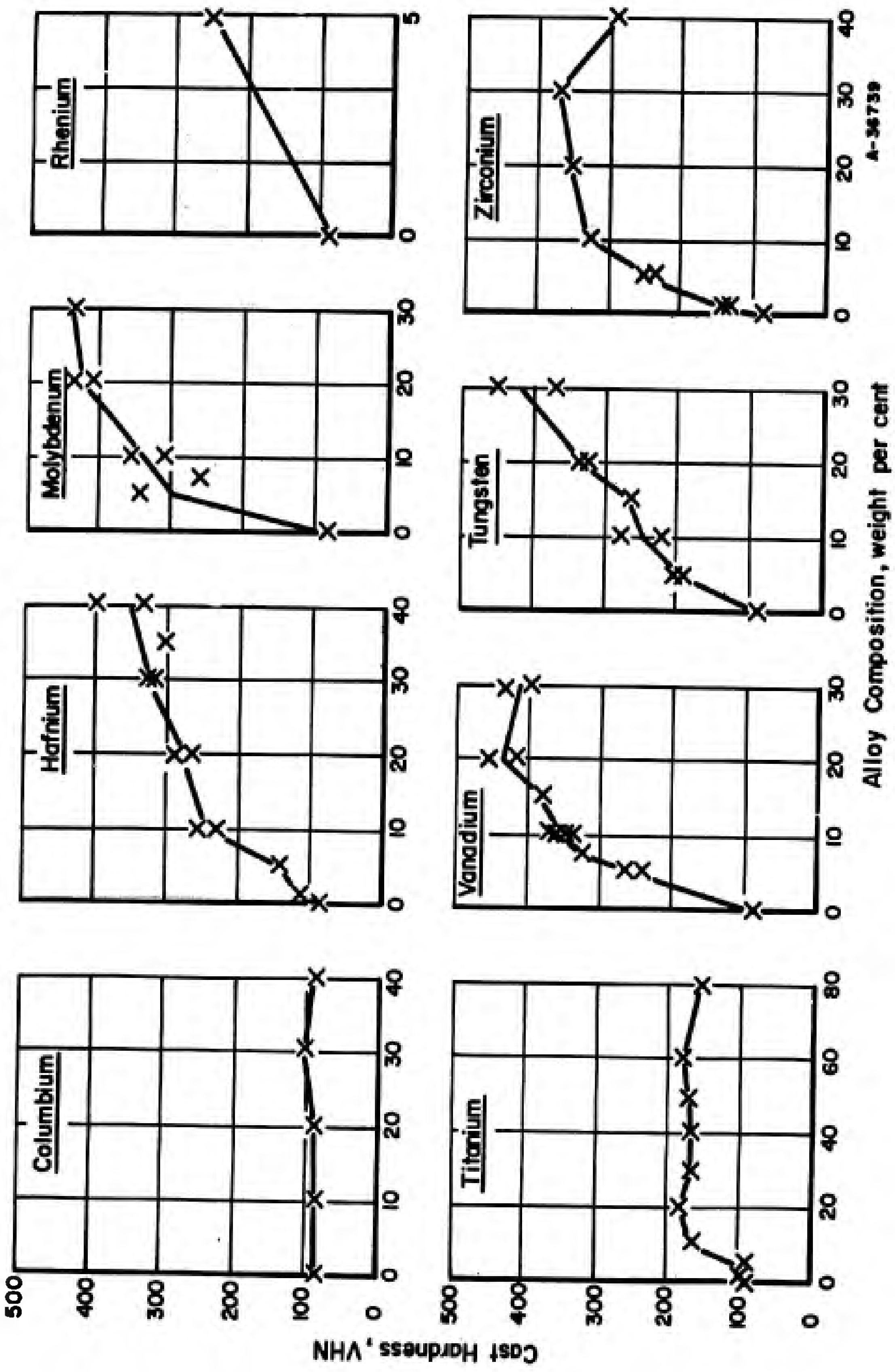


FIGURE 18. CAST HARDNESS OF BINARY TANTALUM ALLOYS

FIGURE 19. STRAINED PORTION OF ROOM-TEMPERATURE TENSILE SPECIMEN ON THE Ta-40Ti ALLOY

the poor tensile ductility was tentatively ascribed to unsound metal (probably surface cracks retained from fabrication) in the reduced sections of these samples. Crack-free specimens of the Ta-20Ti-5Mo and Ta-20Ti-10W alloys have shown ductile behavior during bend testing at -196 C (-320 F), Table 6. Accordingly, this suggests that the low tensile elongation values reported for these alloys are unreliable. On the other hand, the Ta-20Ti-5W alloy sample was badly segregated and its poor tensile ductility is explainable on this basis.

Interstitial additions of carbon or oxygen to binary tantalum alloys containing hafnium, titanium, vanadium, tungsten, or zirconium caused considerable strengthening with respect to the corresponding binary (carbon or oxygen free) alloys. The addition of 580 ppm carbon was particularly effective in raising the tensile strength of the Ta-5V alloy from 87,000 to 133,900 psi without having any noticeable effect on elongation, bend ductility (Table 6), and fabricability (Table 2).

Carbon additions to the binary alloys containing 1 per cent hafnium, titanium, or zirconium showed marked strength improvements caused by the carbon; however, the yield strengths for the carbon-containing Ta-1Hf and Ta-1Ti alloys were considerably lower than that of the carbon-free alloy. The reason for this behavior was not investigated. The apparent anomalous behavior shown for the Ta-10Hf-5W and Ta-10Hf-5W+C (540 ppm) alloys is attributed to a 2-hour annealing treatment given the carbon-containing alloy prior to testing instead of the standard 1-hour annealing treatment.

1200 C (2190 F)

Tensile properties of tantalum and tantalum alloys at 1200 C (2190 F) in the recrystallized and wrought conditions are given in Tables 8 and 9, respectively, and are shown in Figures 20 through 23.

The maximum solid-solution strengthening for various binary alloy additions, tested at 1200 C (2190 F) in the recrystallized condition, is given below:

Alloy Addition	Binary Alloy Addition for Maximum Strengthening	
	Weight Per Cent	Atomic Per Cent
Cb	20	33
Hf	20	20
Mo	>10	>17
Re	>5	>5
Ti	10	28
V	15	39
W	>20	>20
Zr	10	17

TABLE 8. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent	Testing Method (a)	Testing Method (b)
100Ta	7.4	(3.8)$^{(c)}$	48		x
100Ta	11.4	--	45	x	
Ta-5Cb	11.9	--	46	x	
Ta-10Cb	11.3	--	50	x	
Ta-20Cb	13.9	--	47	x	
Ta-30Cb	11.6	--	6$^{(d)}$	x	
Ta-40Cb	12.9	--	47	x	
Ta-50Cb	11.9	--	52	x	
Ta-1Hf	27.7	--	23	x	
Ta-1Hf + C (700 ppm)	33.0	--	34	x	
Ta-1Hf + 0 (170 ppm)	43.4	36.0	8		x
Ta-5Hf	39.7	--	30	x	
Ta-10Hf	53.5	--	36	x	
Ta-10Hf + C (630 ppm)	>41.4$^{(e)}$	31.0	(6)		x
Ta-20Hf	60.2	48.7	14		x
Ta-30Hf	53.6	--	7	x	
Ta-35Hf	29.0	18.5	100		x
Ta-5Mo	43.5	--	3	x	
Ta-7.5Mo	>25.8$^{(e)}$	23.4	0		x
Ta-10Mo	66.4	50.2	10		x
Ta-5Re	34.0	25.8	25		x
Ta-1Ti	19.1	--	12	x	
Ta-1Ti + C (2300 ppm)	29.0	--	33	x	
Ta-1Ti + O (280 ppm)	19.0	--	21	x	
Ta-5Ti	17.8	--	32	x	
Ta-10Ti	20.4	--	66	x	
Ta-20Ti	14.2	--	3$^{(d)}$	x	
Ta-30Ti	6.6	--	120	x	
Ta-40Ti	4.2	--	152	x	

TABLE 8. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent	Testing Method	
				(a)	(b)
Ta-5V	49.2	--	48	x	
Ta-5V + C (580 ppm)	44.0	32.2	56		x
Ta-7.5V	68.4	53.1	27		x
Ta-10V	79.7	46.7	6		x
Ta-15V	83.1	64.5	10		x
Ta-20V	56.4	39.0	4		x
Ta-5W	25.6	15.7	47		x
Ta-10W	41.8	--	13	x	
Ta-10W + C (590 ppm)	>37.2(e)	26.3	(7)		x
Ta-15W	47.5	32.5	3		x
Ta-20W	49.6	45.1	5		x
Ta-1Zr	38.3	--	18	x	
Ta-1Zr + C (1400 ppm)	45.0	--	20	x	
Ta-1Zr + O (400 ppm)	42.3	--	15	x	
Ta-5Zr	40.5	29.3	7		x
Ta-10Zr	44.0	--	21	x	
Ta-20Zr	25.6	--	25	x	
Ta-40Zr	10.8	--	50	x	
Ta-5Cb-10Ti	27.3	--	53	x	
Ta-5Cb-20Ti	16.6	--	69	x	
Ta-10Cb-20Ti	10.7	--	8	x	
Ta-20Cb-10Ti	11.8	--	7	x	
Ta-30Cb-10Ti	14.0	--	22	x	
Ta-30Cb-10Cr	24.2	--	37	x	
Ta-30Cb-10Hf	37.8	--	30	x	
Ta-30Cb-20Hf	49.2	37.4	6		x
Ta-30Cb-10Mo	32.4	--	4	x	
Ta-30Cb-10W	27.8	--	22	x	
Ta-30Cb-5V	40.5	--	53	x	

TABLE 8. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent	Testing Method (a)	Testing Method (b)
Ta-30Cb-5V	48.8	40.3	52		x
Ta-30Cb-5V-1Zr	43.3	33.2	35		x
Ta-30Cb-7.5V	60.6	47.6	35		x
Ta-30Cb-10V	63.9	34.8	18		x
Ta-30Cb-1Zr	34.6	23.8	26		x
Ta-30Cb-5Zr	37.7	--	4	x	
Ta-10Hf-5W	63.8	--	6	x	
Ta-10Hf-5W + C (540 ppm)	59.8	42.9	10		x
Ta-10Hf-15W	49.8	--	0		x
Ta-10Hf-1Zr	52.2	40.4	18		x
Ta-10Hf-10Zr	22.6	15.1	22		x
Ta-20Hf-5Al	42.5	--	3	x	
Ta-20Hf-10W	64.9	--	2		x
Ta-5Mo-10Hf	80.8	58.6	7		x
Ta-5Mo-5V	66.8	--	14		x
Ta-5Mo-10W	72.7	42.4	(7)		x
Ta-10Ti-5W	39.3	--	17	x	
Ta-10Ti-10Hf	28.7	20.8	34		x
Ta-10Ti-10Zr	13.5	11.3	84		x
Ta-20Ti-5Al	16.8	--	95	x	
Ta-20Ti-5Cr	10.8	--	4	x	
Ta-20Ti-5Mo	15.0	--	5	x	
Ta-20Ti-5V	18.5	--	88	x	

TABLE 8. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, Per cent	Testing Method (a)	Testing Method (b)
Ta-20Ti-5W	20.7	--	0	x	
Ta-20Ti-10W	17.9(e)	--	0	x	
Ta-30Ti-1Be	4.0	--	(50)		x
Ta-30Ti-1.5Si	5.3	--	(50)		x
Ta-30Ti-5Al	3.7	--	(37)		x
Ta-30Ti-5Al-5Cr	5.6	--	(53)		x
Ta-40Ti-10Al	2.3	--	(53)		x
Ta-5V-10W	75.5	59.0	10		x
Ta-5V-1Zr	49.3	29.4	12		x
Ta-10V-5W	87.4	--	17	x	
Ta-10W-1Zr	39.1	32.5	6		x
Ta-10W-5Hf	56.5	38.3	9		x

(a) Tested in vacuum using conventional creep-rupture equipment. Specimen loaded by lead shot until the ultimate tensile strength was reached.

(b) Tested in vacuum using conventional hydraulic loading and a crosshead speed of approximately 0.01 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture.

(c) Values in parentheses are estimated.

(d) Considerable localized necking and reduction in area.

(e) Failed along grain-boundary cracks.

TABLE 9. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE WROUGHT CONDITION

Alloy Composition, weight per cent	Condition(a)	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent	Testing Method (b)	Testing Method (c)
100Ta	CW 50 per cent	8.8	6.4	32		X
100Ta	CW 50 per cent	17.0	--	6	X	
Ta-5Cb	CW 50 per cent	17.2	--	10	X	
Ta-30Cb	CW 50 per cent	22.2	--	10	X	
Ta-40Cb	CW 50 per cent	17.1	--	21	X	
Ta-50Cb	CW 50 per cent	15.6	--	19	X	
Ta-1Hf	CW 50 per cent	36.6	--	6	X	
Ta-1Hf + C (700 ppm)	CW 65 per cent	48.1	--	16	X	
Ta-1Hf + O (170 ppm)	CW 65 per cent	49.9	--	4	X	
Ta-5Hf	CW 50 per cent	51.5	--	15	X	
Ta-10Hf	PR 980 C/CW 30 per cent	59.2	--	27	X	
Ta-20Hf	PR 980 C/CW 75 per cent	58.9	--	38	X	
Ta-5Re	CW 65 per cent	59.1	--	8	X	
Ta-1Ti	CW 50 per cent	22.2	--	6	X	
Ta-1Ti + C (2300 ppm)	PR 980 C/C 10 per cent	24.5	--	29	X	
Ta-1Ti + O (280 ppm)	CW 65 per cent	25.4	--	4	X	
Ta-10Ti	CW 50 per cent	25.0	--	12	X	
Ta-20Ti	CW 50 per cent	11.4	--	13	X	
Ta-30Ti	CW 50 per cent	7.5	--	104	X	
Ta-40Ti	CW 50 per cent	4.5	--	95	X	
Ta-5V	PR 980 C/CW 30 per cent	53.0	--	27	X	
Ta-5V + C (580 ppm)	PR 980 C/CW 40 per cent	58.0	31.4	33		X
Ta-10V	PR 980 C/CW 75 per cent	51.0	--	6	X	
Ta-20V	PR 980 C/CW 10 per cent	50.8	--	54	X	
Ta-20V	PR 980 C/CW 75 per cent	47.4	--	14	X	
Ta-5W	CW 65 per cent	48.9	--	6	X	
Ta-1Zr	CW 50 per cent	50.6	--	8	X	
Ta-1Zr + O (400 ppm)	CW 65 per cent	54.9	--	4	X	
Ta-20Zr	PR 980 C/CW 20 per cent	10.2	--	6	X	
Ta-40Zr	PR 980 C	5.7	--	50	X	
Ta-5Cb-10Ti	CW 75 per cent	28.3	--	23	X	
Ta-5Cb-20Ti	CW 65 per cent	19.6	--	35	X	
Ta-10Cb-20Ti	CW 50 per cent	9.1	--	11	X	
Ta-20Cb-10Ti	CW 50 per cent	18.3	--	14	X	
Ta-30Cb-10Ti	CW 50 per cent	15.4	--	7	X	

TABLE 9. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE WROUGHT CONDITION (Continued)

Alloy Composition, weight per cent	Condition(a)	Ultimate Tensile Strength, 1000 psi	Yield Strength, 0.2 Per Cent Offset, 1000 psi	Elongation in 1 Inch, per cent	Testing Method (b)	Testing Method (c)
Ta-30Cb-10W	PR 980 C	43.0	--	7	X	
Ta-30Cb-5V	PR 980 C/CW 55 per cent	47.7	--	38	X	
Ta-30Cb-1Zr	CW 65 per cent	34.9	19.5	30		X
Ta-10Hf-5W	PR 980 C/CW 30 per cent	72.4	--	28	X	
Ta-10Hf-1Zr	PR 980 C/CW 50 per cent	64.7	37.5	15		X
Ta-10Hf-10Zr	PR 980 C/CW 70 per cent	33.8	--	23	X	
Ta-10Ti-5W	CW 65 per cent	49.3	--	18	X	
Ta-10Ti-10Hf	CW 65 per cent	31.4	--	4	X	
Ta-10Ti-10Zr	PR 980 C/CW 70 per cent	33.8	--	23	X	
Ta-20Ti-5Al	CW 70 per cent	18.1	--	87	X	
Ta-20Ti-5Cr	CW 65 per cent	17.6	--	12	X	
Ta-20Ti-5Mo	PR 980 C/CW 70 per cent	27.5	--	38	X	
Ta-20Ti-5V	CW 65 per cent	14.4	--	9	X	
Ta-20Ti-10W	PR 980 C/CW 70 per cent	23.4	--	8	X	

(a) PR = Pack Rolled
CW = Cold Worked.

(b) Tested in vacuum using conventional creep-rupture equipment. Specimen loaded by lead shot until the ultimate tensile strength was reached.

(c) Tested in vacuum using conventional hydraulic loading and a crosshead speed of approximately 0.01 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture.

It is seen that the maxima are all tantalum-rich for Group IVA and Group VA solutes. At 1200 C less columbium, hafnium, titanium, vanadium, and zirconium are required, as binary additions, for strengthening tantalum to the "optimum degree" than at room temperature. On the other hand, approximately the same amounts of binary molybdenum, rhenium, and tungsten additions are required for optimum strengthening at both temperatures. This observation is explainable on the basis of a lowering of the alloy melting point as the binary alloy additions, such as titanium or vanadium, are increased. Consequently, smaller binary alloy additions at 1200 C (2190 F) than at room temperature result in maximized strength.

A four- to eightfold strengthening improvement over unalloyed tantalum is noted for binary additions of 5 to 30 per cent hafnium, 5 to 10 per cent molybdenum, 5 to 20 per cent vanadium, 10 to 20 per cent tungsten, and 1 to 10 per cent zirconium. The strength peaks of 83,100, 66,400, and 60,200 psi exhibited for the Ta-15V, Ta-10Mo, and Ta-20Hf alloys, respectively, represent a potent strengthening of the high-purity base. The Ta-15V alloy is particularly attractive since this composition not only shows high strength at 1200 C (2190 F) but excellent bend ductility at cryogenic temperatures [-196 C (-320 F), Table 6].

Small additions (1 per cent) of the Group IVA metals, titanium, zirconium, and hafnium, give significant strengthening improvement over unalloyed tantalum. The addition of 1 per cent zirconium is particularly effective, indicating that zirconium is more effective in retaining dispersion hardening effects at 1200 C (2190 F) than either titanium or hafnium.

Several of the ternary alloys exhibited excellent strength levels ranging in improvement, as compared with unalloyed tantalum, from six- to ninefold. Ternary alloys containing Ta-Cb-V, Ta-Hf-W, Ta-Mo-Hf, Ta-Mo-V, Ta-Mo-W, and Ta-V-W exhibited tensile strength in excess of 60,000 psi at 1200 C (2190 F). The 87,400 psi measured for the Ta-10V-5W alloy represents the highest strength level attained.

As expected, many of the alloys designed for improved oxidation resistance, such as the ternary Ta-Ti-Al alloys, had low 1200 C (2190 F) tensile strengths by virtue of the high alloy content of a lower melting constituent, e.g., titanium.

Interstitial additions of 700 to 2300 ppm carbon or 170 to 400 ppm oxygen to the Ta-1Hf, Ta-1Ti, and Ta-1Zr alloys caused additional strengthening over the carbon or oxygen-free alloy. These data show that the greatest hot strengthening was caused by carbon additions; however, none of the dispersion-hardening additives appear as effective in improving the 1200 C (2190 F) strength of tantalum as higher additions of solid-solution strengtheners.

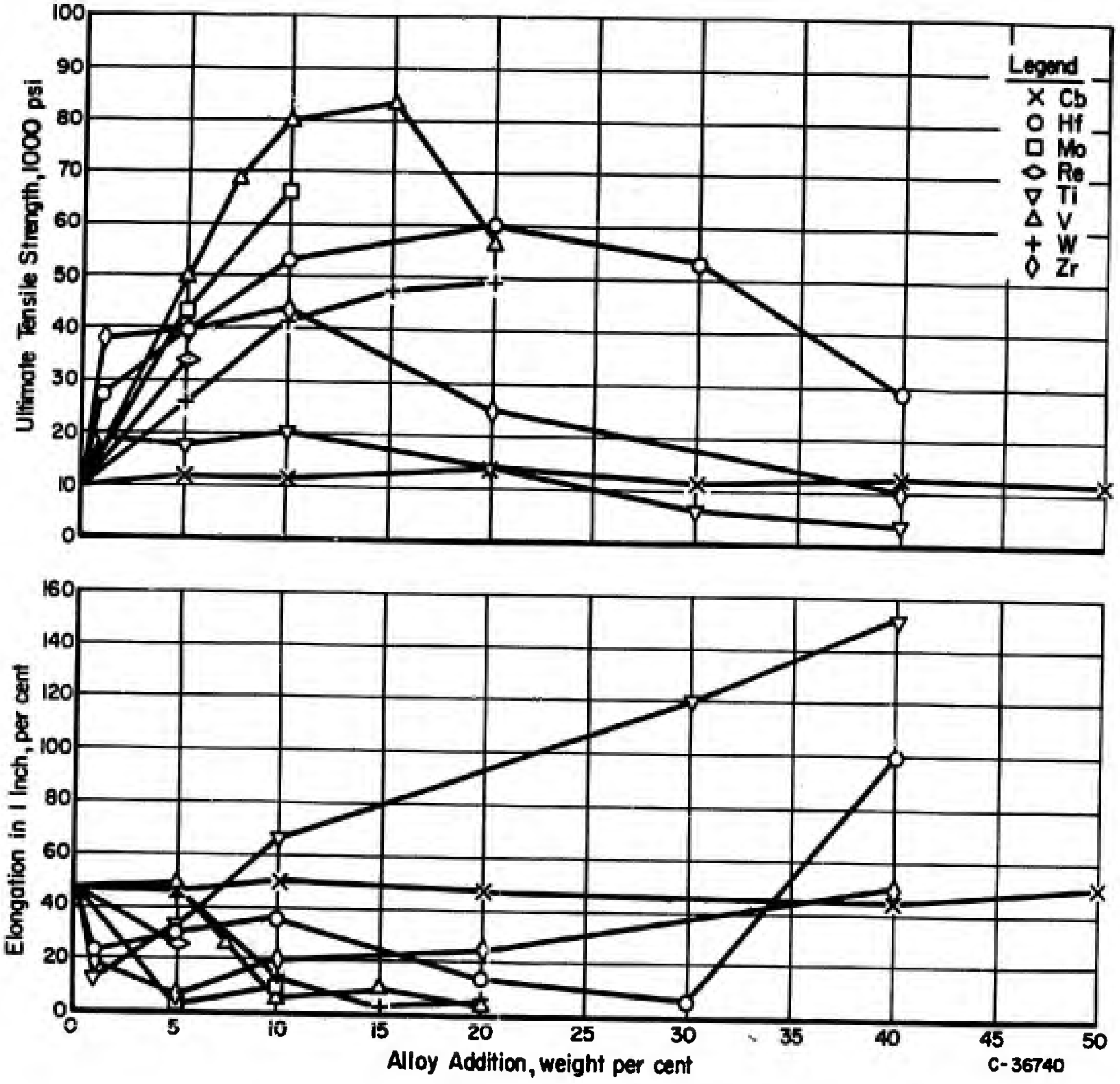


FIGURE 20. TENSILE PROPERTIES OF BINARY TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

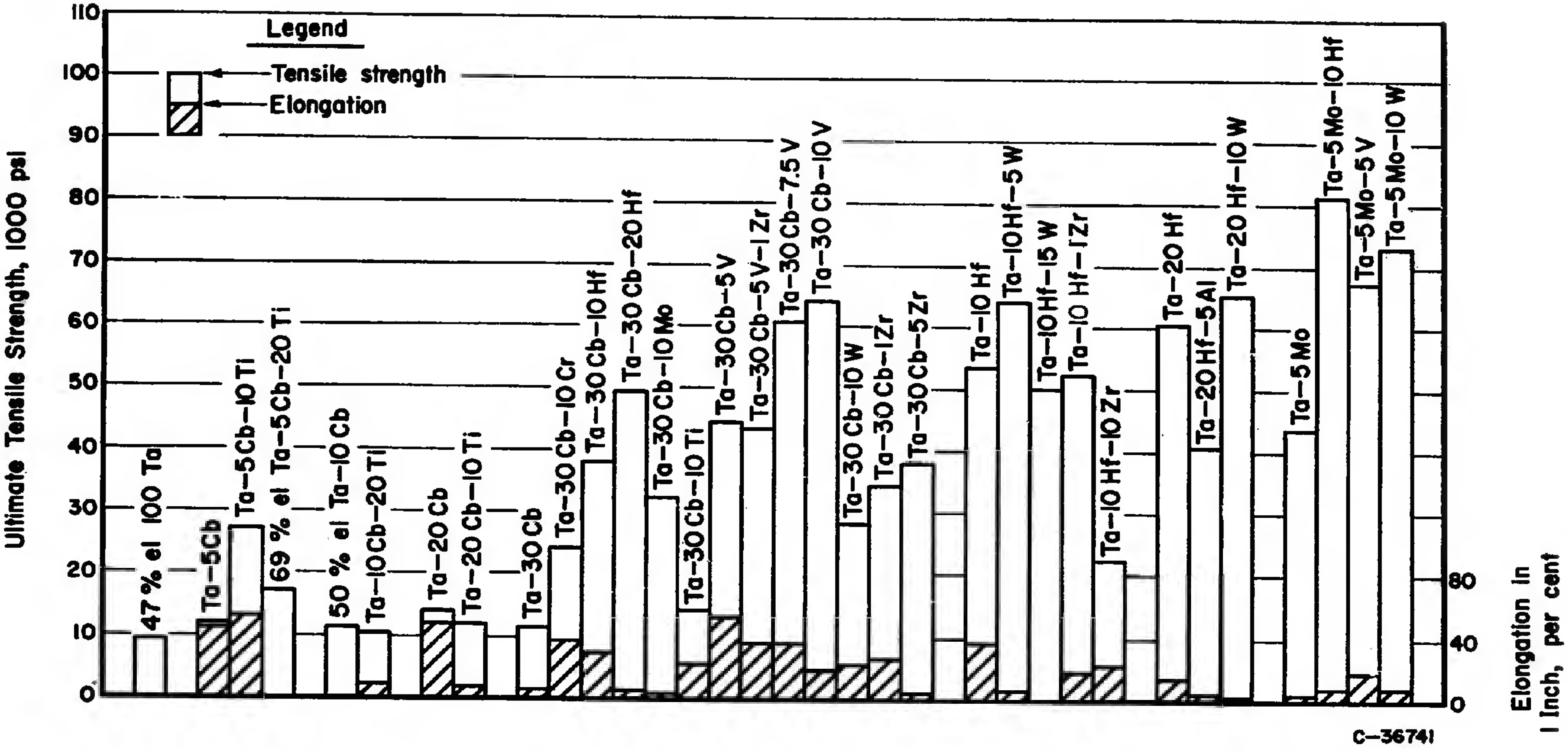


FIGURE 21. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

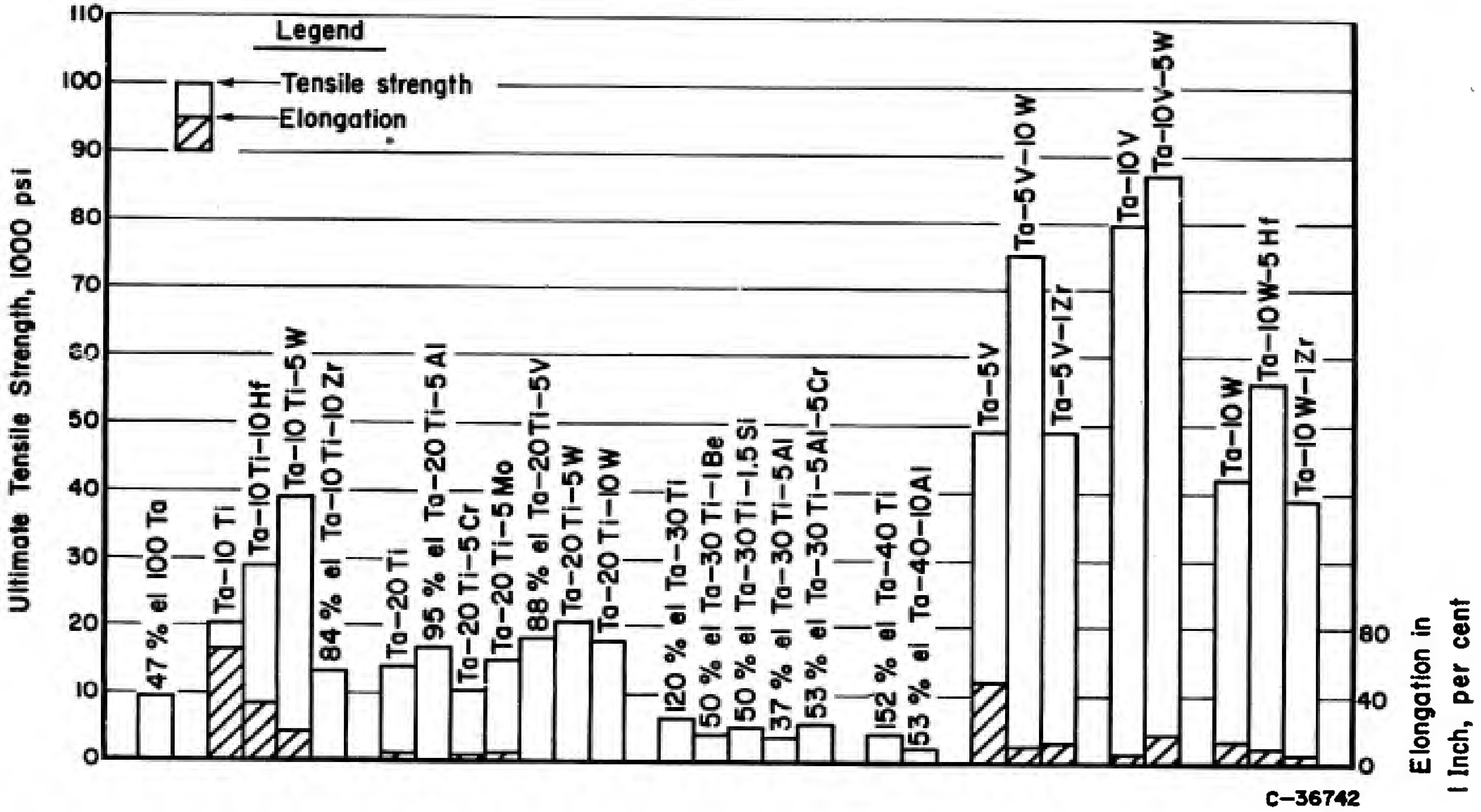


FIGURE 21. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

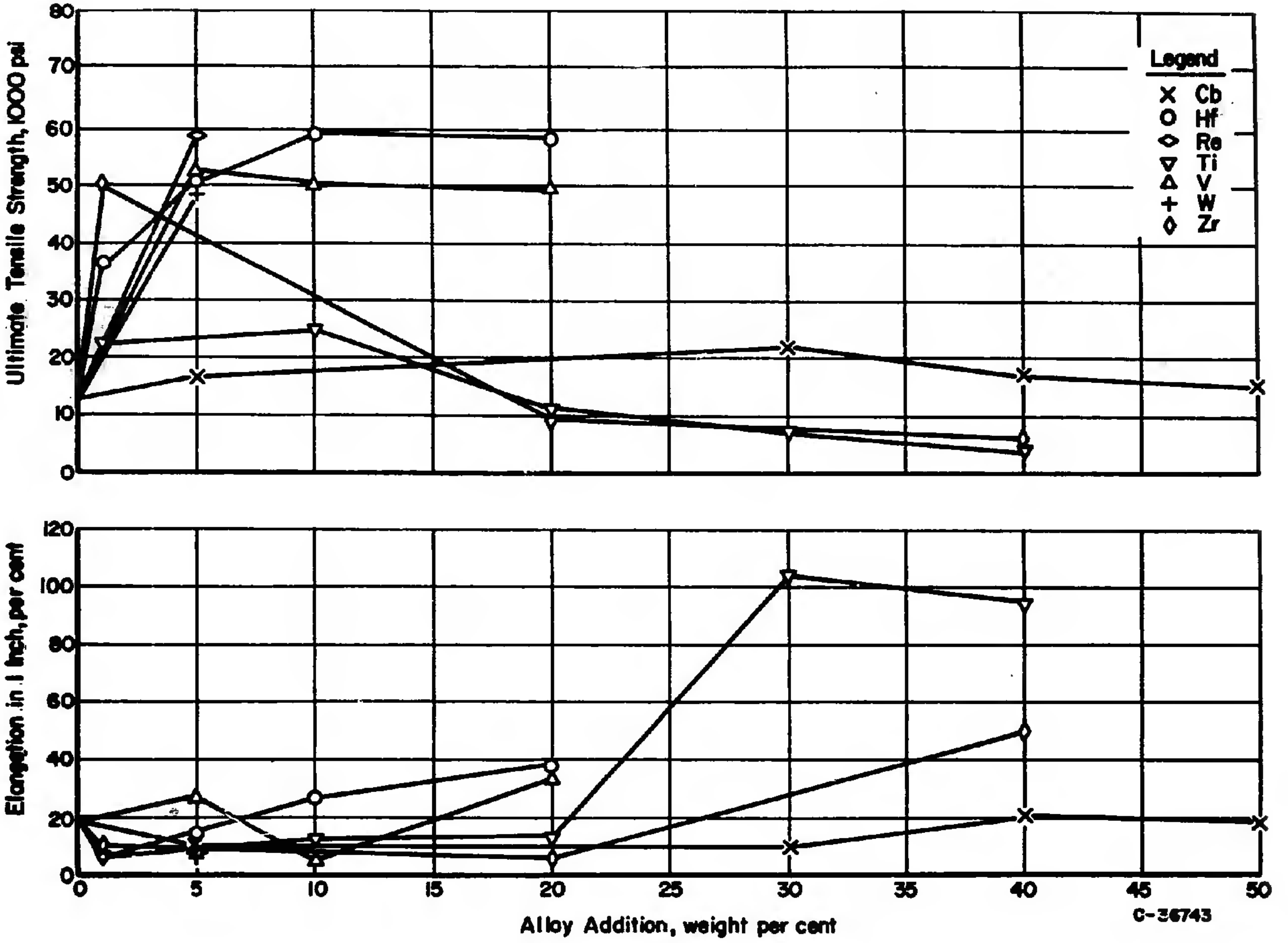


FIGURE 22. TENSILE PROPERTIES OF BINARY TANTALUM ALLOYS AT 1200 C (2190 F) IN THE WROUGHT CONDITION

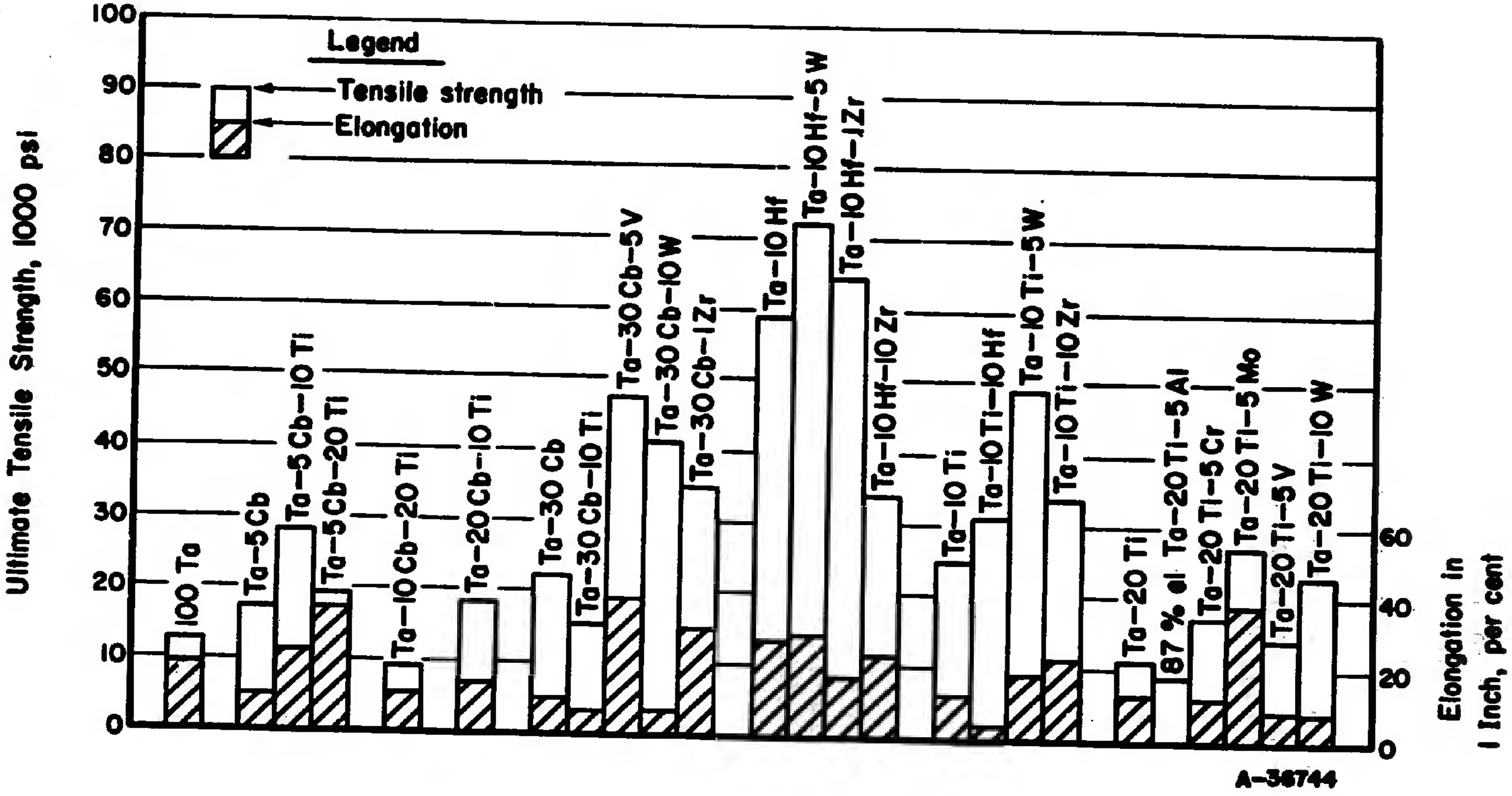


FIGURE 23. TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS AT 1200 C (2190 F) IN THE WROUGHT CONDITION

The addition of 580-ppm carbon to the Ta-5V alloy apparently has a detrimental effect by reducing the tensile strength from 49,200 to 44,000 psi. This difference might be explained by the test method and slower strain rate used for the carbon-containing alloy.

As expected, in most cases, the as-worked alloys show higher tensile strengths than the corresponding recrystallized alloy; however, some alloys, such as Ta-10V, Ta-20V, Ta-20Zr, and Ta-40Zr, exhibit higher recrystallized tensile strengths. The reason for this behavior is not known. The wrought Ta-10Hf-5W had the highest tensile strength, 72,400 psi, of any of the wrought alloys tested.

Table 10 gives the densities and relative strengthening of tantalum alloys as compared with unalloyed tantalum at 1200 C (2190 F). These increases and decreases in strengthening, relative to pure tantalum, uncorrected and corrected for density are illustrated in Figures 24 through 27.

Densities were calculated by means of the equation given at the bottom of Table 10, using elemental densities at 20 C (70 F) as given by Hansen and Andesko.(70) These calculated densities were checked on three Ta-Cb-V alloys using a standard volume-displacement technique. Good agreement between calculated and measured densities was obtained as shown below:

Alloy Composition, weight per cent	Alloy Density, g/cm^3	
	Calculated	Measured
Ta-30Cb-5V	12.2	12.29
Ta-30Cb-7.5V	11.8	11.75
Ta-30Cb-10V	11.4	11.62

Several binary and ternary tantalum alloys show marked strengthening improvements over pure tantalum at 1200 C (2190 F). Most of these alloys show even greater improvements when corrected for density, particularly when the 16.6 g/cm^3 for pure tantalum is considered. Of the high-strength binary and ternary alloys, vanadium or columbium and vanadium show the greatest increase in tensile strength. For example, the Ta-30Cb-10V alloy shows a 580 per cent strength increase relative to unalloyed tantalum. When corrected for density, a further 300 per cent strength increase for this alloy is obtained by considering density. The highest strength-to-weight ratios found were for the Ta-15V and Ta-10V-5W alloys; these values are 174,000 and 169,000 $psi/lb/in.^3$, respectively.

Effect of Temperature

Tensile properties of tantalum and a number of the tantalum alloys at 25 and 1200 C (75 and 2190 F) are compared in Table 11. It is apparent that several attractive alloys with high room-temperature strength retain only a

TABLE 10. DENSITIES AND RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

Alloy Composition, weight per cent	Calculated Density(a)		1200 C (2190 F)		Strength Increase, per cent, as Compared With Unalloyed Tantalum at 1200 C (2190 F)	
	G/CM^3	Lb/In.^{3}	Ultimate Tensile Strength, 1000 psi	Strength-to-Weight Ratio, 1000 psi/lb/in.^{3}	Uncorrected For Density	Corrected For Density
100Ta	16.6	0.600	9.4(b)	15.7	--	--
Ta-5Cb	15.9	0.574	11.9	20.7	25	30
Ta-10Cb	15.2	0.549	11.3	20.6	20	30
Ta-20Cb	14.0	0.506	13.9	27.5	50	75
Ta-30Cb	13.0	0.470	11.6	24.7	25	55
Ta-40Cb	12.1	0.437	12.9	29.5	35	90
Ta-50Cb	11.3	0.408	11.9	29.2	25	85
Ta-1Hf	16.6	0.600	27.7	46.2	195	195
Ta-1Hf + C (700 ppm)	16.6	0.600	33.0	55.0	250	250
Ta-1Hf + O (170 ppm)	16.6	0.600	43.4	72.3	360	360
Ta-5Hf	16.4	0.593	39.7	66.9	320	325
Ta-10Hf	16.2	0.585	53.5	91.5	470	485
Ta-10Hf + C (630 ppm)	16.2	0.585	>41.4(c)	>70.8	>340	>350
Ta-20Hf	15.8	0.571	60.2	105	540	570
Ta-30Hf	15.4	0.556	53.6	96.4	470	515
Ta-35Hf	15.2	0.549	29.0	52.8	210	235
Ta-5Mo	16.1	0.582	43.5	74.7	365	375
Ta-7.5Mo	15.9	0.574	>25.8(c)	>44.9	>175	>185
Ta-10Mo	15.6	0.564	66.4	118	605	650
Ta-5Re	16.8	0.607	34.0	56.0	260	255
Ta-1Ti	16.2	0.585	19.1	32.6	105	110
Ta-1Ti + C (2300 ppm)	16.2	0.585	29.0	49.6	210	215
Ta-1Ti + O (280 ppm)	16.2	0.585	19.0	32.5	100	105
Ta-5Ti	14.7	0.531	17.8	33.5	90	115
Ta-10Ti	13.1	0.473	20.4	43.1	115	175
Ta-20Ti	10.8	0.390	14.2	36.4	50	130
Ta-30Ti	9.2	0.332	6.6	19.9	-30	25
Ta-40Ti	8.0	0.289	4.2	14.5	-55	-10
Ta-5V	15.3	0.553	49.2	89.0	425	465
Ta-5V + C (580 ppm)	15.3	0.553	44.0	80.0	370	410
Ta-7.5V	14.7	0.531	68.4	129	630	720
Ta-10V	14.2	0.513	79.7	155	750	885
Ta-15V	13.2	0.477	83.1	174	785	1010
Ta-20V	12.4	0.448	56.4	126	500	705

TABLE 10. DENSITIES AND RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Calculated Density(a) G/CM^3	Calculated Density(a) Lb/In.^{3}	1200 C (2190 F) Ultimate Tensile Strength, 1000 psi	1200 C (2190 F) Strength-to-Weight Ratio, 1000 psi/lb/in.^{3}	Strength Increase, per cent, as Compared With Unalloyed Tantalum at 1200 C (2190 F) Uncorrected For Density	Strength Increase, per cent, as Compared With Unalloyed Tantalum at 1200 C (2190 F) Corrected For Density
Ta-5W	16.8	0.607	25.6	42.2	170	170
Ta-10W	16.8	0.607	41.8	68.9	345	340
Ta-10W + C (590 ppm)	16.8	0.607	>37.2(c)	>61.3	>295	>290
Ta-15W	17.0	0.614	47.5	77.4	405	395
Ta-20W	17.1	0.618	49.6	80.3	430	410
Ta-1Zr	16.4	0.593	38.3	64.6	305	310
Ta-1Zr + C (1400 ppm)	16.4	0.593	45.0	75.9	380	385
Ta-1Zr + O (400 ppm)	16.4	0.593	42.3	71.3	350	355
Ta-5Zr	15.4	0.556	40.5	72.8	330	365
Ta-10Zr	14.4	0.520	44.0	84.6	370	440
Ta-20Zr	12.7	0.459	25.6	55.8	170	255
Ta-40Zr	10.2	0.369	10.8	29.3	15	85
Ta-5Cb-10Ti	12.6	0.455	27.3	60.0	190	280
Ta-5Cb-20Ti	10.5	0.379	16.6	43.8	75	180
Ta-10Cb-20Ti	10.2	0.369	10.7	29.0	15	85
Ta-20Cb-10Ti	11.4	0.412	11.8	28.6	25	80
Ta-30Cb-10Ti	10.7	0.387	14.0	36.2	50	130
Ta-30Cb-10Cr	11.8	0.426	24.2	56.8	155	260
Ta-30Cb-10Hf	12.7	0.459	37.8	82.4	300	425
Ta-30Cb-20Hf	12.4	0.448	49.2	110	425	600
Ta-30Cb-10Mo	12.4	0.448	32.4	72.3	245	360
Ta-30Cb-10W	13.1	0.473	27.8	58.8	195	275
Ta-30Cb-5V	12.2	0.441	44.7(b)	101	375	545
Ta-30Cb-5V-1Zr	12.0	0.434	43.3	99.8	360	535
Ta-30Cb-7.5V	11.8	0.426	60.6	142	545	805
Ta-30Cb-10V	11.4	0.412	63.9	155	580	885
Ta-30Cb-1Zr	12.8	0.462	34.6	74.9	270	375
Ta-30Cb-5Zr	12.2	0.441	37.7	85.5	300	445
Ta-10Hf-5W	16.3	0.589	63.8	108	580	590
Ta-10Hf-5W + C (540 ppm)	16.3	0.589	59.8	102	535	550
Ta-10Hf-15W	16.5	0.596	49.8	83.6	430	430
Ta-10Hf-1Zr	16.0	0.578	52.2	90.3	455	475
Ta-10Hf-10Zr	14.0	0.506	22.6	44.7	140	185
Ta-20Hf-5Al	12.7	0.459	42.5	92.6	350	490

TABLE 10. DENSITIES AND RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Calculated Density(a) G/CM^3	Calculated Density(a) Lb/In.^{3}	1200 C (2190 F) Ultimate Tensile Strength, 1000 psi	1200 C (2190 F) Strength-to-Weight Ratio, 1000 psi/lb/in.^{3}	Strength Increase, per cent, as Compared With Unalloyed Tantalum at 1200 C (2190 F): Uncorrected For Density	Strength Increase, per cent, as Compared With Unalloyed Tantalum at 1200 C (2190 F): Corrected For Density
Ta-20Hf-10W	16.0	0.578	64.9	112	590	615
Ta-5Mo-10Hf	15.7	0.567	80.8	143	760	810
Ta-5Mo-5V	14.9	0.538	66.8	124	610	690
Ta-5Mo-10W	16.4	0.593	72.7	123	675	685
Ta-10Ti-5W	13.2	0.477	39.3	82.4	320	425
Ta-10Ti-10Hf	12.8	0.462	28.7	62.1	205	295
Ta-10Ti-10Zr	11.7	0.423	13.5	31.9	45	105
Ta-20Ti-5Al	9.3	0.336	16.8	50.0	80	220
Ta-20Ti-5Cr	10.4	0.376	10.8	28.7	15	85
Ta-20Ti-5Mo	10.6	0.383	15.0	39.2	60	150
Ta-20Ti-5V	10.2	0.369	18.5	50.1	95	220
Ta-20Ti-5W	10.9	0.394	20.7	52.5	120	235
Ta-20Ti-10W	10.9	0.394	17.9	45.4	90	190
Ta-30Ti-1Be	8.8	0.318	4.0	12.6	-55	-20
Ta-30Ti-1.5Si	8.8	0.318	5.3	16.7	-45	5
Ta-30Ti-5Al	8.1	0.293	3.7	12.6	-60	-20
Ta-30Ti-5Al-5Cr	7.8	0.282	5.6	19.9	-40	25
Ta-40Ti-10Al	6.4	0.231	2.3	9.95	-75	-35
Ta-5V-10W	15.5	0.560	75.5	135	705	760
Ta-5V-1Zr	15.1	0.546	49.3	90.3	425	475
Ta-10V-5W	14.3	0.517	87.4	169	830	975
Ta-10W-1Zr	16.6	0.600	39.1	65.2	315	315
Ta-10W-5Hf	16.7	0.603	56.5	93.7	500	495

(a) Calculated from $d = \dfrac{100}{\dfrac{A}{d_A} + \dfrac{B}{d_B} + \ldots\ldots}$, where d = alloy density; A = weight per cent Element A; B = weight per cent Element B; d_A = density of Element A; and d_B = density of Element B.

(b) Average of two tests.

(c) Failed along grain-boundary cracks.

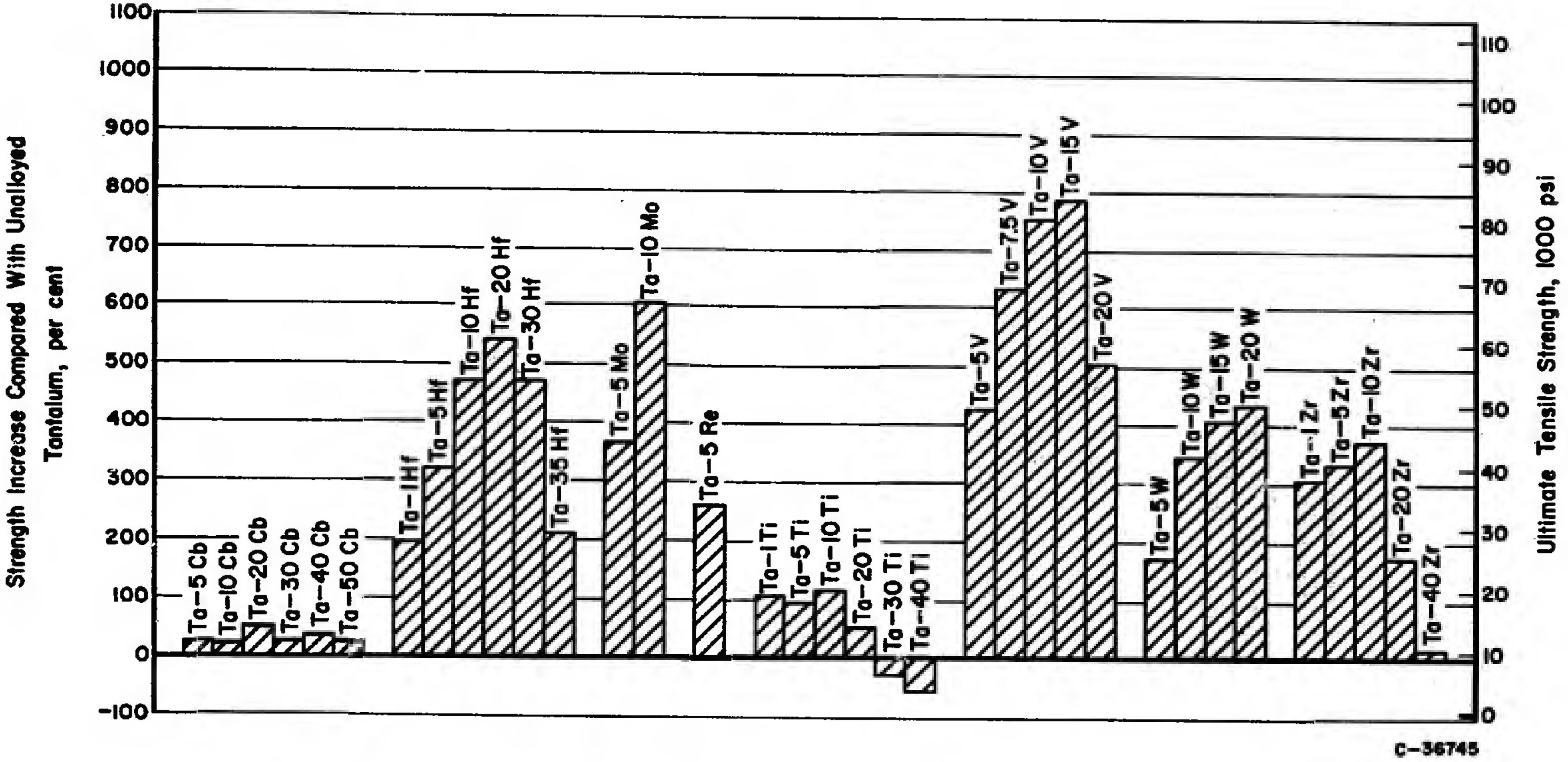


FIGURE 24. RELATIVE STRENGTHENING OF BINARY TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND UNCORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

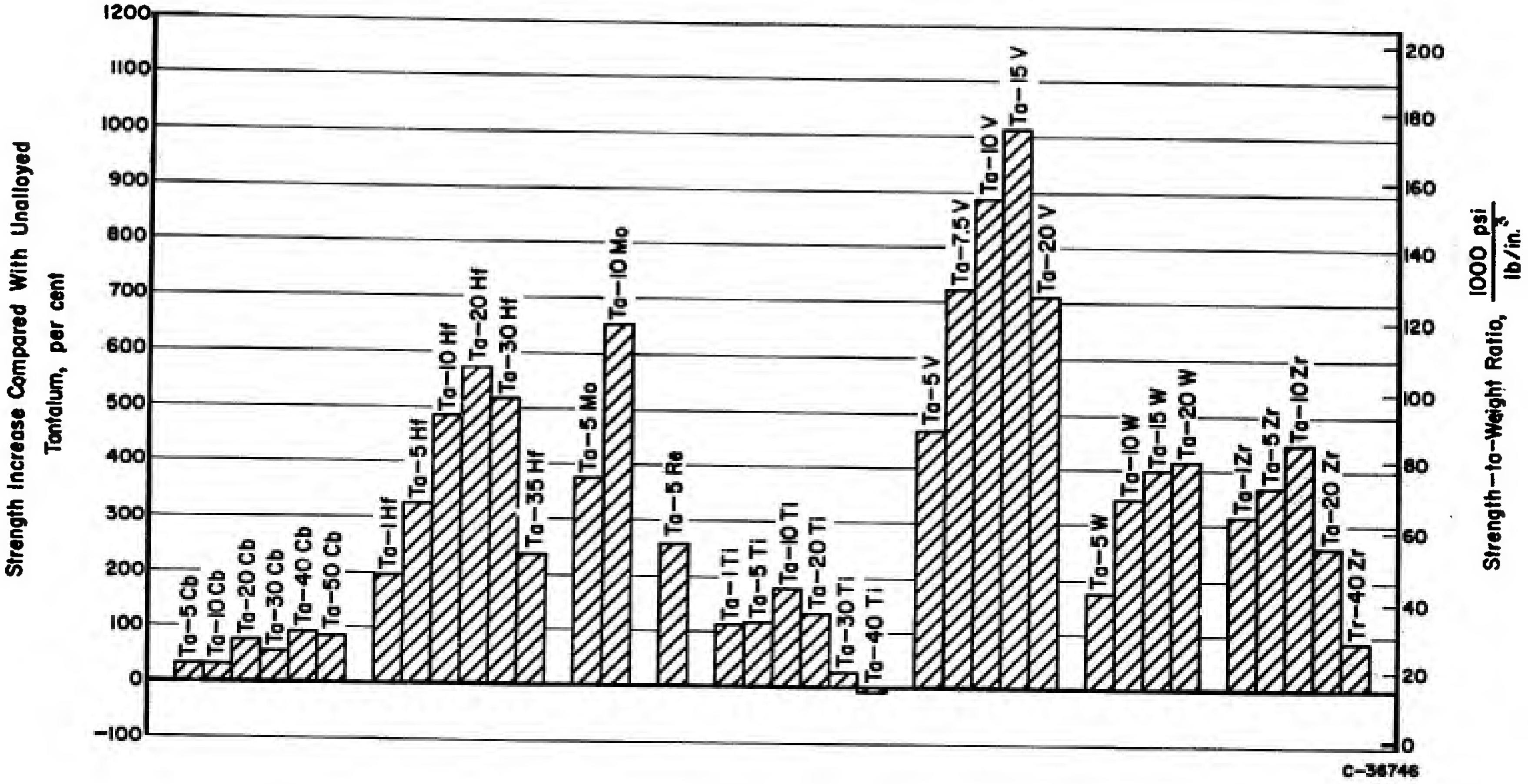


FIGURE 25. RELATIVE STRENGTHENING OF BINARY TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND CORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

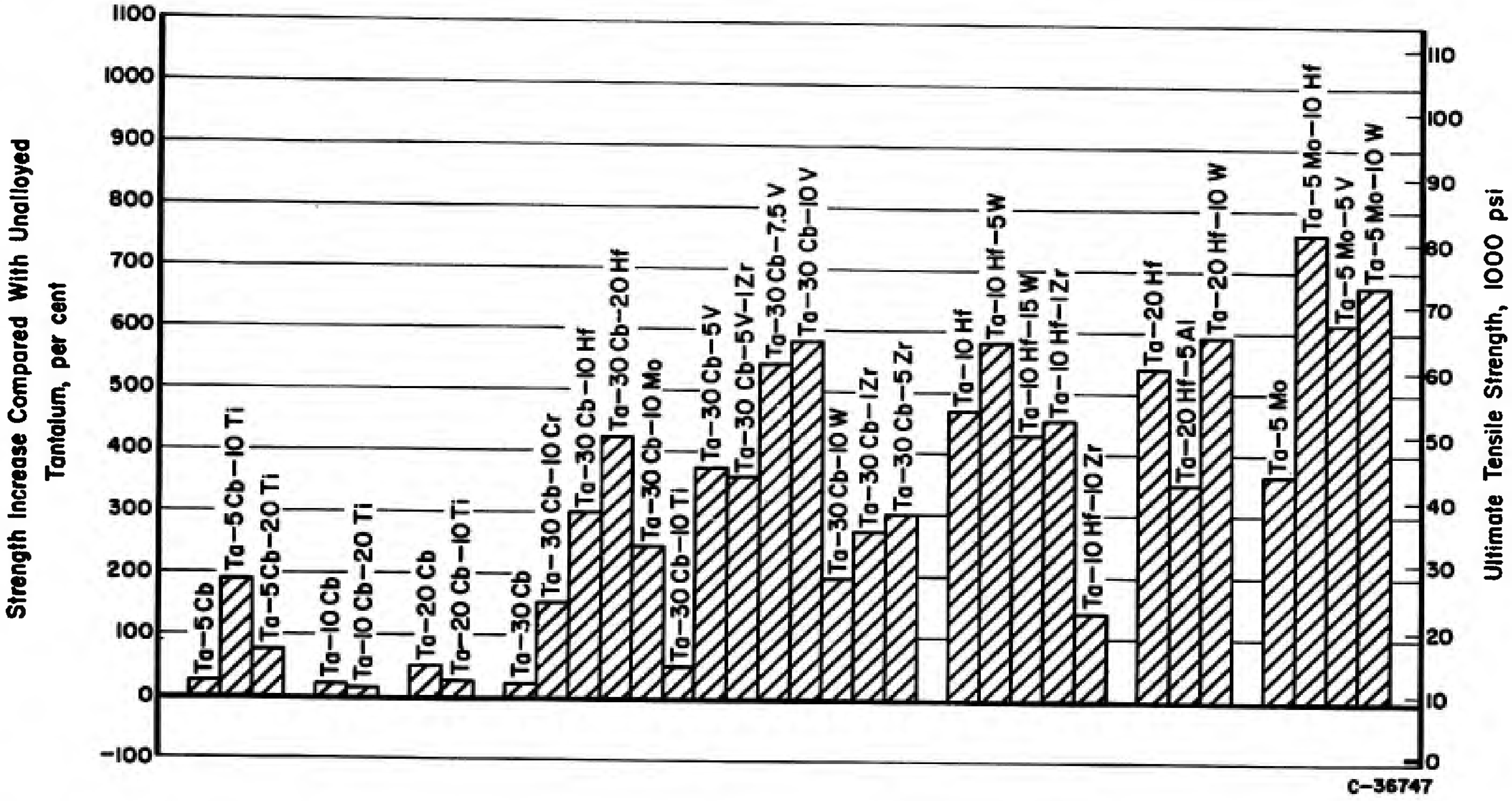


FIGURE 26. RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND UNCORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

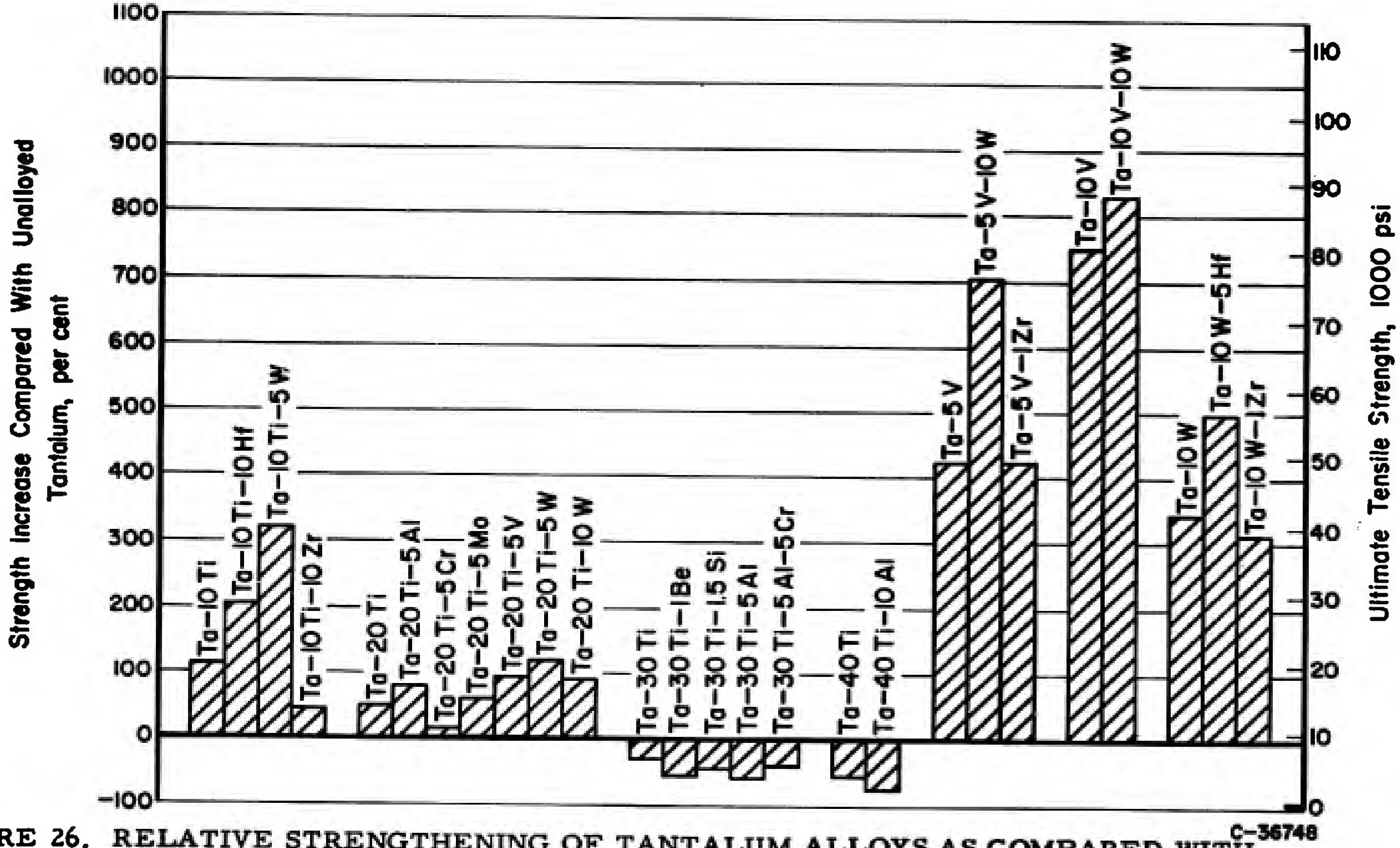


FIGURE 26. RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND UNCORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

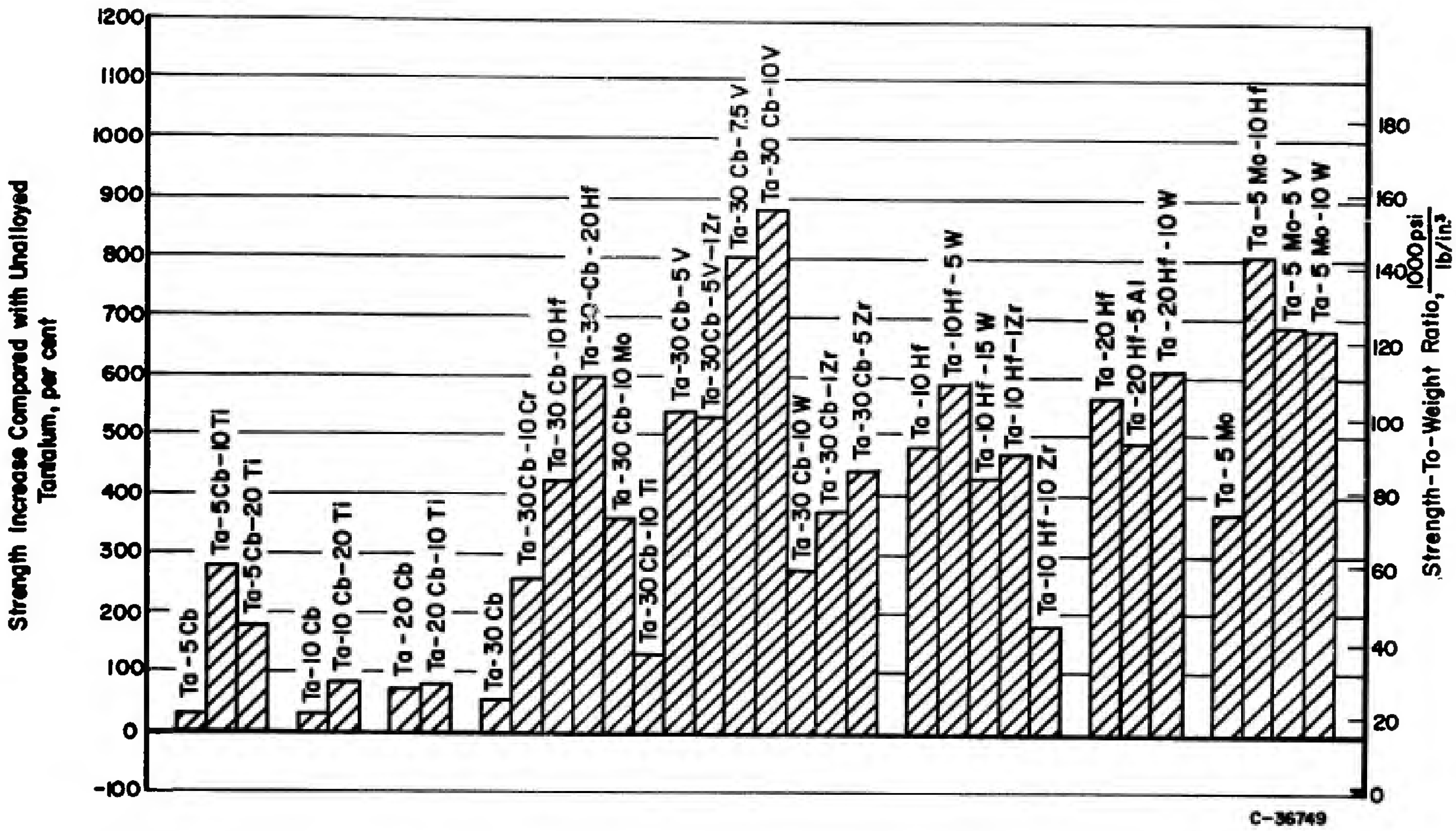


FIGURE 27. RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND CORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION

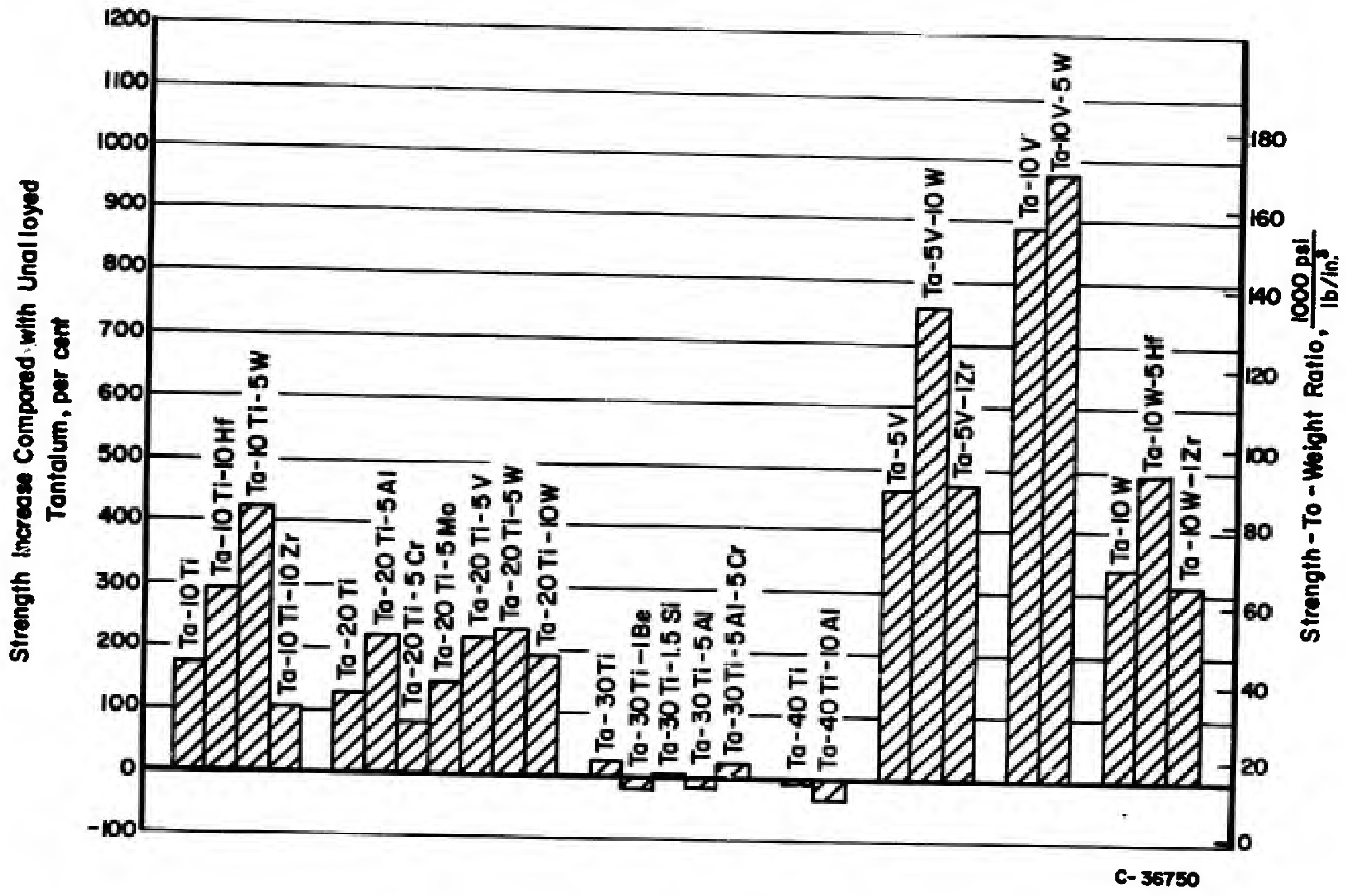


FIGURE 27. RELATIVE STRENGTHENING OF TANTALUM ALLOYS AS COMPARED WITH UNALLOYED TANTALUM AND CORRECTED FOR DENSITY AT 1200 C (2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

TABLE 11. RETAINED ULTIMATE TENSILE STRENGTH AT 1200 C (2190 F) AS COMPARED WITH ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi		Retained Strength[(a)], per cent
	25 C (75 F)	1200 C (2190 F)	
100Ta	30.6[(b)]	9.4[(b)]	30
Ta-5Cb	38.2	11.9	30
Ta-10Cb	39.5	11.3	30
Ta-20Cb	41.8	13.9	35
Ta-30Cb	46.9	11.6	25
Ta-40Cb	50.5	12.9	25
Ta-50Cb	42.7	11.9	30
Ta-1Hf	52.6	27.7	55
Ta-5Hf	45.4	39.7	85
Ta-10Hf	86.3	53.5	60
Ta-20Hf	120.0	60.2	50
Ta-30Hf	146.8	53.6	35
Ta-35Hf	138.0	29.0	20
Ta-5Mo	110.3	43.5	40
Ta-10Mo	72.4	66.4	90[(c)]
Ta-5Re	98.0	34.0	35
Ta-1Ti	71.5	19.1	25
Ta-5Ti	52.8	17.8	35
Ta-10Ti	66.9	20.4	30
Ta-20Ti	82.8	14.2	15
Ta-30Ti	91.9	6.6	5
Ta-40Ti	106.0	4.2	5
Ta-5V	87.0	49.2	55
Ta-10V	161.2	79.7	50
Ta-20V	177.6	56.4	30
Ta-5W	84.0	25.6	30
Ta-10W	79.6	41.8	55
Ta-15W	89.0	47.5	55

TABLE 11. RETAINED ULTIMATE TENSILE STRENGTH AT 1200 C (2190 F) AS COMPARED WITH ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi		Retained Strength(a), per cent
	25 C (75 F)	1200 C (2190 F)	
Ta-1Zr	57.6	38.3	65
Ta-5Zr	94.5	40.5	45
Ta-10Zr	109.5	44.0	40
Ta-20Zr	112.5	25.6	25
Ta-40Zr	102.4	10.8	10
Ta-5Cb-10Ti	78.6	27.3	35
Ta-5Cb-20Ti	87.3	16.6	20
Ta-10Cb-20Ti	78.5	10.7	15
Ta-20Cb-10Ti	75.3	11.8	15
Ta-30Cb-10Ti	69.4	14.0	20
Ta-30Cb-10Hf	65.1	37.8	60
Ta-30Cb-20Hf	85.9	49.2	55
Ta-30Cb-10W	65.0	27.8	45
Ta-30Cb-5V	95.8	44.7(b)	45
Ta-30Cb-5V-1Zr	111.0	43.3	40
Ta-30Cb-7.5V	139.1	60.6	45
Ta-30Cb-10V	147.5	63.9	45
Ta-30Cb-1Zr	61.3	34.6	55
Ta-30Cb-5Zr	73.8	37.7	50
Ta-10Hf-5W	115.3	63.8	55
Ta-10Hf-1Zr	98.6	52.2	55
Ta-10Hf-10Zr	132.0	22.6	15
Ta-5Mo-10Hf	106.0	80.8	75
Ta-5Mo-5V	133.2	66.8	50
Ta-10Ti-5W	97.1	39.3	40
Ta-10Ti-10Hf	104.6	28.7	25
Ta-10Ti-10Zr	120.7	13.5	10

TABLE 11. RETAINED ULTIMATE TENSILE STRENGTH AT 1200 C (2190 F) AS COMPARED WITH ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Ultimate Tensile Strength, 1000 psi		Retained Strength(a), per cent
	25 C (75 F)	1200 C (2190 F)	
Ta-20Ti-5Al	133.9	16.8	15
Ta-20Ti-5Cr	109.4	10.8	10
Ta-20Ti-5Mo	92.0	15.0	15
Ta-20Ti-5V	107.6	18.5	15
Ta-20Ti-5W	47.5	20.7	45
Ta-20Ti-10W	129.0	17.9	15
Ta-30Ti-1Be	105.0	4.0	5
Ta-30Ti-5Al	113.5	3.7	5
Ta-30Ti-5Al-5Cr	72.0	5.6	10
Ta-40Ti-10Al	101.0	2.3	2
Ta-5V-10W	152.9	75.5	50
Ta-5V-1Zr	108.2	49.3	45
Ta-10W-1Zr	87.5	39.1	45
Ta-10W-5Hf	105.0	56.5	55

(a) $\frac{\text{UTS at 1200 C (2190 F)}}{\text{UTS at 25 C (75 F)}}$.

(b) Average of two tests.

(c) Value high because of brittle behavior at room temperature.

small per cent of this strength at 1200 C (2190 F). However, binary alloys containing 1 to 20 per cent hafnium, 5 to 10 per cent molybdenum, 5 to 10 per cent vanadium, 10 to 15 per cent tungsten, and 1 per cent zirconium retain at least one-half their room-temperature tensile strength at 1200 C (2190 F). Ternary alloys, which also retain at least one-half their room-temperature tensile strength at 1200 C (2190 F) include the Ta-Cb-Hf, Ta-Cb-Zr, Ta-Hf-W, Ta-Hf-Zr, Ta-Mo-Hf, Ta-Mo-V, and Ta-V-W alloys. The binary Ta-5Hf and Ta-5Mo-10Hf alloys are outstanding in retention of room-temperature strength, retaining 85 and 75 per cent, respectively, at 1200 C (2190 F). These data are shown in Figures 28 and 29.

The recrystallized tensile properties of unalloyed tantalum, five binary, and 6 ternary tantalum alloys over the temperature range -196 to 1690 C (-320 to 3075 F) are given in Table 12. The effect of temperature on the tensile strength is shown in Figure 30.

The strength curve for pure tantalum is characterized by a rapid increase in strength with decreasing temperature below about 200 C (390 F). This rapid increase is a basic characteristic of body-centered-cubic metals and only a small strength increment is added by interstitial impurities.(67) Serrated load-strain curves were obtained on the unalloyed tantalum samples tested between about 200 and 500 C (390 and 930 F). The specimen tested at 325 C (615 F) yielded the greatest number of serrations, the largest strain-hardening exponent, and the highest tensile strength. The observed behavior is indicative of strain aging due to the presence of interstitials.(1) At higher temperatures strength decreases relatively slowly to a value of 3,600 psi at 1670 C (3040 F).

Although great differences in strength are noted for tantalum and the alloys of tantalum over the temperature range of -196 to 1200 C (-320 to 2190 F) only slight differences are seen at higher temperatures. However, at 1650 C (3000 F) all of the alloys tested showed a considerable strength advantage over unalloyed tantalum. These data are further illustrated in Figures 31 and 32, uncorrected and corrected for density, respectively, over the temperature range 1200 to 1690 C (2190 to 3075 F).

All 11 alloys show good strengthening improvement over the high-purity base with the binary Ta-V and Ta-Zr and ternary Ta-Cb-V alloys showing approximately the same tensile strengths above 1425 C (2600 F), although considerable difference in tensile strength is observed at lower temperatures. The Ta-10Hf-5W, Ta-5V-5W, and Ta-5V-7.5W alloys represent a still higher strength level above 1425 C (2600 F). At 1650 C (3000 F), these alloys show about a fivefold strengthening improvement over pure tantalum and about a twofold strengthening improvement over the binary Ta-V and Ta-Zr, and ternary Ta-Cb-V alloys. As expected, when corrected for density, most of the alloys show greater strength-to-weight improvements because of the lower alloy densities as compared with pure tantalum.

The effect of vanadium content on the tensile strength and strength-to-weight ratio of tantalum and the Ta-30Cb alloy from 25 to 1650 C (75 to 3000 F) is shown in Figures 33 through 36.

On the basis of these data, the following vanadium contents are indicated for maximum strengthening of tantalum and the Ta-30Cb-base alloy.

Temperature		Vanadium Content, weight per cent, Necessary for Maximum Strengthening at Indicated Temperature	
C	F	Ta	Ta-30Cb
25	75	>20	>20
1200	2190	15	10
1315	2400	10	7.5
1425	2600	7.5	7.5
1500	2730	7.5	7.5
1650	3000	5	7.5

As shown in Figures 33 and 35, the strength peak shifts toward lower vanadium contents as the test temperature is increased. As noted earlier, this behavior of vanadium appears related to a lowering of alloy melting point with increasing alloy content.(71) Thus, at high temperatures, on the order of 1315 C (2400 F) and above, an alloy with a high vanadium content will be less strong than one with a low vanadium content. It appears that the addition of about 7.5 per cent vanadium to either tantalum or the Ta-30Cb alloy gives the best strength properties from 1200 to 1650 C (2190 to 3000 F).

The effect of temperature on the tensile strength and strength-to-weight ratio of tantalum and tantalum alloys as compared with other refractory metals and alloys over the temperature range 1000 to 1800 C (1830 to 3270 F) is shown in Figures 37 and 38, respectively. It is apparent that the elevated-temperature strengths of many of the tantalum alloys compare favorably with those of the leading columbium and molybdenum alloy candidates (i.e., the F-48, Mo-0.5Ti, and TZM alloys). At temperatures to about 1425 C (2600 F), many of the tantalum alloys show equal or greater strengths than tungsten. The Ta-10Hf-5W, Ta-5V-5W, and Ta-5V-7.5W alloys show approximately the same strength level as tungsten at 1650 C (3000 F). When these tensile data are corrected for density, most of the tantalum alloys show attractively high strength-to-weight ratios up to at least 1650 C (3000 F).

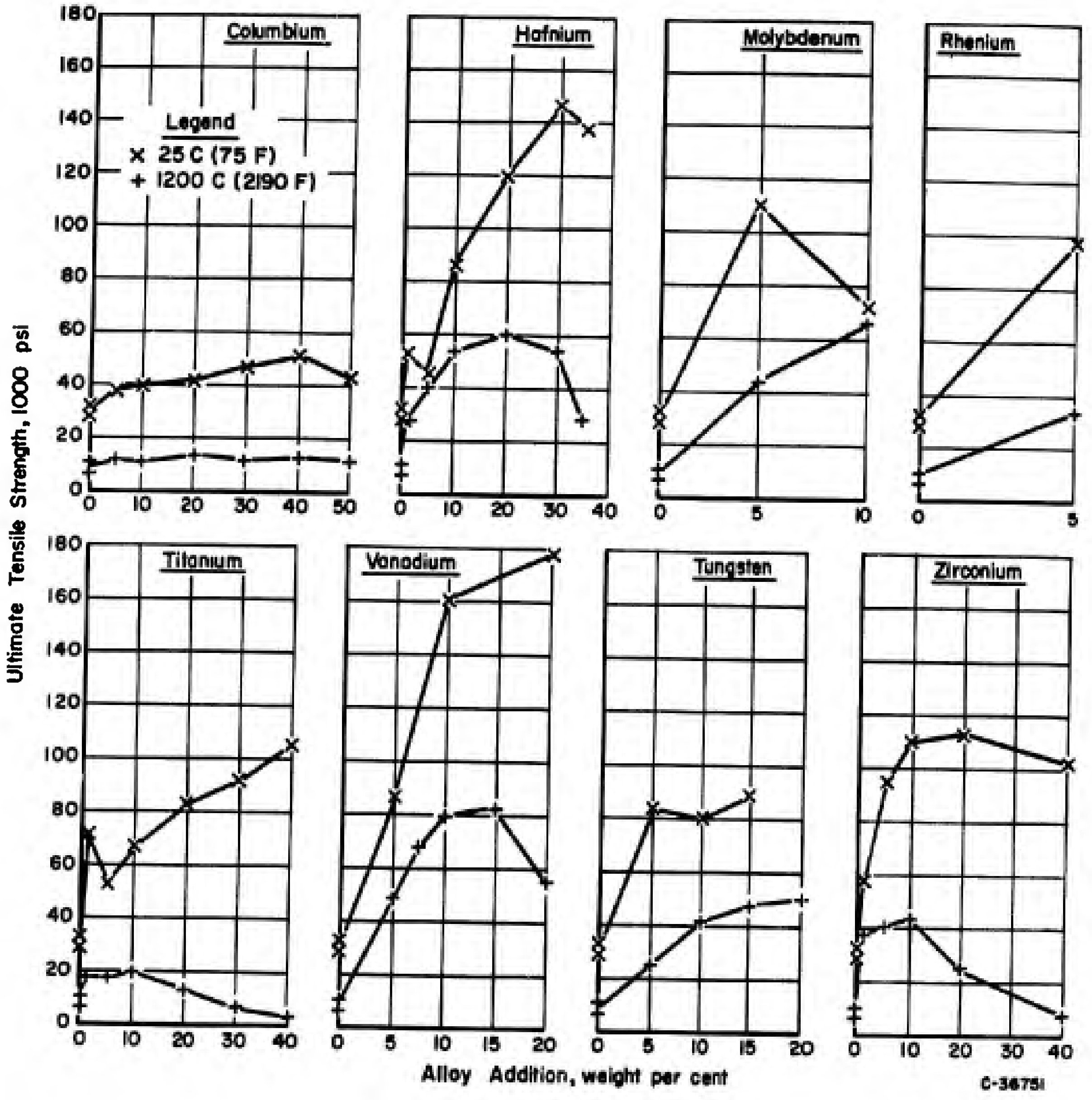


FIGURE 28. EFFECT OF BINARY ALLOY ADDITIONS ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AT 25 AND 1200 C (75 AND 2190 F) IN THE RECRYSTALLIZED CONDITION

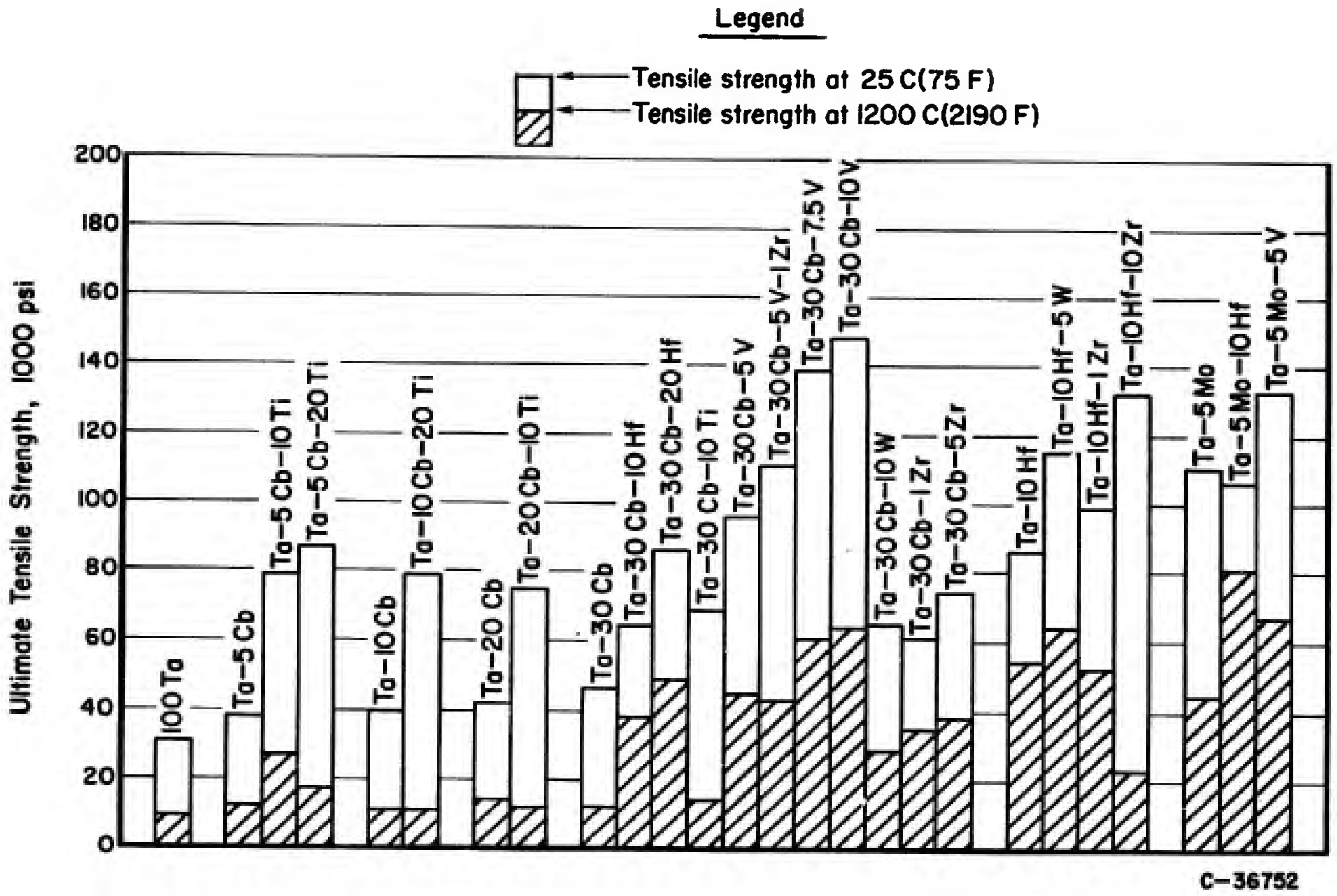


FIGURE 29. EFFECT OF ALLOY ADDITIONS ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS AT 25 AND 1200 C (75 AND 2190 F) IN THE RECRYSTALLIZED CONDITION

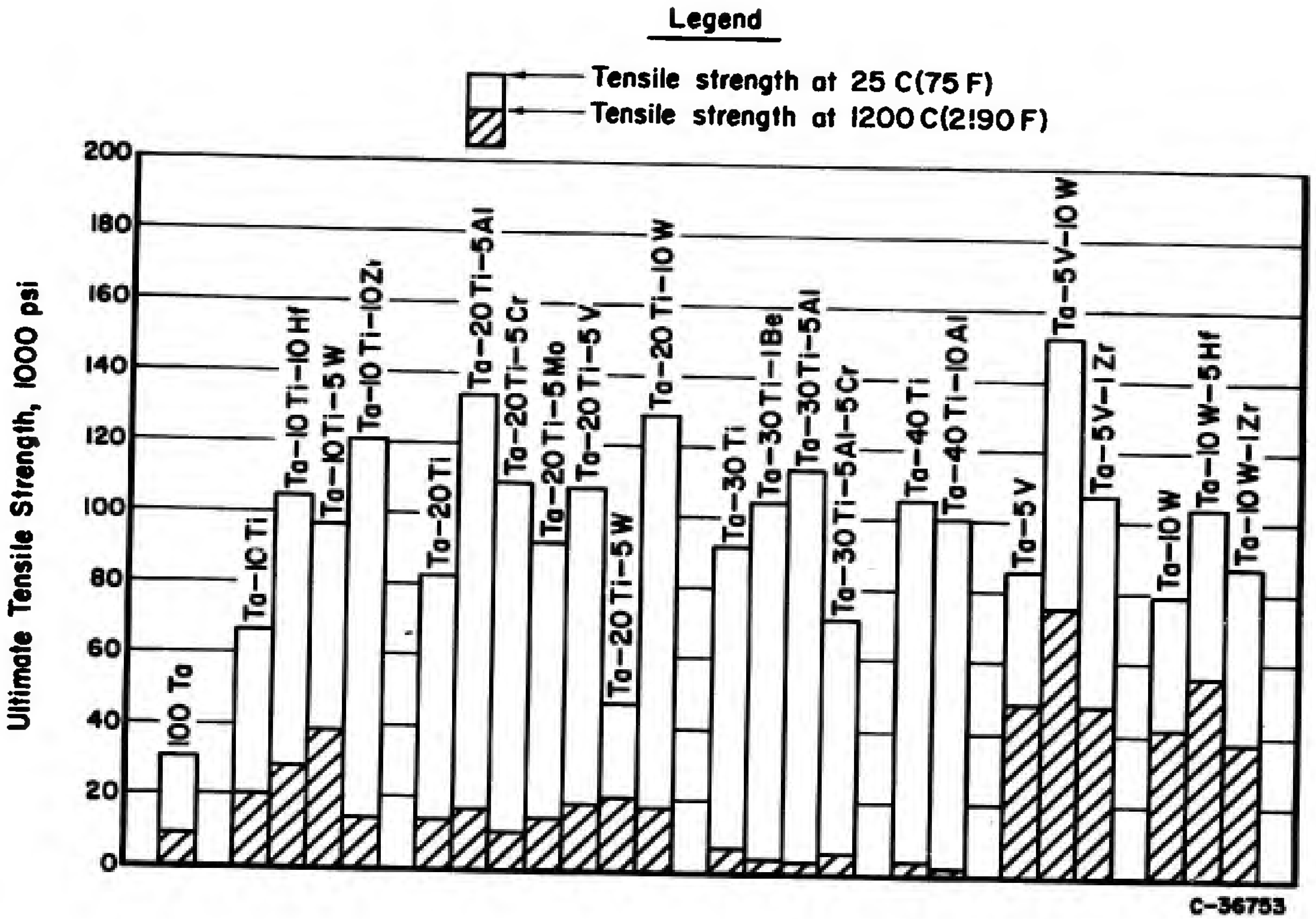


FIGURE 29. EFFECT OF ALLOY ADDITIONS ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS AT 25 AND 1200 C (75 AND 2190 F) IN THE RECRYSTALLIZED CONDITION (Continued)

TABLE 12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

Alloy Composition, weight per cent	Calculated Density(a) G/Cm^3	Calculated Density(a) Lb/In.^{3}	Test Temperature C	Test Temperature F	Ultimate Tensile Strength, 1000 psi	Yield Strength 0.2 per cent offset, 1000 psi	Elongation in 1 Inch, per cent	Strength-To-Weight Ratio, 1000 psi/lb/in.^{3}	Testing Method (b)	Testing Method (c)	Testing Method (d)	Testing Method (e)
100Ta	16.6	0.600	-196	-320	101.0	96.5	8(f)	168	x			
			25	75	29.4	26.3	36	49.0	x			
			25	75	31.8	20.0	47	53.0	x			
			135	275	29.1	14.6	51	48.5		x		
			225	435	25.6	9.3	44	42.7		x		
			230	445	27.9	8.5	23	46.5		x		
			300	570	27.9	9.6	29	46.5		x		
			325	615	31.1	6.7	30	51.8		x		
			350	660	26.4	7.6	29	44.0		x		
			390	735	30.1	--	25	50.2		x		
			425	795	28.1	6.4	23	46.8		x		
			490	915	27.0	6.4	20	45.0		x		
			1175	2145	14.7	13.9	13	24.5			x	
			1200	2190	7.4	(3.8)(g)	48	12.3			x	
			1200	2190	11.4	--	45	19.0				x
			1315	2400	10.0	8.4	32	16.7			x	
			1425	2600	4.6	--	66	7.67			x	
			1480	2700	5.3	(3.8)	42	8.84			x	
			1570	2860	3.3	--	69	5.50			x	
			1670	3040	3.6	--	82	6.00			x	
Ta-5V	15.3	0.553	25	75	87.0	70.0	27	157	x			
			1200	2190	49.2	--	48	89.0				x
			1425	2600	25.6	24.0	78	46.3			x	
			1650	3000	13.0	12.2	125	23.5			x	
Ta-7.5V	14.7	0.531	1200	2190	68.4	53.1	27	129			x	
			1425	2600	36.8	27.5	75	69.3			x	
			1650	3000	12.0	10.3	>158	22.6			x	
Ta-10V	14.2	0.513	25	75	161.2	144.0	16	314	x			
			1200	2190	79.7	46.7	6	155			x	
			1425	2600	34.1	25.6	68	66.5			x	
			1650	3000	11.4	7.5	160	22.2			x	

TABLE 12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Calculated Density[(a)]		Test Temperature		Ultimate Tensile Strength, 1000 psi	Yield Strength 0.2 per cent offset, 1000 psi	Elongation in 1 Inch, per cent	Strength-To-Weight Ratio, 1000 psi/lb/in.^{3}	Testing Method			
	G/Cm^3	Lb/In.^{3}	C	F					(b)	(c)	(d)	(e)
Ta-15V	13.2	0.477	1200	2190	83.1	64.5	10	174			x	
			1425	2600	27.0	(23.1)	44	56.6			x	
			1650	3000	8.8	--	142	18.4			x	
Ta-1Zr	16.4	0.593	25	75	57.6	43.9	27	97.1	x			
			1200	2190	38.3	--	18	64.6				x
			1295	2365	29.6	18.0	46	49.9			x	
			1480	2700	17.1	11.3	100	28.8			x	
			1690	3075	9.8	6.0	83	16.5			x	
Ta-30Cb-5V	12.2	0.441	-196	-320	167.5	158.0	26	380	x			
			25	75	95.8	78.0	22	217	x			
			1200	2190	40.5	--	53	91.8				x
			1200	2190	48.8	40.3	52	111			x	
			1315	2400	28.1	20.4	48	63.7			x	
			1425	2600	20.8	17.3	(40)	47.2			x	
			1425	2600	22.1	18.3	86	50.1			x	
			1500	2730	16.4	14.6	111	37.2			x	
			1595	2900	13.1	9.3	107	29.7			x	
			1650	3000	9.4	4.6	85	21.3			x	
Ta-30Cb-7.5V	11.8	0.426	-196	-320	>147.9[(h)]	--	--	>347	x			
			25	75	139.1	125.2	27	327	x			
			1200	2190	60.6	47.6	35	142			x	
			1425	2600	36.1	22.3	76	84.7			x	
			1650	3000	10.2	6.2	99	23.9			x	
Ta-30Cb-10V	11.4	0.412	-196	-320	217.0	189.0	21	527	x			
			25	75	147.5	126.5	21	358	x			
			1200	2190	63.9	34.8	18	155			x	
			1350	2462	42.4	30.3	76	103			x	
			1425	2600	26.9	18.7	104	65.3			x	
			1500	2730	19.6	11.6	114	47.6			x	
			1650	3000	9.1	--	124	22.8			x	

TABLE 12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION (Continued)

Alloy Composition, weight per cent	Calculated Density(a) G/Cm^3	Calculated Density(a) Lb/In.^{3}	Test Temperature C	Test Temperature F	Ultimate Tensile Strength, 1000 psi	Yield Strength 0.2 per cent offset, 1000 psi	Elongation in 1 Inch, per cent	Strength To-Weight Ratio 1000 psi/lb/in.^{3}	Testing Method (b)	Testing Method (c)	Testing Method (d)	Testing Method (e)
Ta-10Hf-5W	16.3	0.589	25	75	115.3	105.0	23	196	x			
			1200	2190	63.8	--	6	108				x
			1325	2415	41.4	30.6	10	70.3			x	
			1430	2605	37.0	25.0	17	62.8			x	
			1675	3045	17.8	12.1	29	30.2			x	
Ta-5V-5W	15.4	0.556	25	75	141.3	131.6	21	254	x			
			1425	2600	35.8	30.8	64	64.3			x	
			1650	2600	16.3	14.1	99	29.3			x	
Ta-5V-7.5W	15.5	0.560	1425	2600	37.2	33.3	31	66.4			x	
			1650	2600	18.1	14.4	35	32.4			x	

(a) Calculated from $d = \dfrac{100}{\dfrac{A}{d_A} + \dfrac{B}{d_B} + \ldots}$.

where
d = alloy density
A = weight per cent Element A
B = weight per cent Element B
d_A = density of Element A
d_B = density of Element B.

(b) Tested using conventional hydraulic loading and a crosshead speed of approximately 0.02 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture.
(c) Tested in air using a crosshead speed of approximately 0.05 inch per minute to fracture.
(d) Tested in vacuum using conventional hydraulic loading and a crosshead speed of approximately 0.01 inch per minute up to the point of yielding, and approximately 0.05 inch per minute to fracture.
(e) Tested in vacuum using conventional creep-rupture equipment. Specimen loaded by lead shot until the ultimate tensile strength was reached.
(f) Considerable localized necking and reduction in area.
(g) Values in parentheses are estimated.
(h) Failed at grip-pin hole.

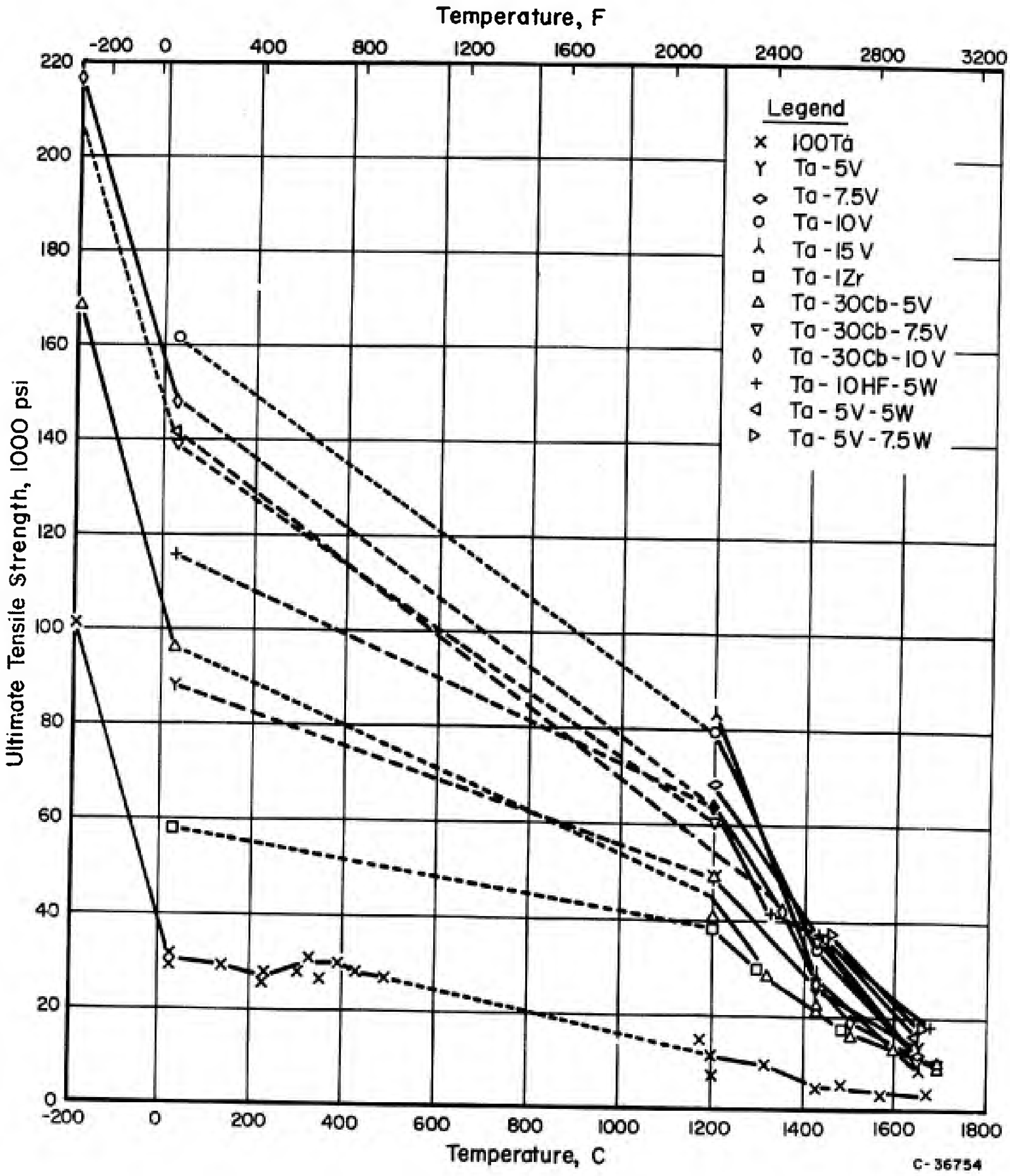


FIGURE 30. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

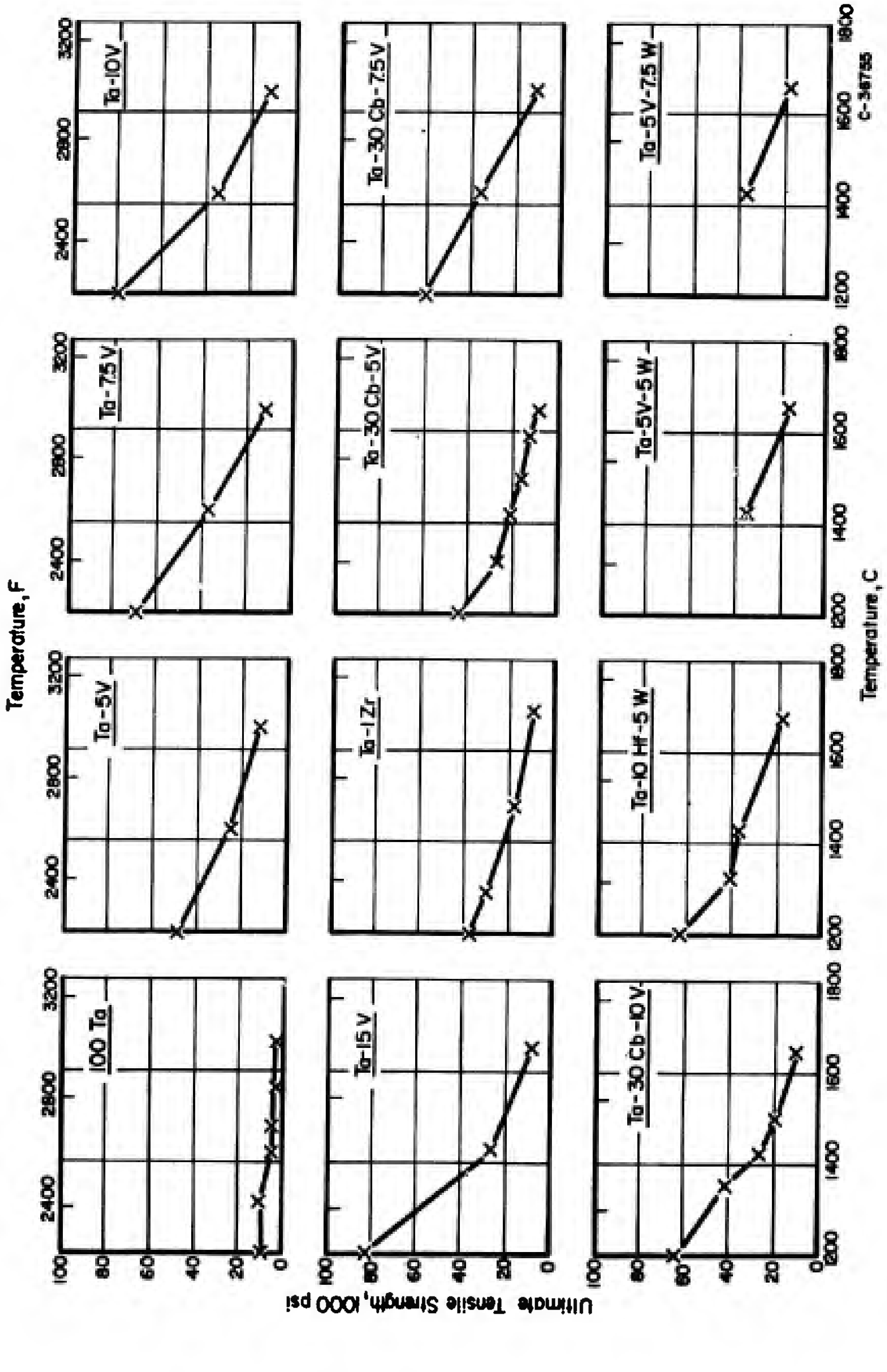


FIGURE 31. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

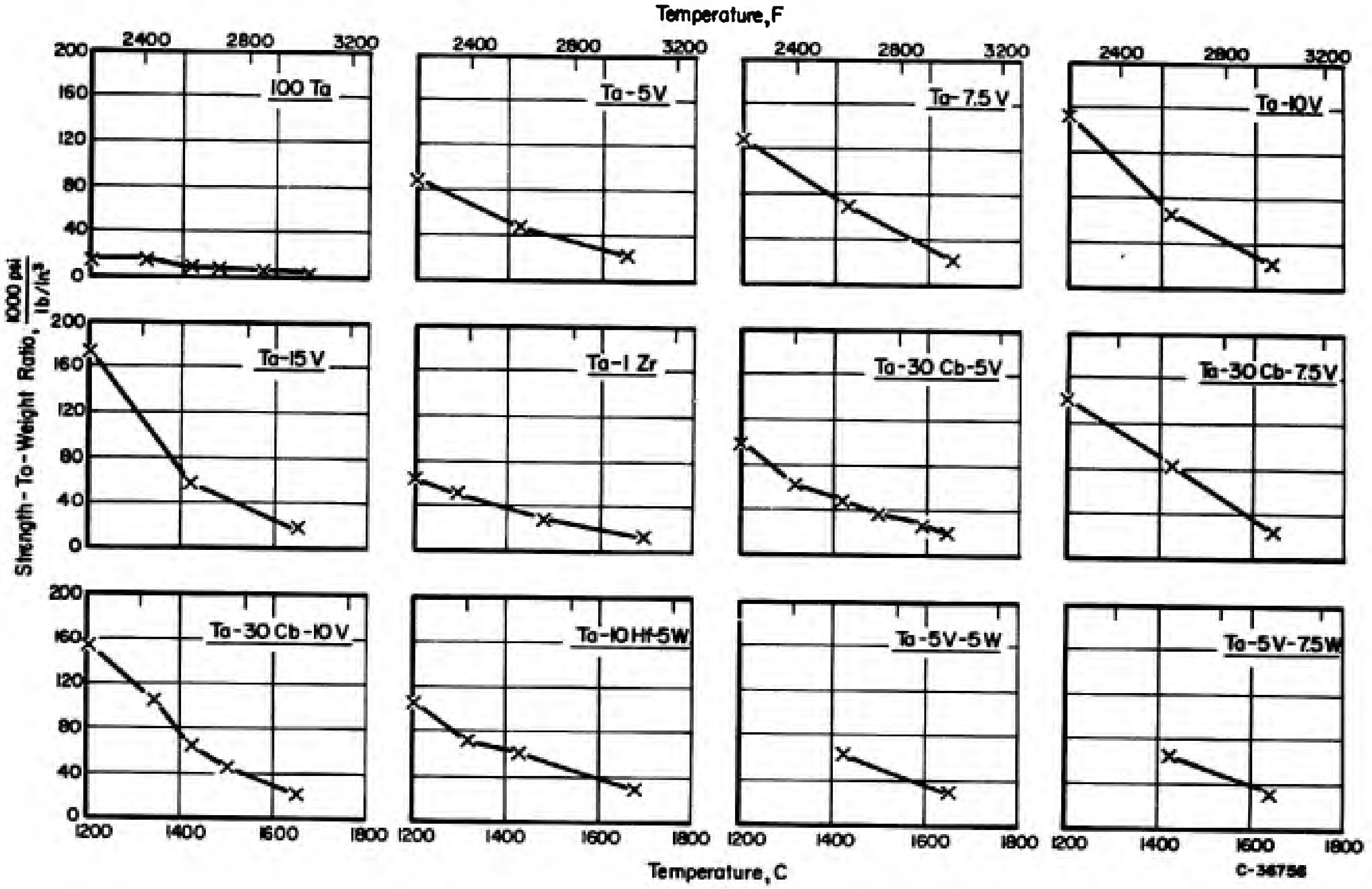


FIGURE 32. EFFECT OF TEMPERATURE ON THE STRENGTH-TO-WEIGHT RATIO OF TANTALUM AND TANTALUM ALLOYS IN THE RECRYSTALLIZED CONDITION

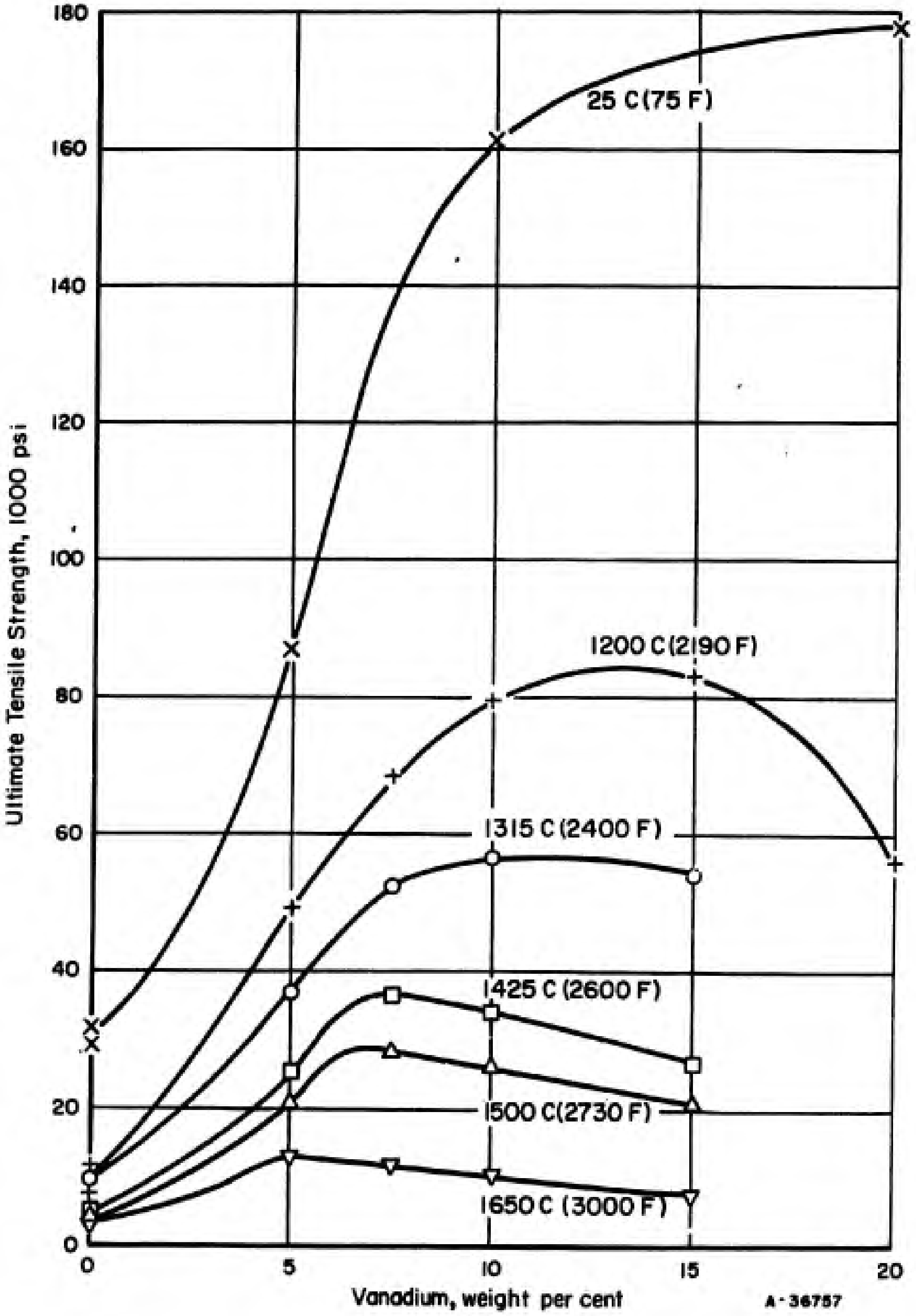


FIGURE 33. EFFECT OF VANADIUM CONTENT ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AT VARIOUS TEMPERATURES IN THE RECRYSTALLIZED CONDITION

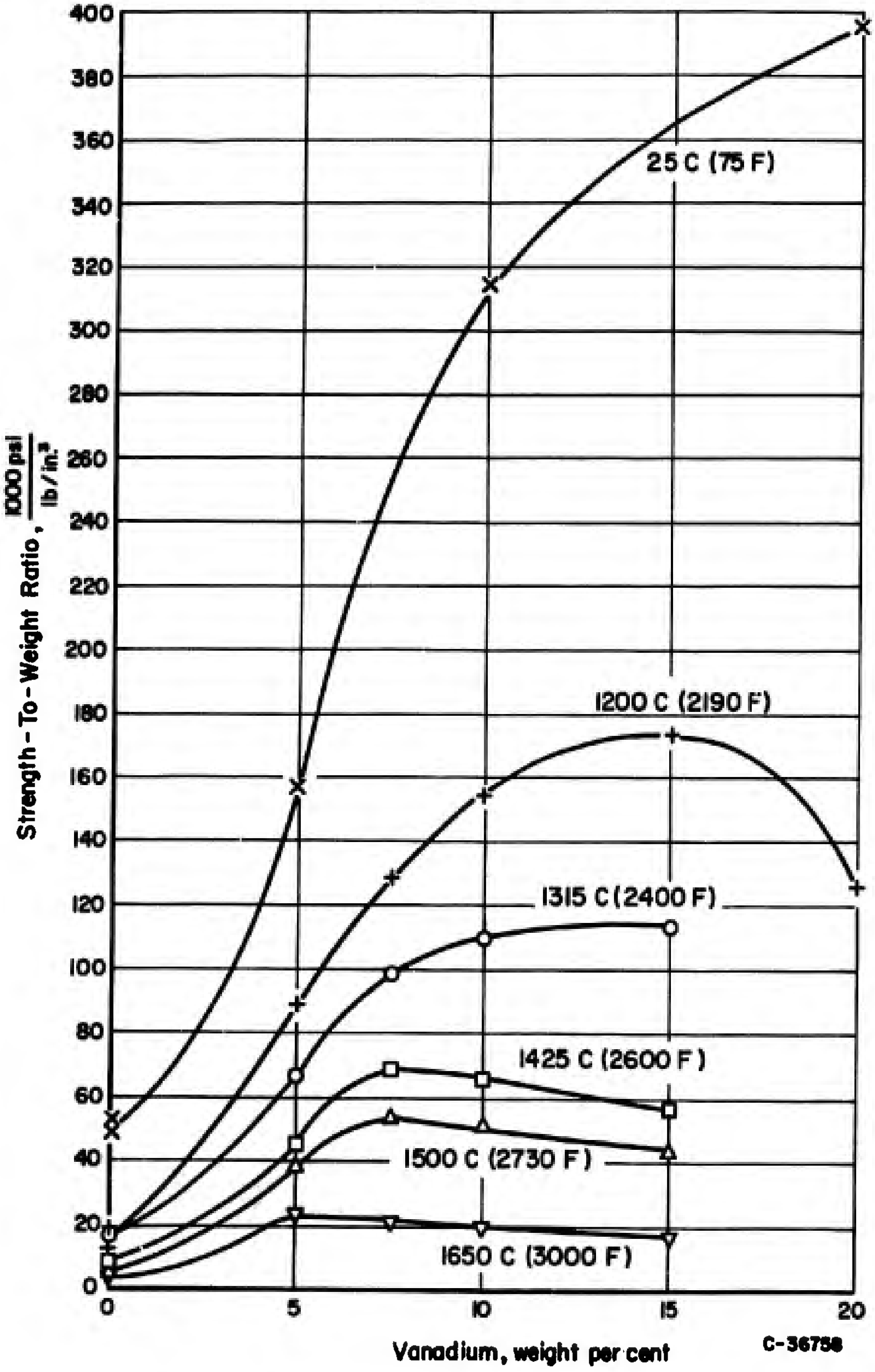


FIGURE 34. EFFECT OF VANADIUM CONTENT ON THE STRENGTH-TO-WEIGHT RATIO OF TANTALUM AT VARIOUS TEMPERATURES IN THE RECRYSTALLIZED CONDITION

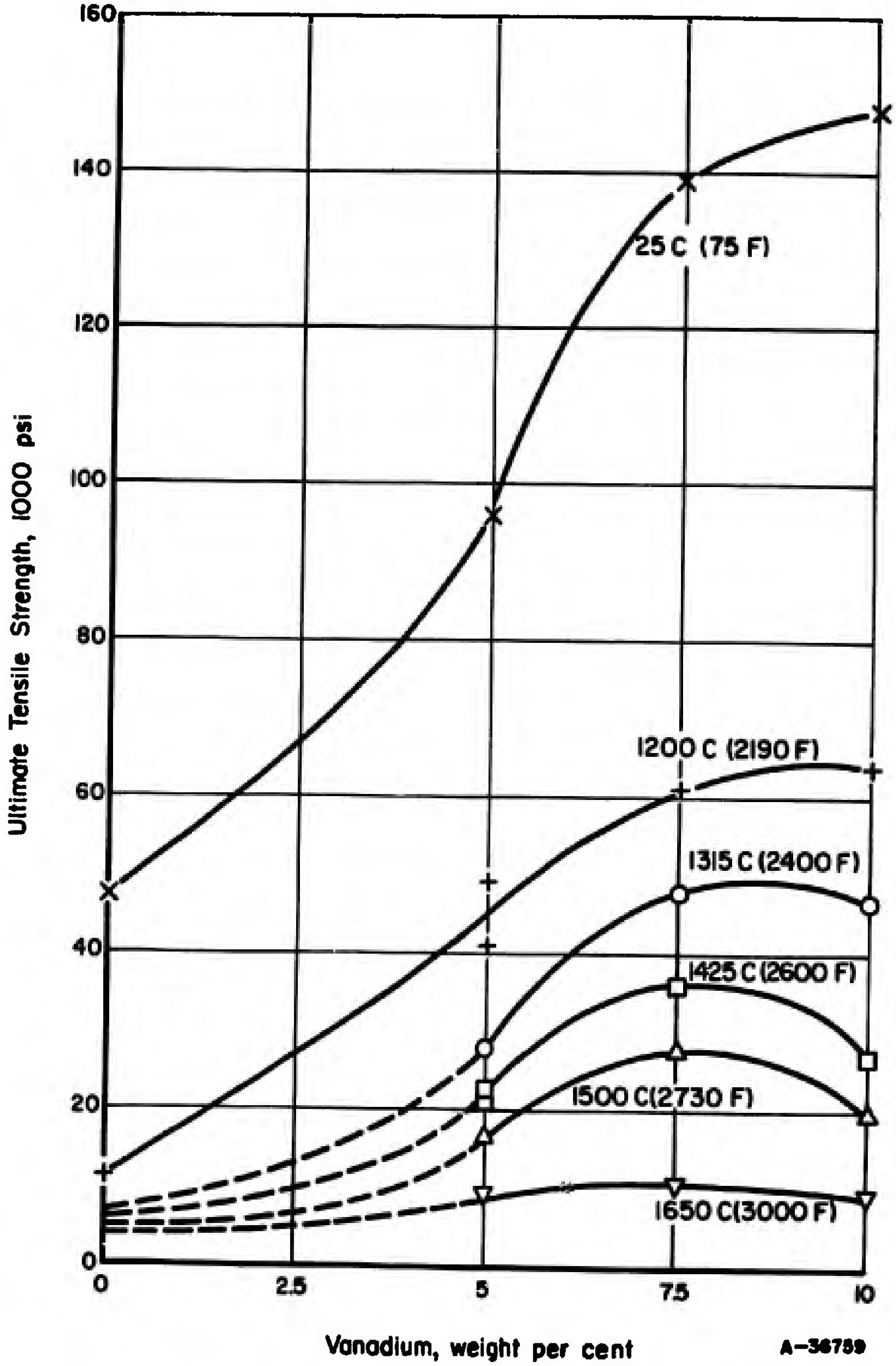


FIGURE 35. EFFECT OF VANADIUM CONTENT ON THE ULTIMATE TENSILE STRENGTH OF THE Ta-30Cb ALLOY AT VARIOUS TEMPERATURES IN THE RECRYSTALLIZED CONDITION

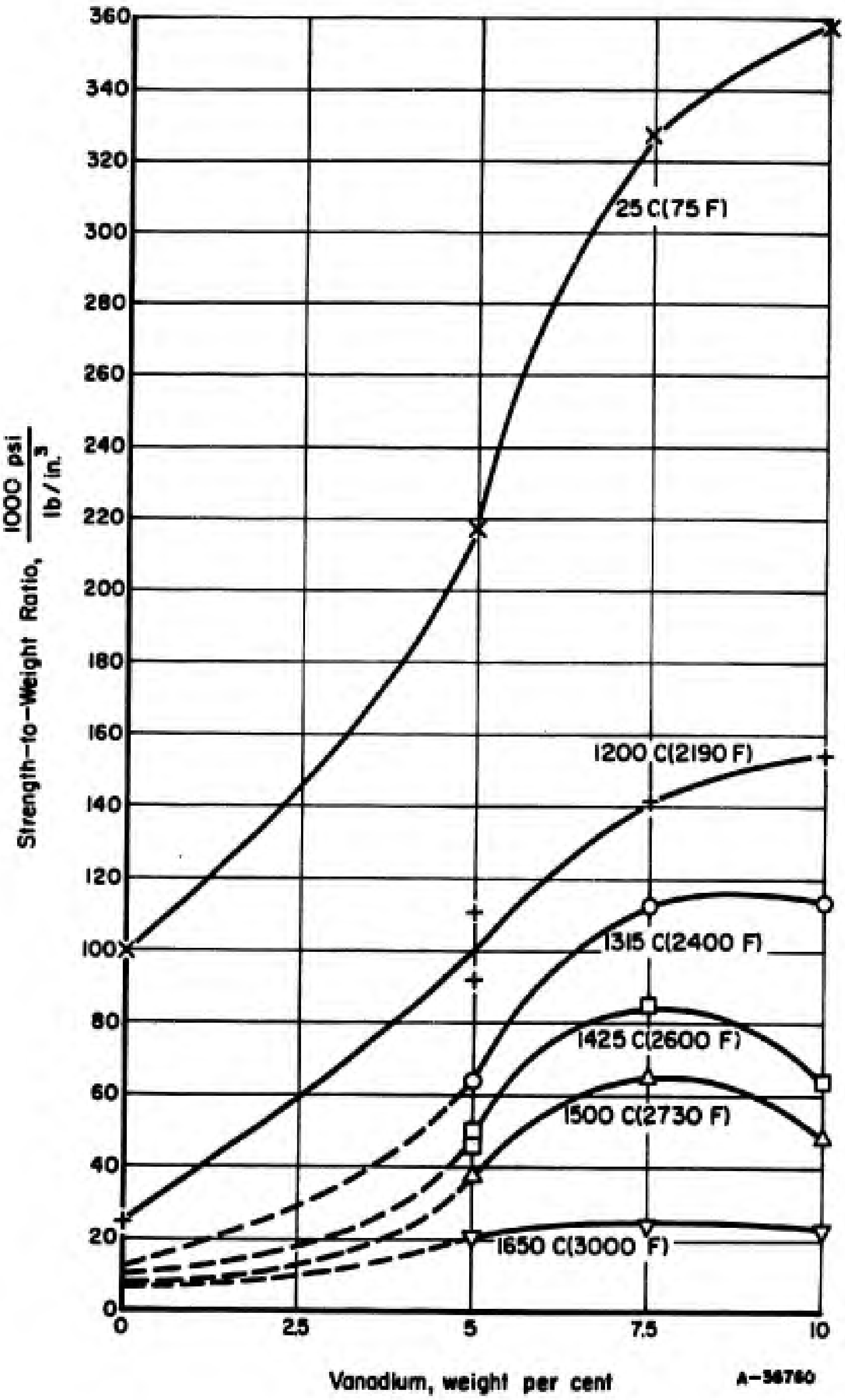


FIGURE 36. EFFECT OF VANADIUM CONTENT ON THE STRENGTH-TO-WEIGHT RATIO OF THE Ta-30Cb ALLOY AT VARIOUS TEMPERATURES IN THE RECRYSTALLIZED CONDITION

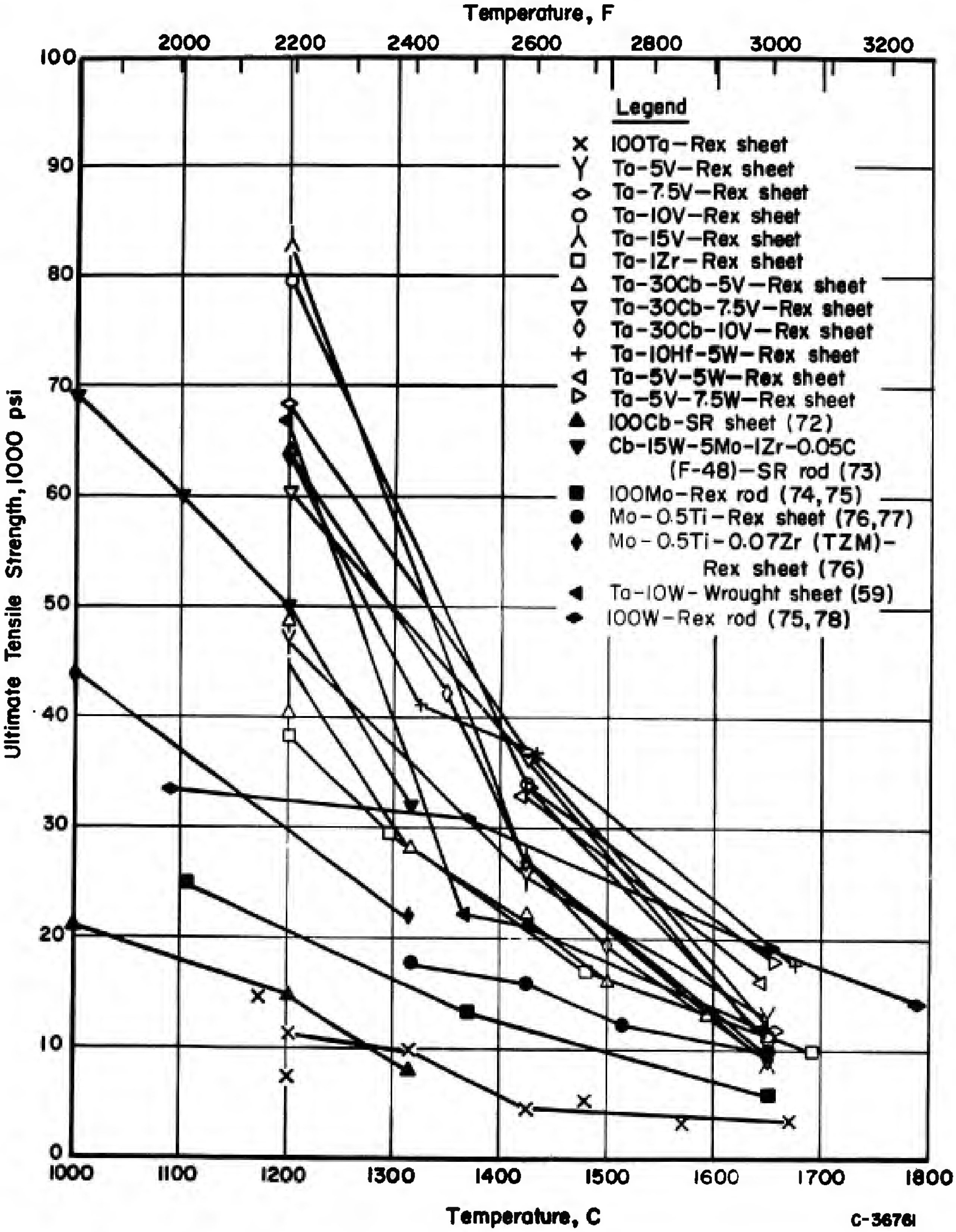


FIGURE 37. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF TANTALUM AND TANTALUM ALLOYS AS COMPARED WITH OTHER REFRACTORY METALS AND ALLOYS

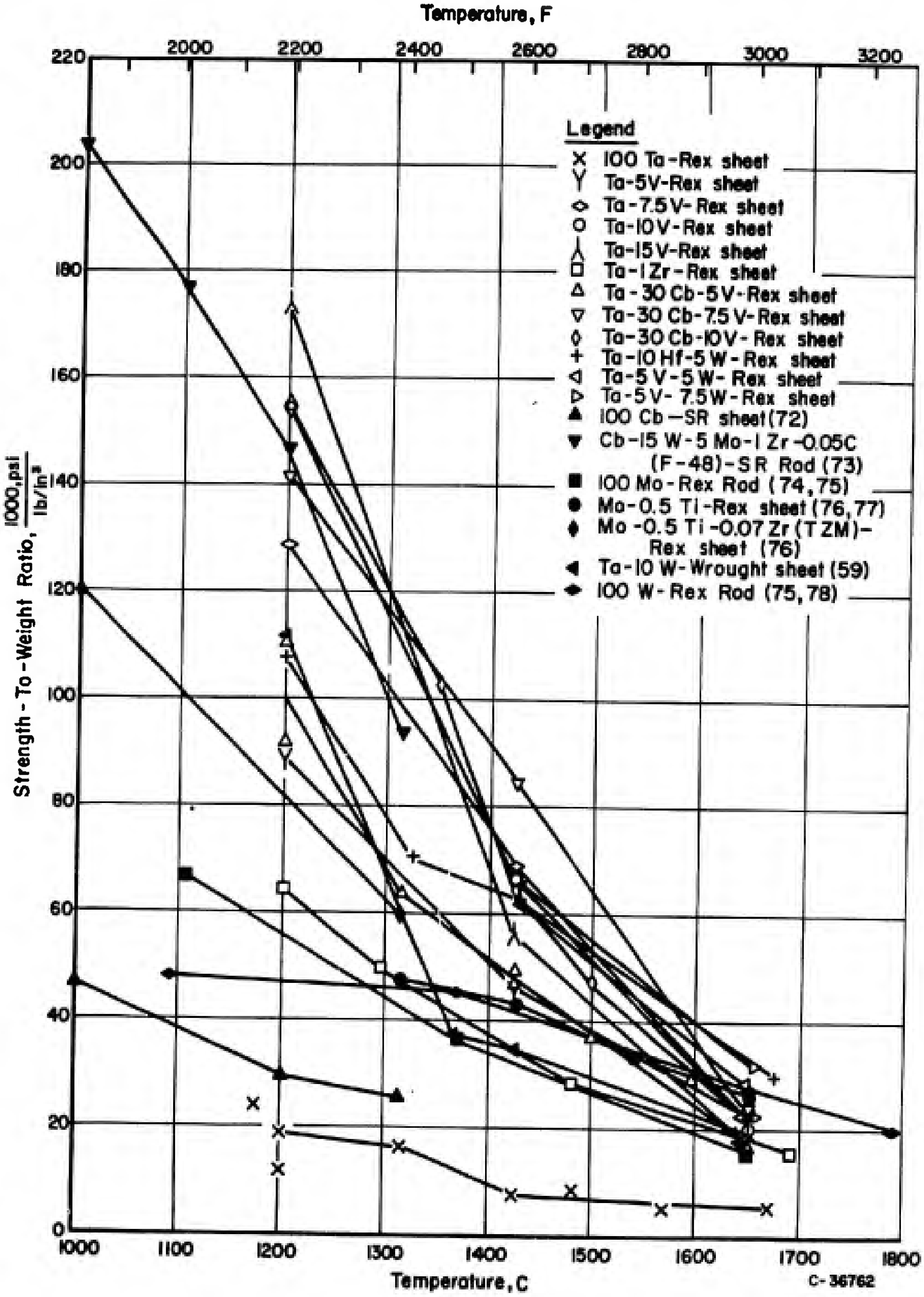


FIGURE 38. EFFECT OF TEMPERATURE ON THE STRENGTH-TO-WEIGHT RATIO OF TANTALUM AND TANTALUM ALLOYS AS COMPARED WITH OTHER REFRACTORY METALS AND ALLOYS

Metallography

A number of vacuum-annealed binary and ternary alloys were examined metallographically in a study of the effect of alloying additions on the structure of tantalum. The results of this work are summarized as follows:

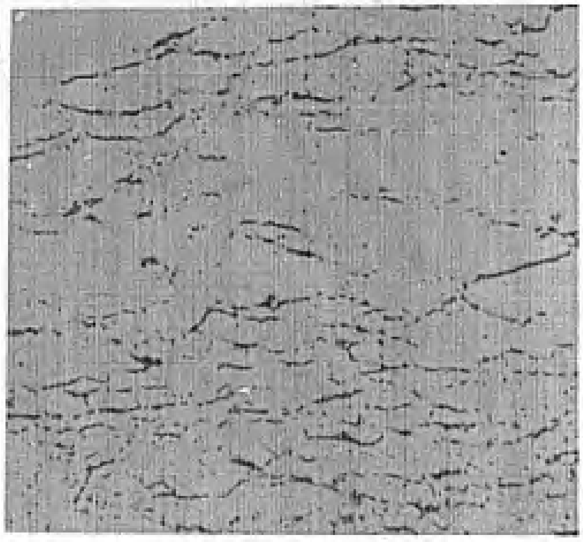
(1) Binary additions of the metals listed below are soluble in the tantalum base to at least the composition levels indicated:

Addition	Minimum Solid Solubility in Tantalum, weight per cent
Cb	50
Hf	10
Mo	10
Re	5
Ti	40
V	30
W	20
Zr	1

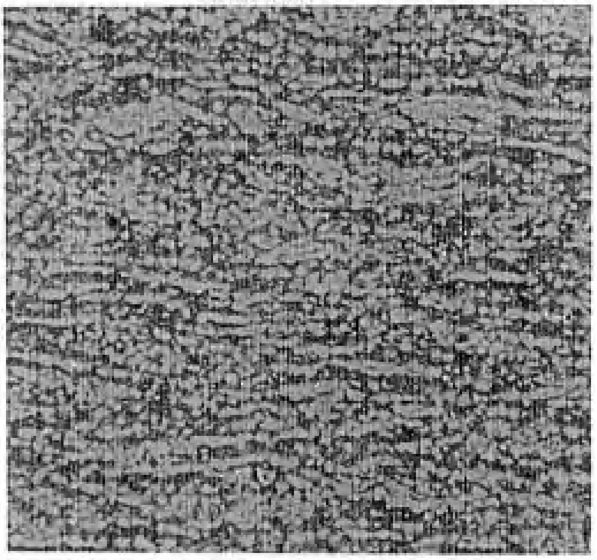
(2) Alloys containing 10 to 40 per cent zirconium contain increasing amounts of a zirconium-rich phase. The latter has tentatively been identified as the decomposition product of the zirconium-rich, body-cubic-centered terminal solid solution according to the phase diagram reported by Emelyanov, Godin, and Evstyuklin(79). Representative structures of these alloys are given in Figure 39 which indicates that the solubility of zirconium in tantalum at 1500 C (2730 F) is slightly under 10 per cent. This is in good agreement with the diagram of Emelyanov, et al.

(3) Binary alloys containing 20 to 35 per cent hafnium showed varying amounts of a hafnium-rich phase, as illustrated in Figure 40. These structures show that the solid solubility of tantalum for hafnium at 1400 to 1500 C (2550 to 2730 F) is about twice that for zirconium.

(4) Additions of titanium, hafnium, and zirconium apparently lower the solubility of tantalum for interstitial impurities, especially carbon. This is supported by the photomicrographs in Figure 41 which show that additions of these metals give rise to structures containing a fine dispersion of an impurity phase. Oxygen additions to these alloys, in amounts up to 400 ppm, do not appear to have any significant effect on their structure, suggesting that the impurity phase observed consists basically of carbides.

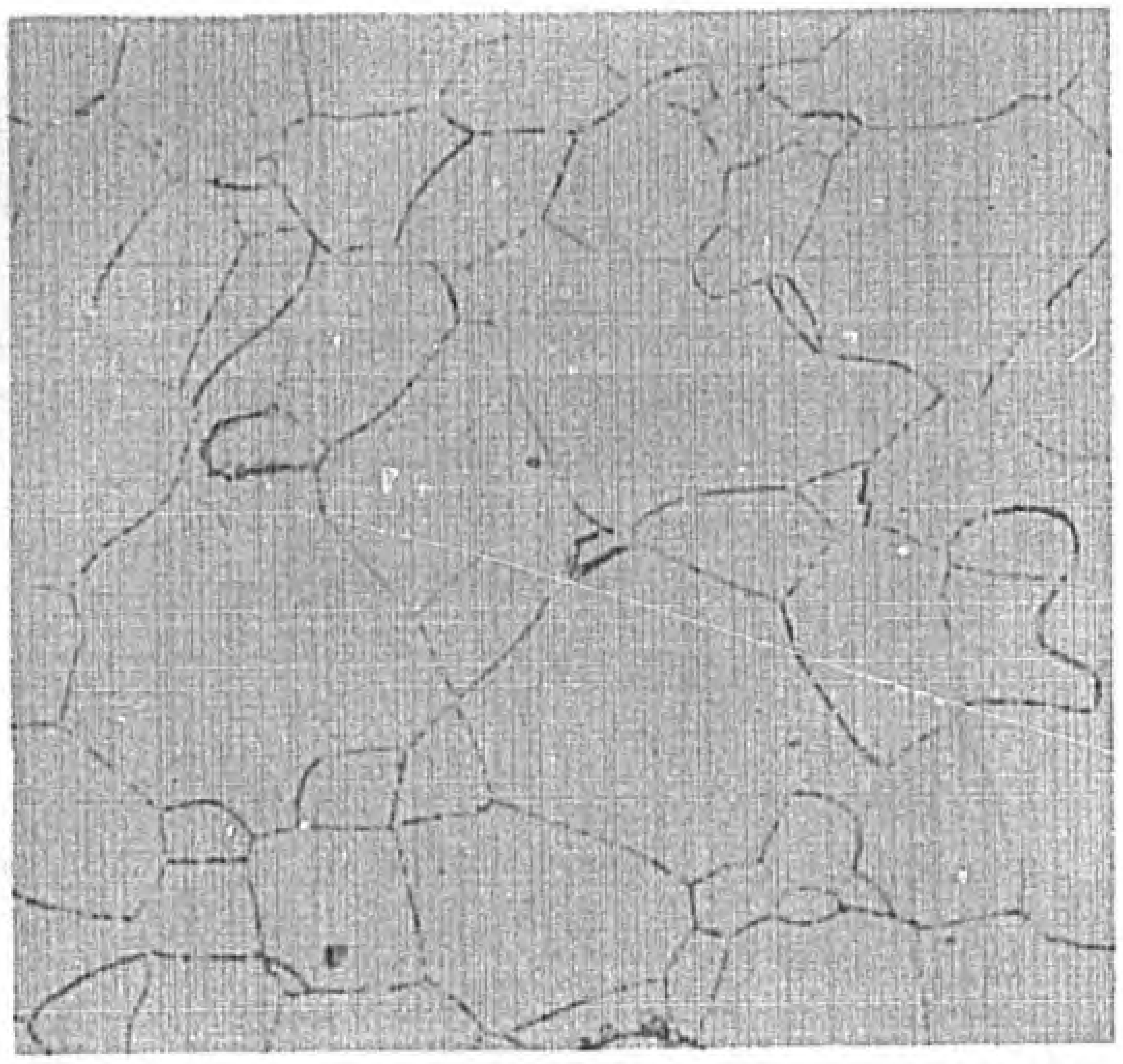


500X Ta-10Zr N71861



500X Ta-40Zr N71858

FIGURE 39. MICROSTRUCTURES OF THE Ta-10Zr AND Ta-40Zr ALLOYS AFTER ANNEALING FOR 1 HOUR AT 1500 C (2730 F)



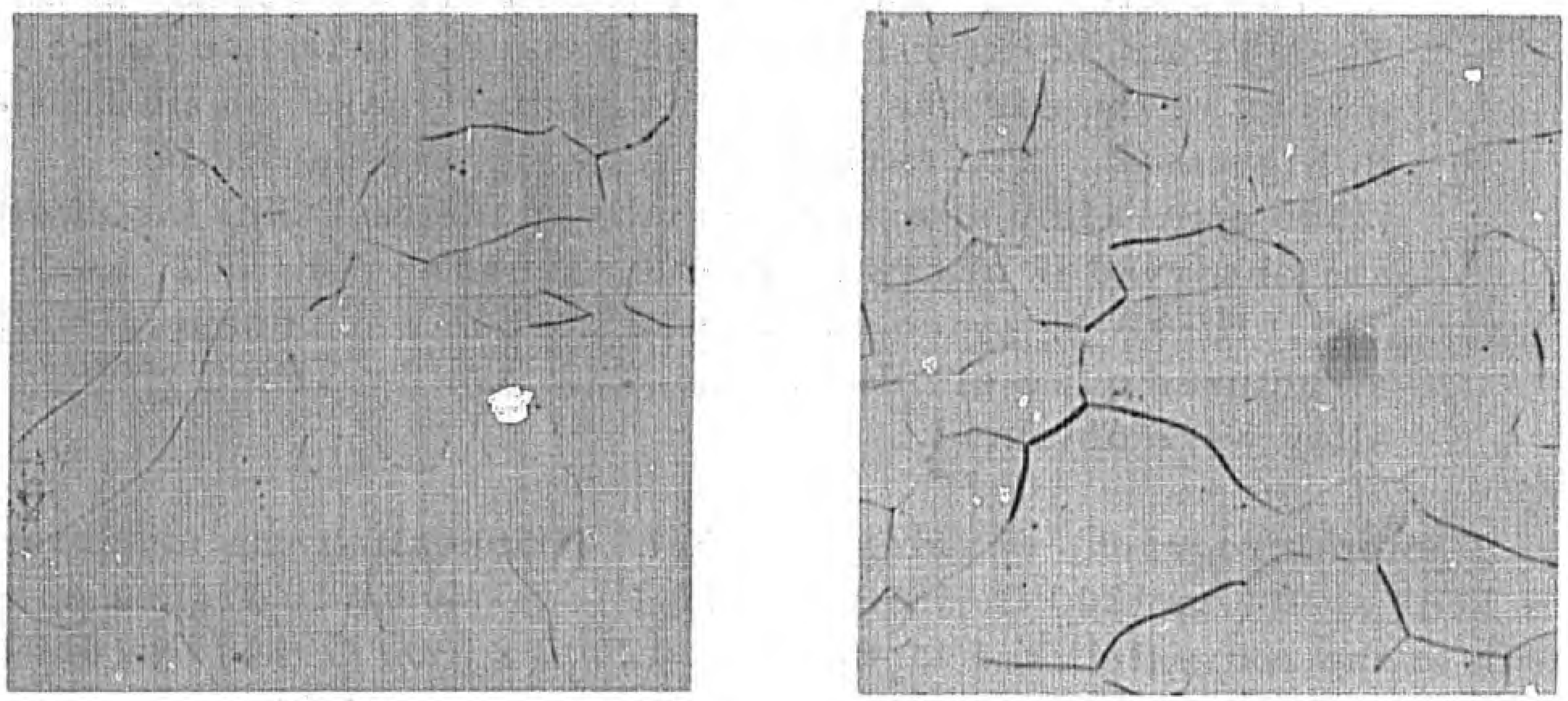
500X Ta-20Hf N71854

Annealed 1 Hour at 1400 C (2550 F)

500X Ta-30Hf N71839

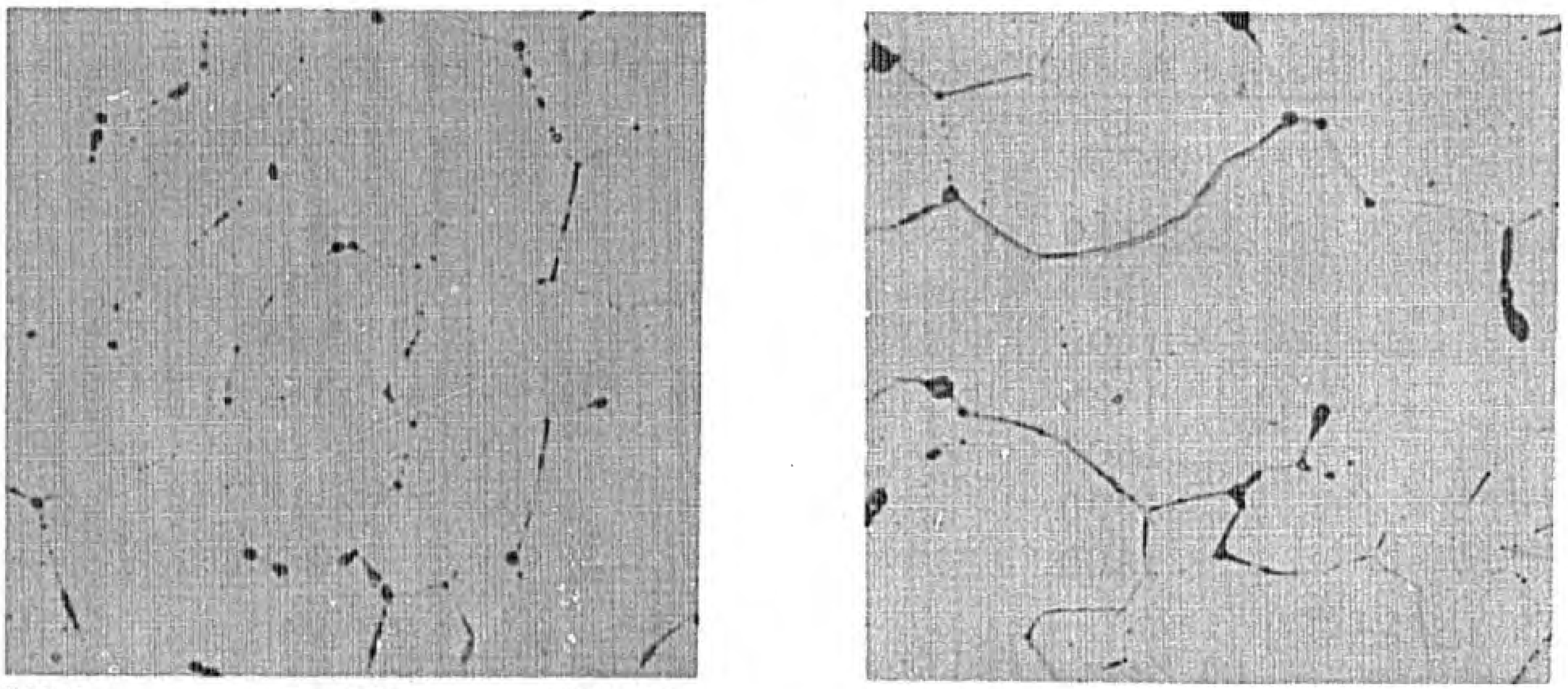
Annealed 1 Hour at 1500 C (2730 F)

FIGURE 40. MICROSTRUCTURES OF THE Ta-20Hf AND Ta-30Hf ALLOYS AFTER ANNEALING FOR 1 HOUR AT 1400 TO 1500 C (2550 TO 2730 F)



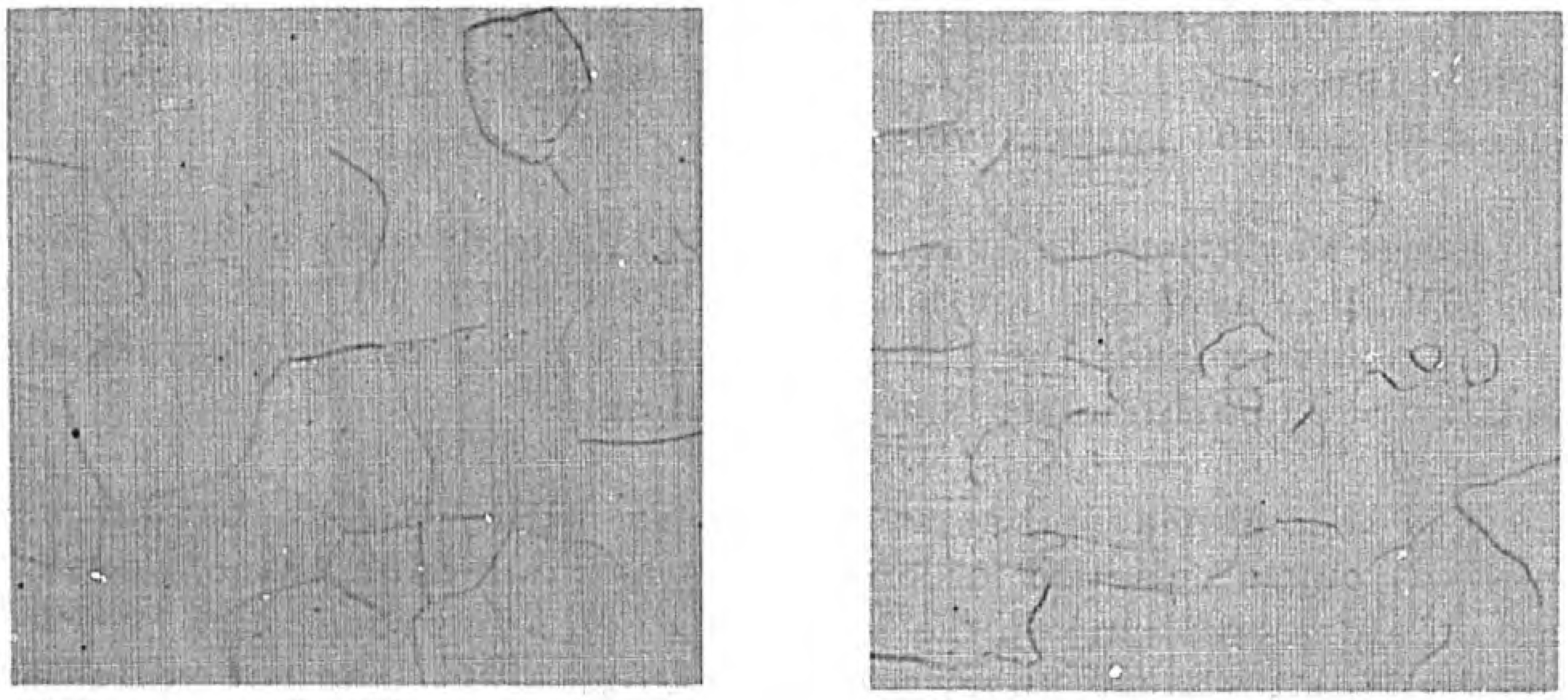
500X Ta-1Ti N71852

500X Ta-1Ti + O (280 ppm) N71846



500X Ta-1Zr N71851

500X Ta-1Zr + O (400 ppm) N71848



500X Ta-1Hf N71855

500X Ta-1Hf + O (170 ppm) N71847

FIGURE 41. MICROSTRUCTURES OF THE Ta-1Ti, Ta-1Zr, AND Ta-1Hf ALLOYS WITH AND WITHOUT OXYGEN ADDITIONS AFTER ANNEALING FOR 1 HOUR AT 1500 C (2730 F)

(5) Carbon additions, in amounts from 700 to 2300 ppm, to the Ta-1(Ti, Zr, Hf) alloys result in a marked increase in the amount of the carbide (i.e., "impurity" phase) as illustrated in Figure 42. The carbide particles in the Ta-1Ti+C (2300 ppm) alloy appear especially massive. Similar effects are observed in alloys of Ta-5V, Ta-10W, Ta-10Hf, and Ta-10Hf-5W to which 500 ppm of carbon was added. Thus, structures quite similar to those for the Ta-1Hf+C (700 ppm) alloy were obtained.

Photomicrographs showing the effect of annealing unalloyed tantalum for 1 hour at 900 to 1800 C (1650 to 3270 F) are shown in Figure 43. Grain growth of the recrystallized tantalum at 1200 to 1800 C (2190 to 3270 F) was observed as follows:

1-Hour Annealing Temperature(a)		Average ASTM Grain Size
C	F	
1200	2190	5-6
1300	2370	4
1400	2550	3-4
1425	2595	3-4
1600	2910	2
1700	3090	1
1800	3270	0-1

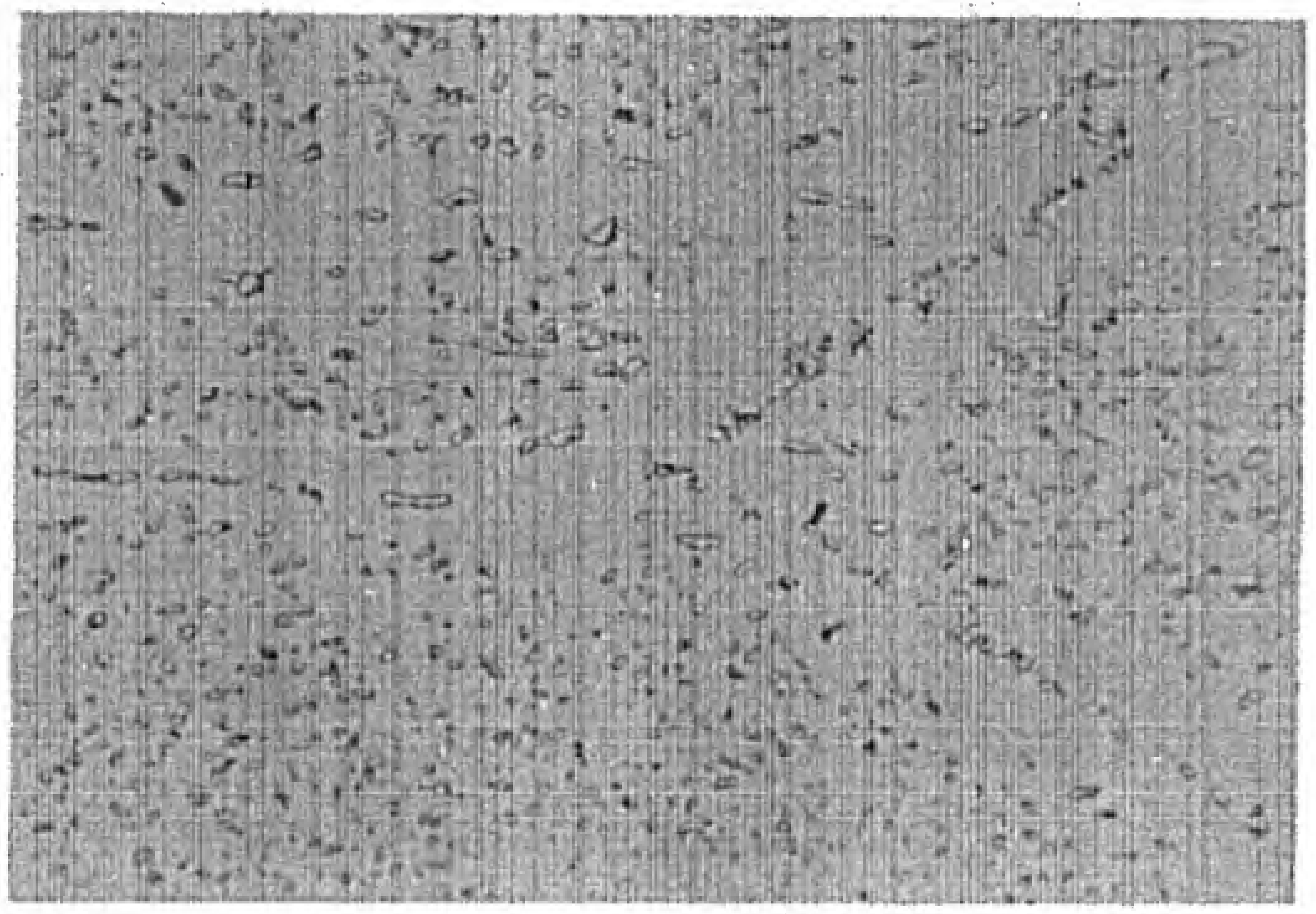
(a) Material cold rolled 75 per cent after intermediate anneal.

The effects of annealing on the microstructure of the single-phase Ta-30Cb-10V alloy and the two-phase Ta-10Hf-5W alloy are shown in Figures 44 and 45, respectively.

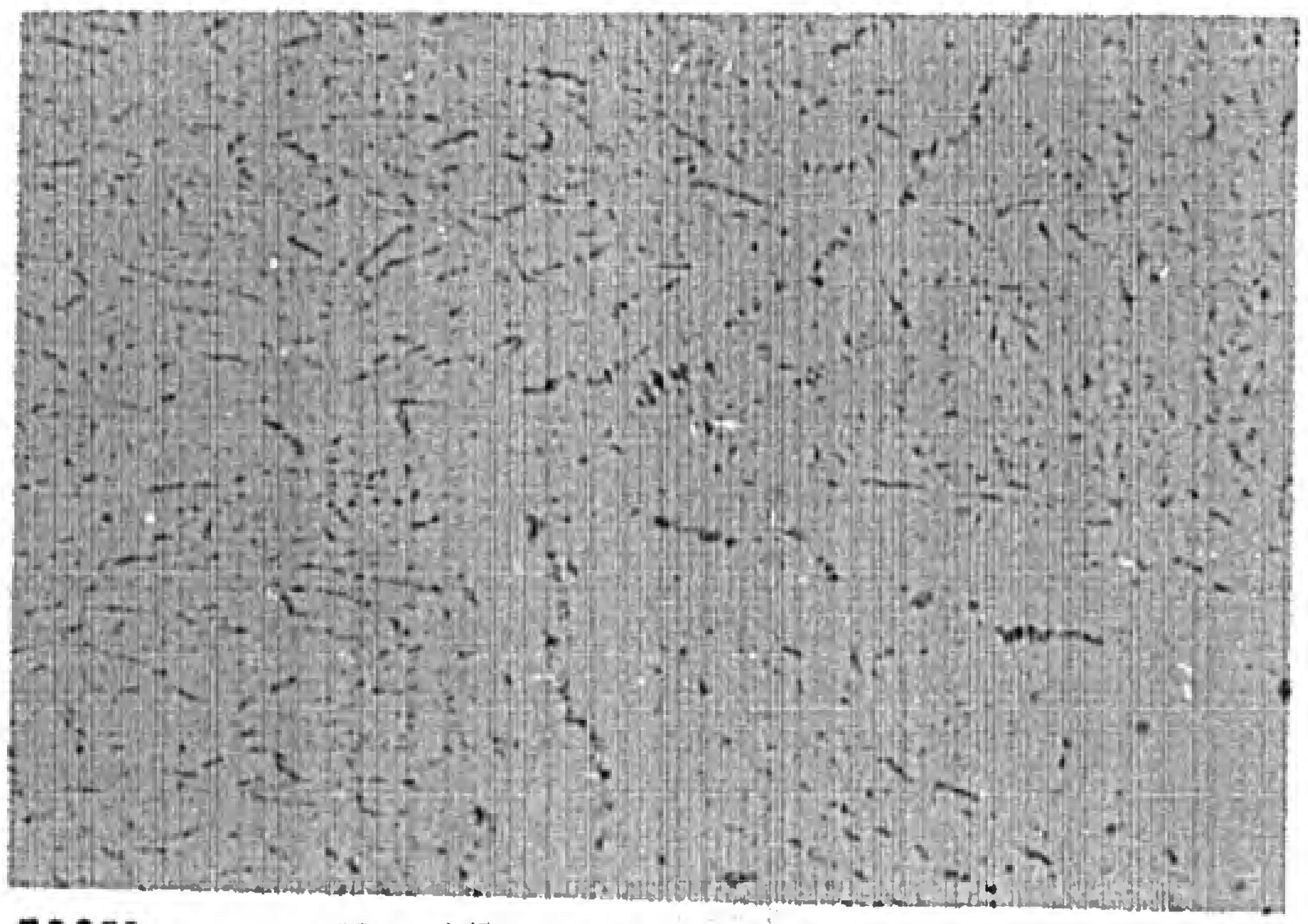
Large variations in grain size (ASTM 3 to 8) were noted in the Ta-30Cb-10V alloy annealed for 1 hour at 1500 C (2730 F). These large differences could probably be eliminated with the use of an intermediate anneal between pack rolling and cold rolling.

The second phase observed in the Ta-10Hf-5W alloy has not been identified, but is believed to consist of a hafnium-rich phase (possibly based on alpha hafnium) on the basis of studies in process on Ta-Hf-W alloys by Westinghouse Research Laboratories(58). As hot rolled and annealed at 1300 C (2370 F), this phase is dispersed as stringers throughout the matrix (Figure 45). Following the 1-hour 1500 C (2730 F) anneal, the second phase appears almost entirely concentrated at the recrystallized grain boundaries (Figure 45).

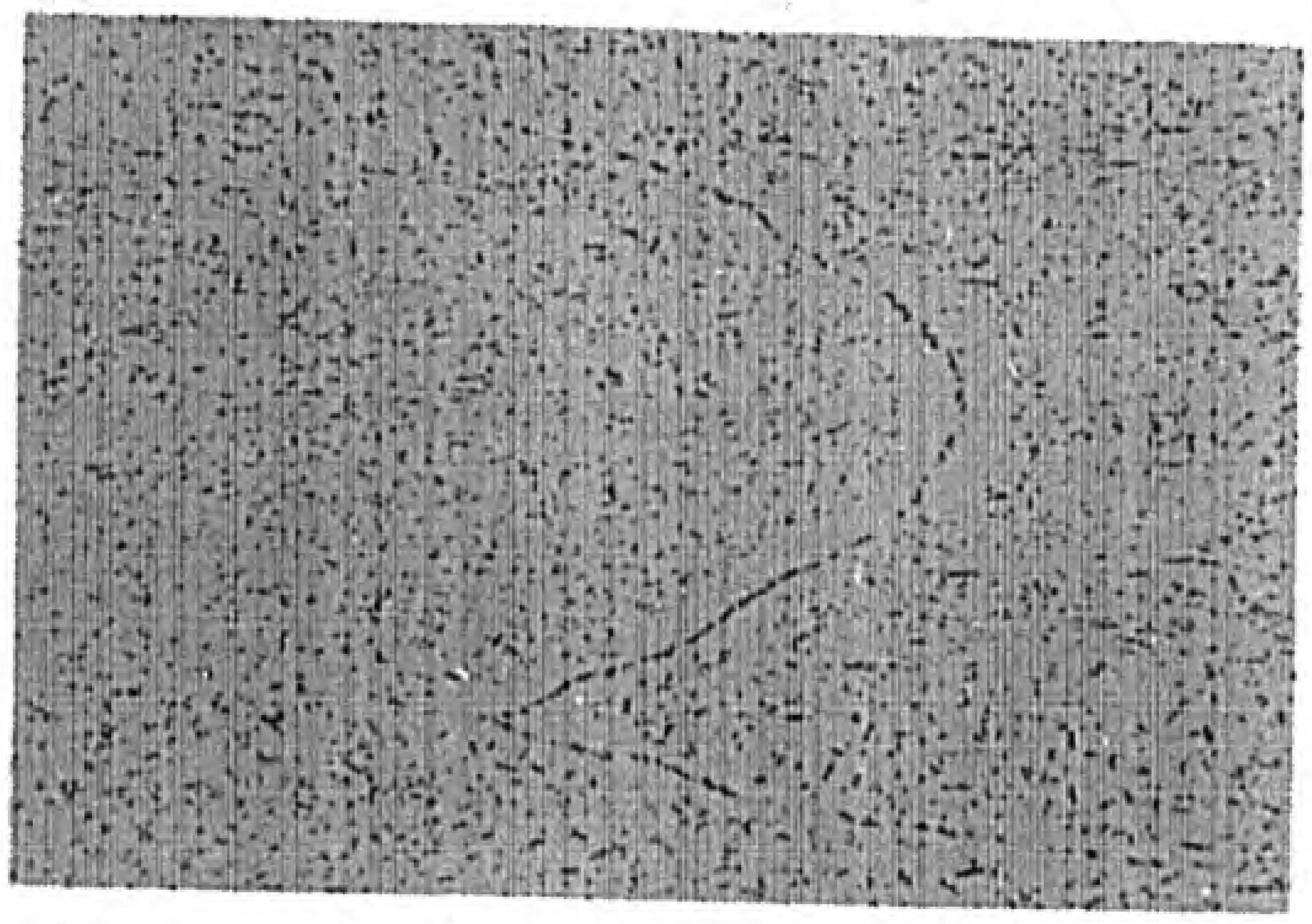
Table 13 shows the effect of various alloy additions on the recrystallized grain size of tantalum. In general, practically all of the alloys



500X Ta-1Ti + C (2300 ppm) N71850

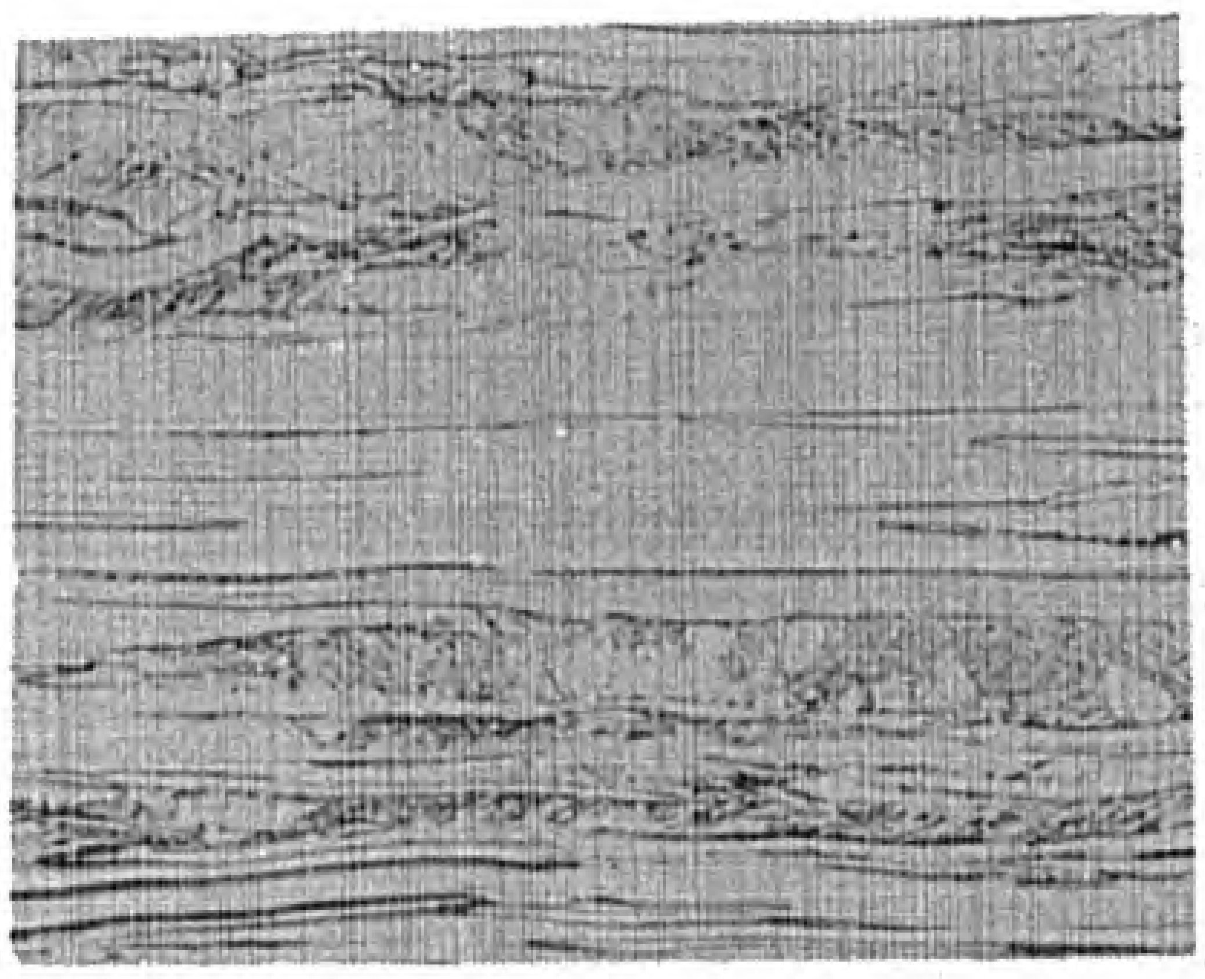


500X Ta-1Zr + C (1400 ppm) N71849



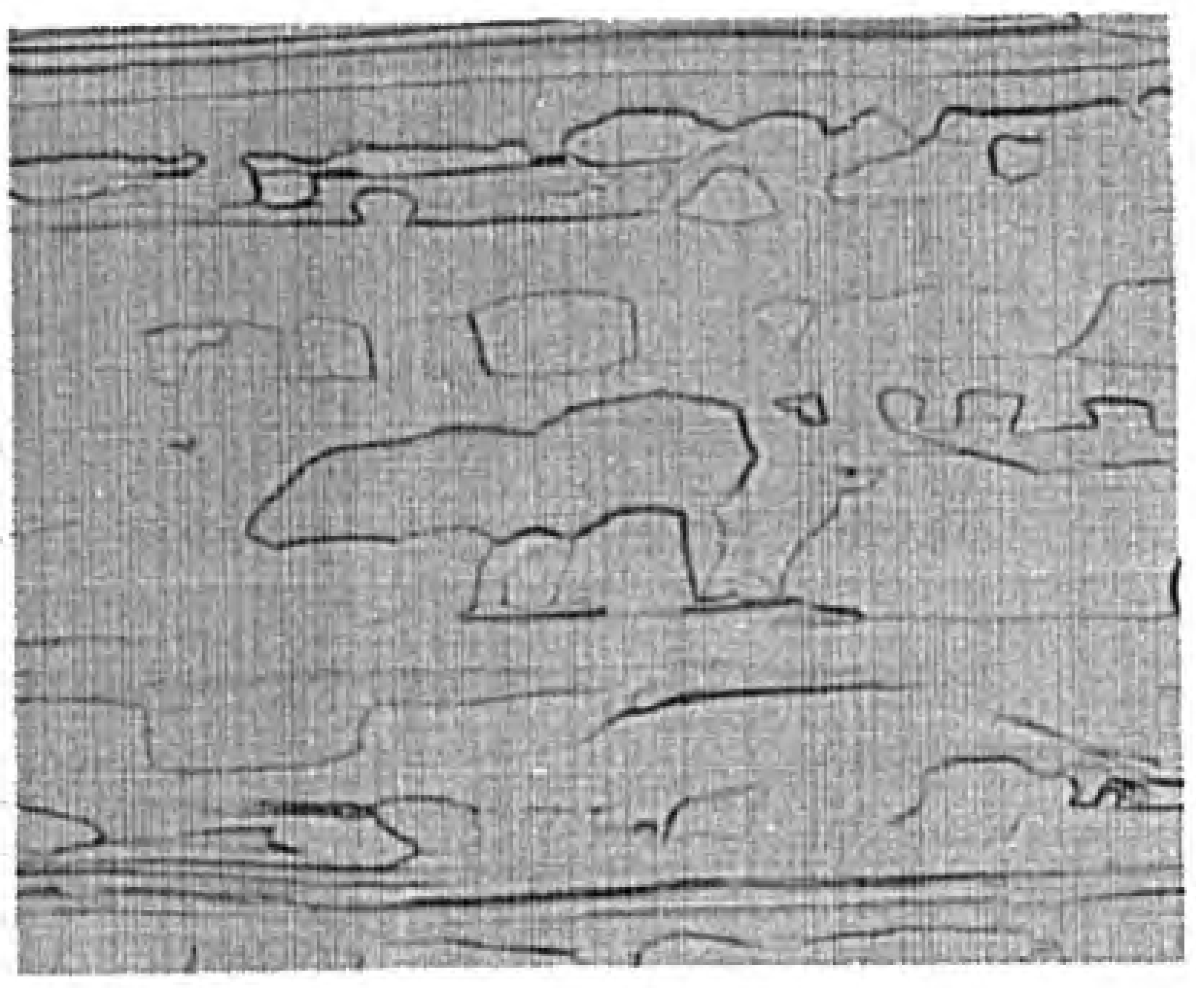
500X Ta-1Hf + C (700 ppm) N71842

FIGURE 42. MICROSTRUCTURES OF THE Ta-1Ti + C, Ta-1Zr + C, AND Ta-1Hf + C ALLOYS AFTER ANNEALING FOR 1 HOUR AT 1500 C (2730 F)



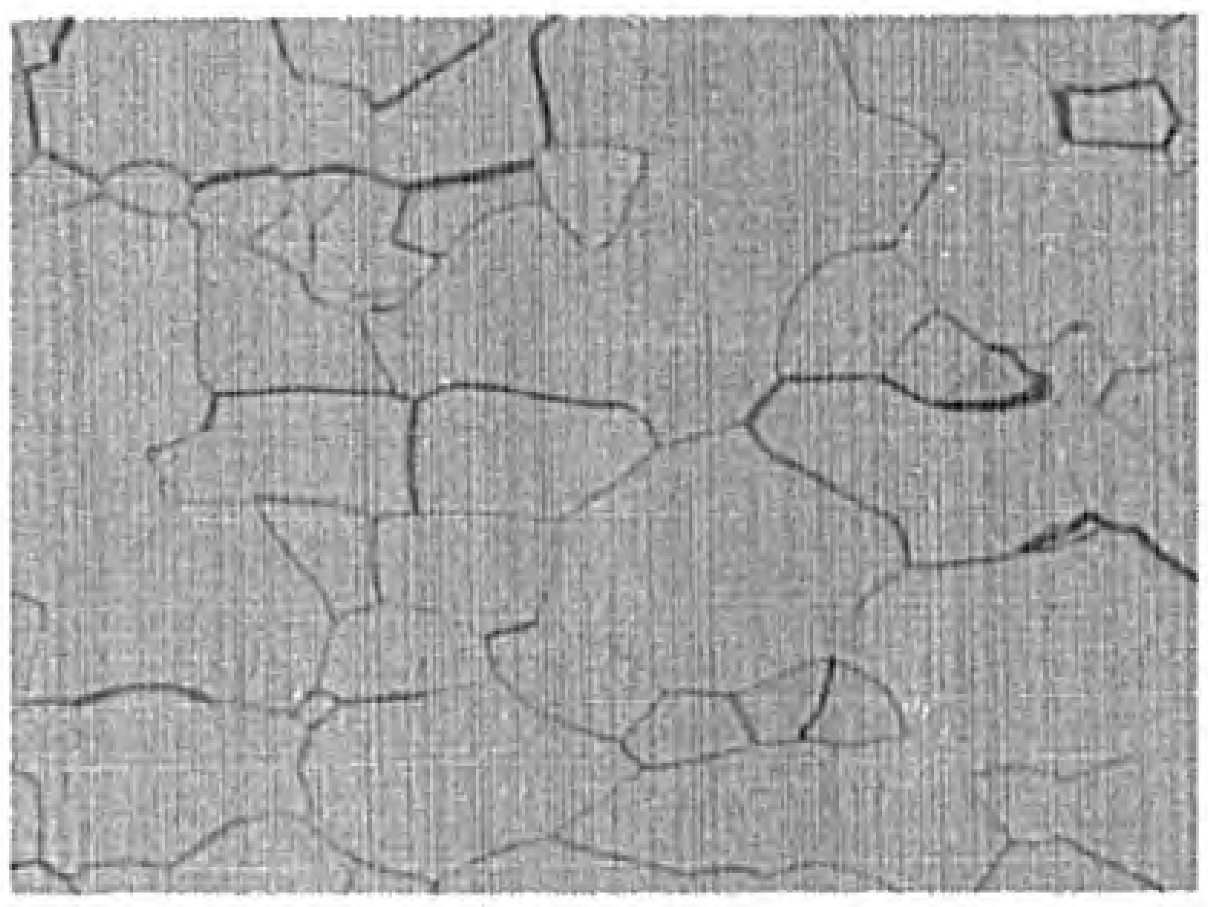
100X N54444

Annealed 1 Hour at 900 C (1650 F)



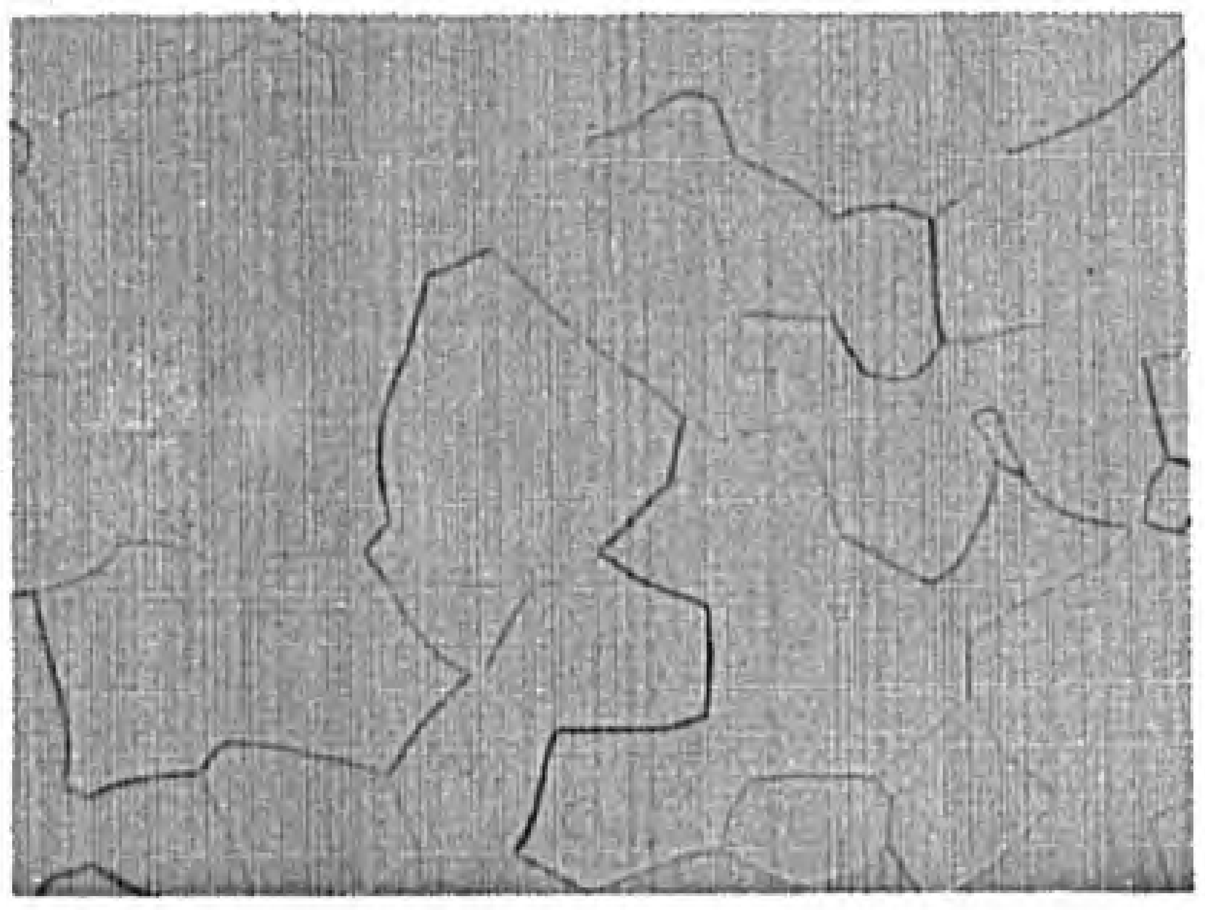
100X N54449

Annealed 1 Hour at 1100 C (2010 F)



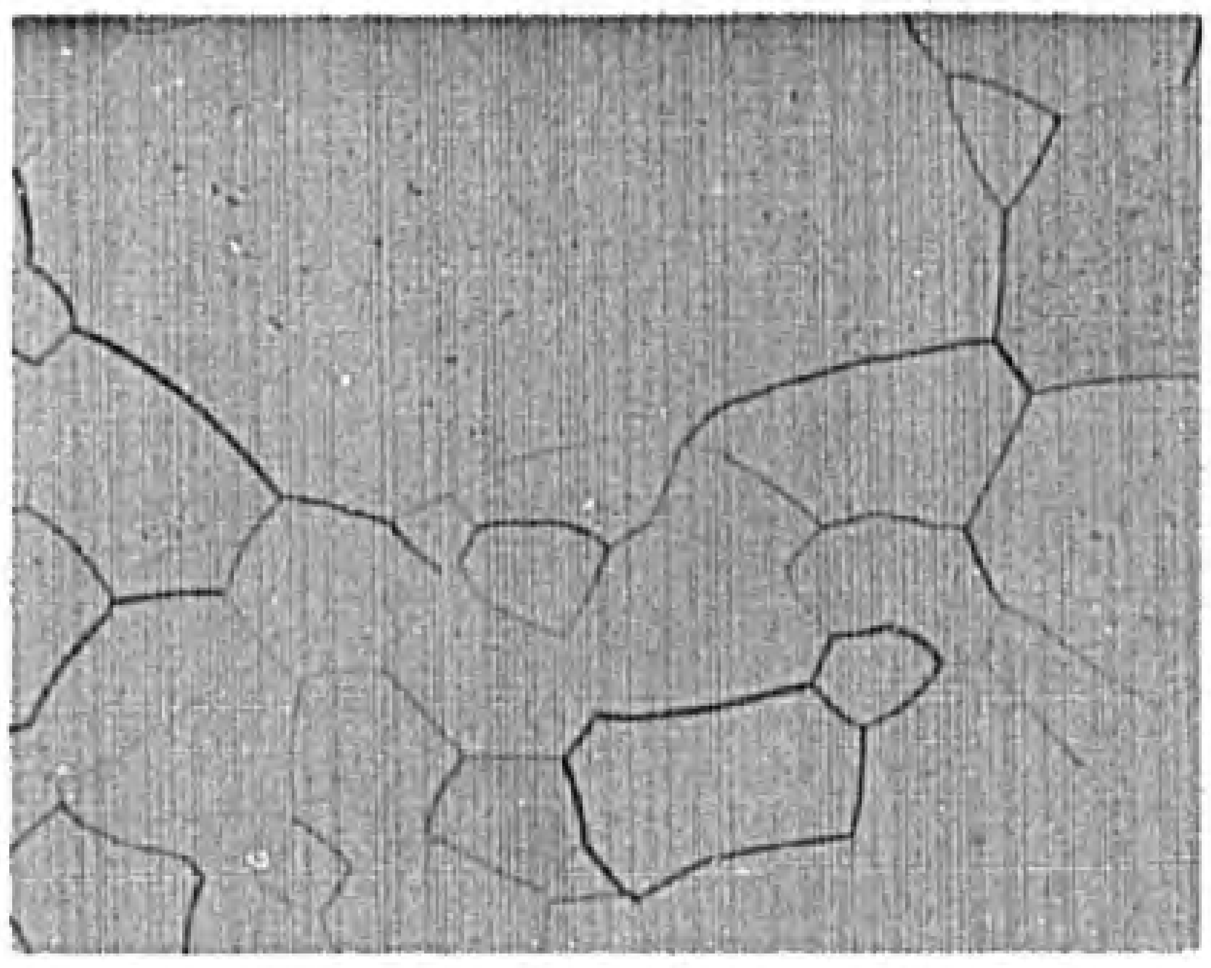
100X N54451

Annealed 1 Hour at 1200 C (2190 F)



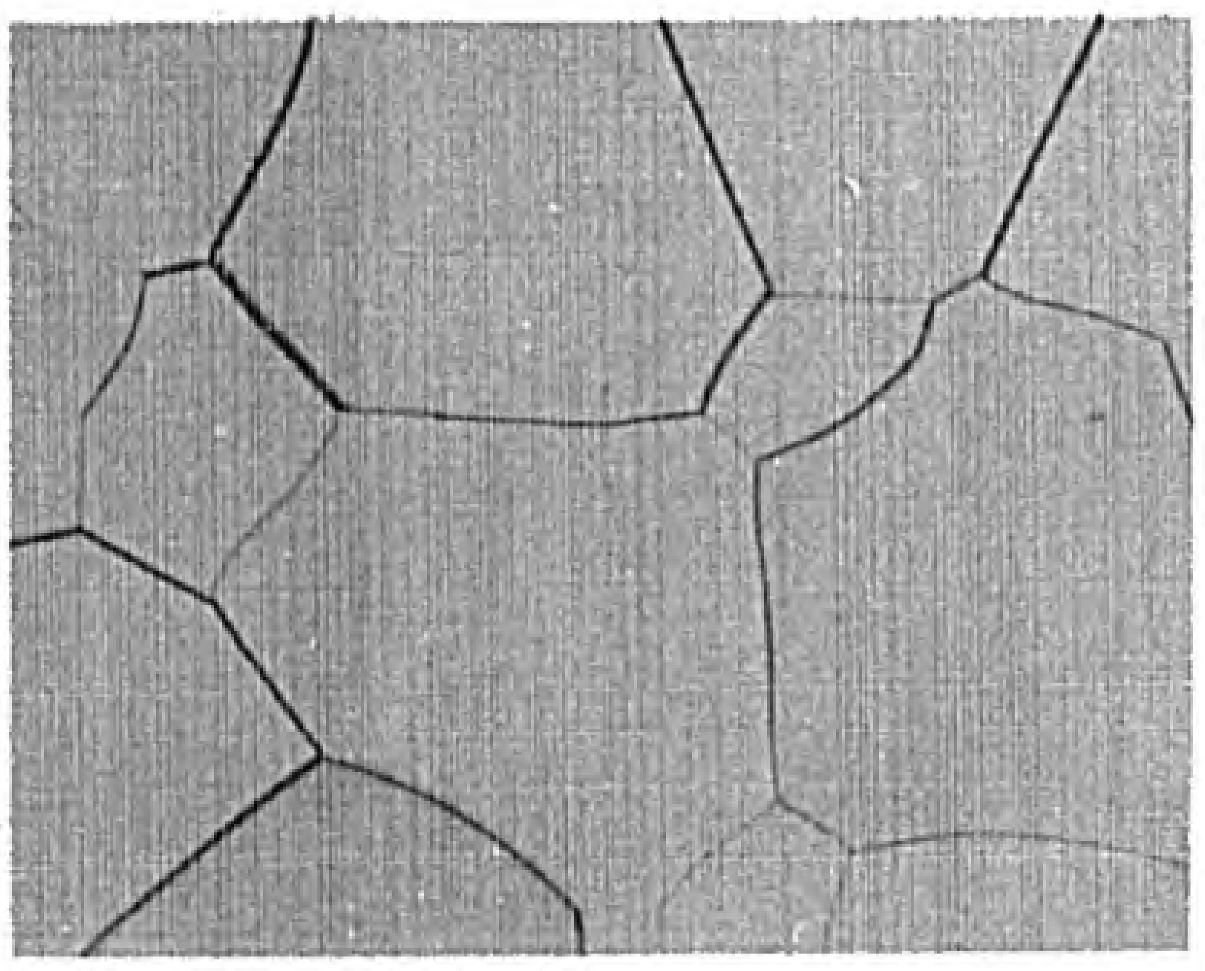
100X N54448

Annealed 1 Hour at 1400 C (2550 F)



100X N56324

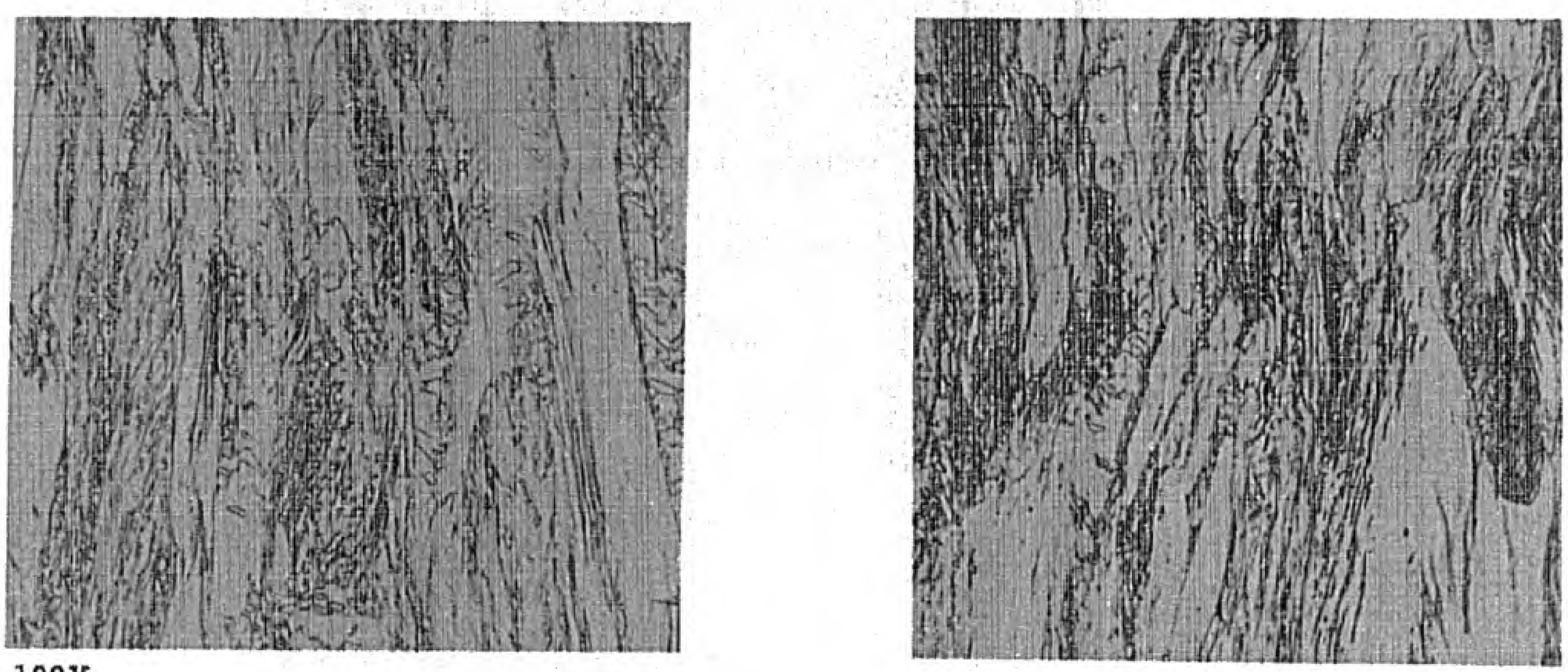
Annealed 1 Hour at 1600 C (2910 F)



100X N56326

Annealed 1 Hour at 1800 C (3270 F)

FIGURE 43. EFFECT OF ANNEALING ON THE MICROSTRUCTURE OF UNALLOYED TANTALUM

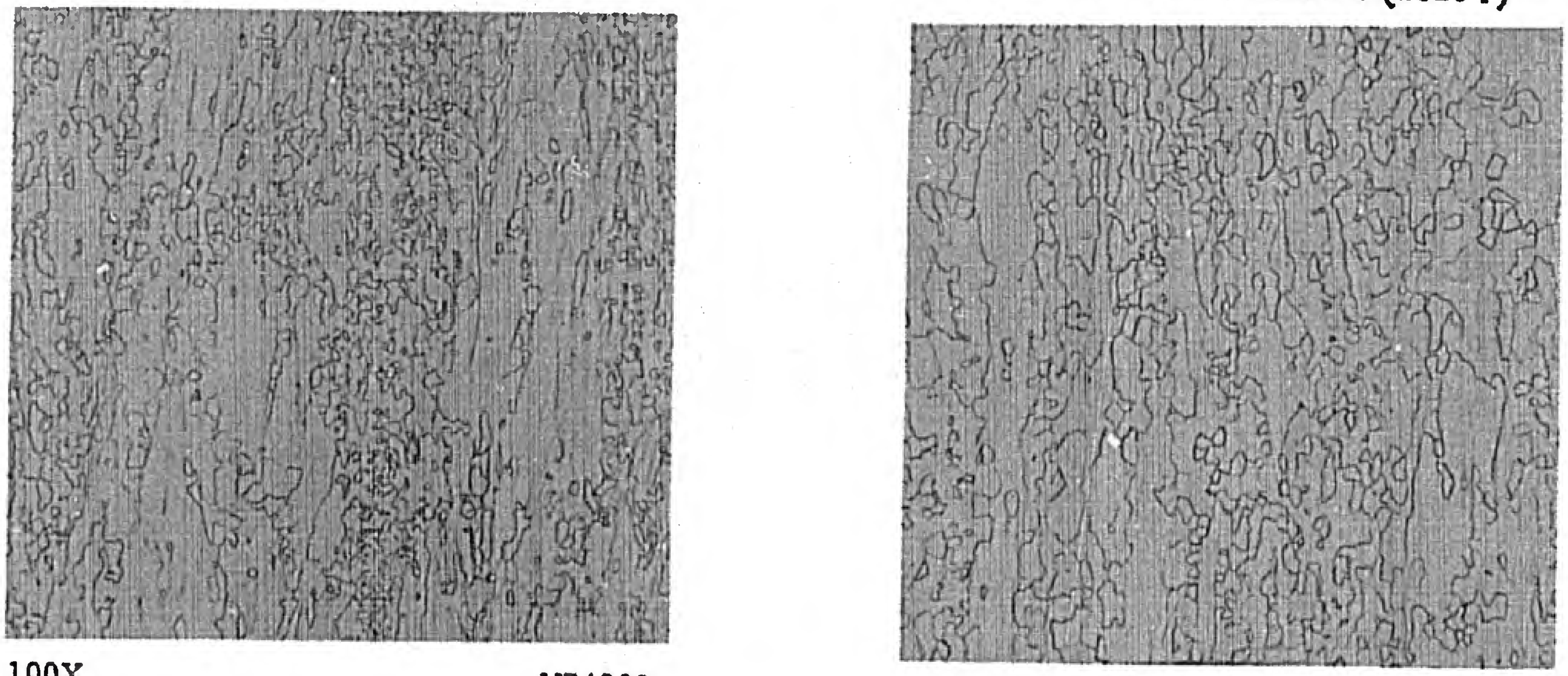


100X N74910

Wrought

100X N74909

Annealed 1 Hour at 1100 C (2010 F)



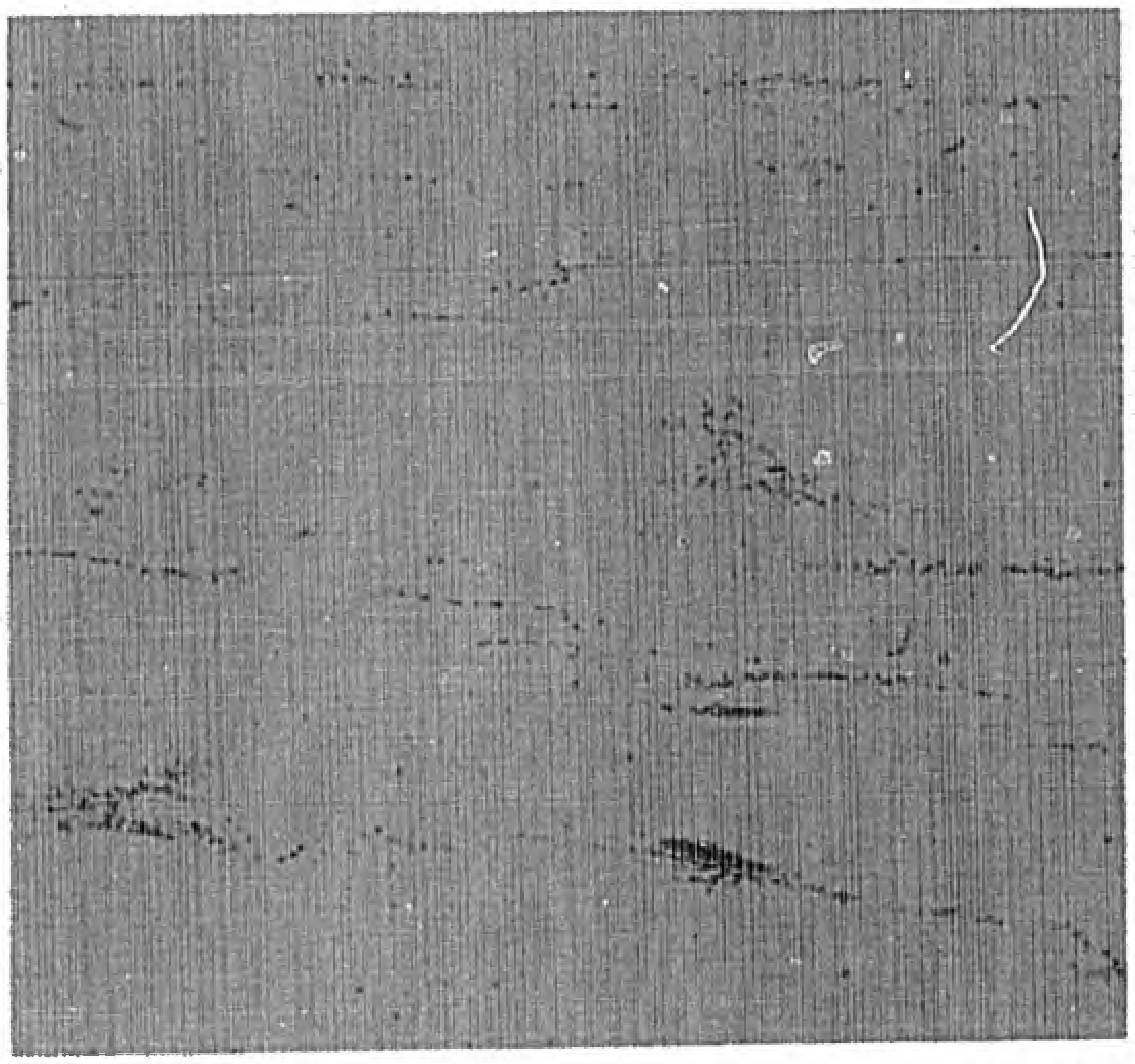
100X N74908

Annealed 1 Hour at 1300 C (2370 F)

100X N74907

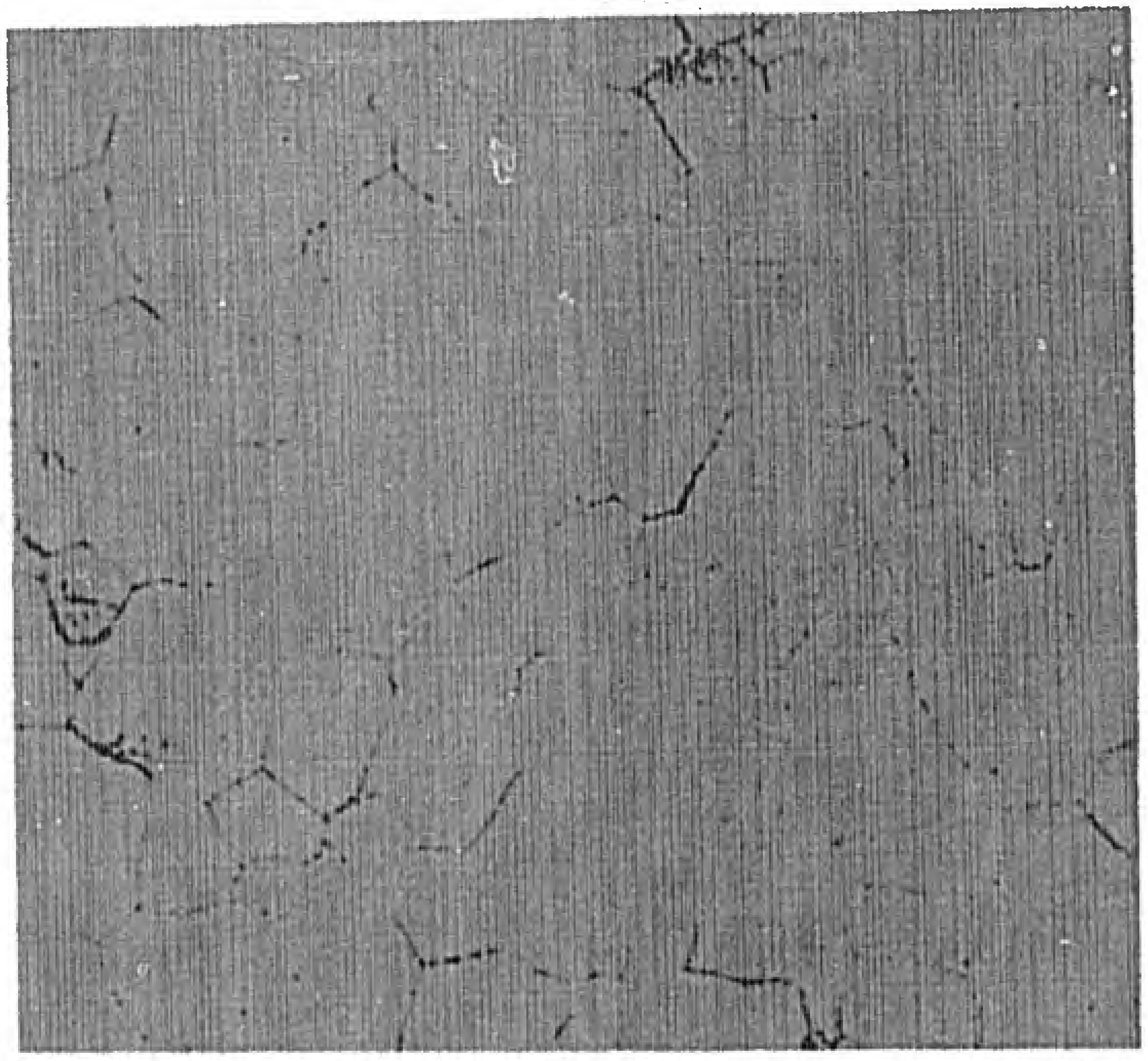
Annealed 1 Hour at 1500 C (2730 F)

FIGURE 44. EFFECT OF ANNEALING ON THE MICROSTRUCTURE OF THE Ta-30Cb-10V ALLOY



500X N74912

Annealed 1 Hr at 1300 C (2370 F)



500X N74913

Annealed 1 Hr at 1500 C (2730 F)

FIGURE 45. EFFECT OF ANNEALING ON THE MICROSTRUCTURE OF THE Ta-10Hf-5W ALLOY

TABLE 13. EFFECT OF ALLOY ADDITIONS ON THE GRAIN-SIZE OF TANTALUM

Alloy Composition, weight per cent	1-Hour Annealing Temperature C	1-Hour Annealing Temperature F	Average ASTM Grain Size[a]
100Ta	1400	2550	3-4
Ta-5Cb	1400	2550	2
Ta-10Cb	1500	2730	4
Ta-20Cb	1500	2730	5
Ta-30Cb	1400	2550	7
Ta-40Cb	1400	2550	6
Ta-50Cb	1500	2730	4
Ta-1Hf	1500	2730	6
Ta-1Hf + O (170 ppm)	1500	2730	7
Ta-5Hf	1400	2550	6
Ta-10Hf	1500	2730	6
Ta-20Hf	1400	2550	8
Ta-30Hf	1500	2730	6
Ta-35Hf	1500	2730	85 per cent 8, 15 per cent 6
Ta-7.5Mo	1500	2730	7
Ta-1Ti	1500	2730	5
Ta-1Ti + O (280 ppm)	1500	2730	7
Ta-5Ti	1300	2370	6
Ta-40Ti	1000	1830	4
Ta-5V	1500	2730	7
Ta-10V	1500	2730	6
Ta-20V	1500	2730	6
Ta-5W	1500	2730	7
Ta-10W	1400	2550	80 per cent 7, 20 per cent 5
Ta-15W	1500	2730	8
Ta-1Zr	1500	2730	6
Ta-1Zr + O (400 ppm)	1500	2730	7
Ta-10Zr	1500	2730	8
Ta-10Hf-5W	1500	2730	7

(a) Obtained by comparison with ASTM grain-size chart at 100X. All microstructures greater than 75 per cent recrystallized.

examined have a smaller grain size than that observed for unalloyed tantalum.

Discussion

Although the study of the various alloy additions on the strengthening of tantalum has not yet been completed, some preliminary conclusions may be drawn from the data presented in this report. Alloys with excellent high-temperature strength properties can be fabricated into good quality sheet. Many of these alloys retain the characteristically low ductile-to-brittle transition of pure tantalum.

Groups IVA, VA, and VIA transition metals appear outstanding as substitutional alloying additions. Molybdenum and tungsten appear to have the greatest effect in raising the recrystallization temperature and elevated-temperature strength. Hafnium and vanadium also have a potent effect in raising the high-temperature strength. Columbium additions have very slight effect on the strength properties. However, columbium does raise the recrystallization temperature and has a great effect in reducing the density of many alloys without altering fabricability.

Small additions of the Group IVA metals (Ti, Zr, and Hf) exhibited pronounced strengthening. This apparently is a result of the gettering action of these metals for interstitial impurities to form a fine dispersion of carbides and/or oxides. Zirconium appears to be more effective as a dispersion strengthener than either titanium or hafnium. Intentional additions of carbon and oxygen were also found to increase strength.

The results of these studies are very encouraging. As further progress is made, both in the experimental and scale-up aspects, it seems certain that tantalum alloys can and will find structural applications at high temperatures.

OXIDATION BEHAVIOR

The oxidation and contamination behavior of tantalum and binary tantalum were studied previously on this project. During the period covered by this report, screening-type oxidation studies were conducted on alloys designed primarily for strength at elevated temperatures and on a group of low-strength alloys designed for oxidation resistance.

Background Information

The oxidation behavior of tantalum and its alloys was studied previously under the current contract.(1,80,81) Unalloyed tantalum forms a thin, protective scale in air below 500 C (930 F) and oxidizes according to the parabolic rate law. In the temperature range 500 to 800 C (930 to 1470 F), the oxidation kinetics are initially parabolic but change to linear after a time period which decreases with increasing temperature. The transition to linear kinetics is associated with the formation of a white, porous scale of Ta_2O_5. In the temperature range 900 to 1200 C (1650 to 2190 F), the oxidation reaction is approximately linear, with the rate increasing from about 13 $mg/cm^2/hr$ to 110 $mg/cm^2/hr$. At 1400 C (2550 F), the reaction rate is very high, about 1200 $mg/cm^2/hr$. Ignition is observed in pure oxygen at this temperature.

Contamination hardening of tantalum occurs by oxygen diffusion into the metal from the surface oxides. Hardening becomes significant at about 500 C (930 F) and increases in depth with increasing exposure time and temperature. After 40 minutes' oxidation at 1200 C (2190 F) tantalum is hardened to a depth of about 0.06 inch.

Alloying additions which significantly improve the oxidation resistance of tantalum in the range 1000 to 1400 C (1830 to 2550 F) include titanium, zirconium, and hafnium. The reductions in oxidation rate are on the order of five- to twentyfold, with titanium being the most beneficial of these three elements. Additions of 5 to 10 per cent vanadium or columbium reduce the oxidation rates at 1000 and 1200 C (1830 and 2190 F) by up to 50 per cent, but are ineffective at 1400 C (2550 F). Improvements in the 1200 C (2190 F) oxidation behavior are also effected by tungsten (30 to 50 per cent), chromium (about 5 per cent), and molybdenum (above 5 per cent).

The rate of contamination hardening of tantalum during oxidation is reduced significantly by additions of titanium, zirconium, hafnium, silicon, thorium, rhenium, tungsten, vanadium, and molybdenum. The first five elements (titanium through thorium) react with the diffusing oxygen to form stable oxides which precipitate to form an internal subscale. The four elements, rhenium through molybdenum, have smaller atomic radii than tantalum. They are believed to reduce contamination by distorting the tantalum lattice and thus hindering the inward diffusion of oxygen.

Experimental Procedures

Samples for both screening and continuous-weighing oxidation studies were cut from warm or cold-rolled strip. The samples measured 0.75 by 1.0 by about 0.03 inch. They were prepared by grinding and polishing to a 600-grit finish, followed by an acid polish in a sulfuric-nitric-hydrofluoric acid mixture.

Screening tests were conducted at 1200 C (2190 F) in laboratory muffle furnaces in undried air. The weighed samples were placed in prefired porcelain crucibles, exposed, and reweighed. The amount of oxidation was expressed as weight gain per unit of original surface area.

Continuous-weighing oxidation studies were conducted on selected alloys at 1000, 1200, and 1400 C (1830, 2190, and 2550 F). These experiments were conducted in dried air for time periods up to 16 hours.

The oxidation studies were supplemented by metallographic studies and cross-sectional hardness measurements on the oxidized samples.

Screening Oxidation Studies

Screening oxidation studies were conducted at 1200 C (2190 F) on alloys designed for strength or for oxidation resistance. Data from these studies are presented in Table 14. Photographs of oxidized tantalum and several selected alloys are shown in Figure 46.

The behaviors of the various binary alloys evaluated are consistent with the alloying effects observed earlier(1,81). Iron, molybdenum, vanadium, and zirconium are moderately effective at the 10 per cent alloying level, while tungsten promotes a slight reduction in oxidation rate up to 15 per cent. The observed reduction in oxidation rate on alloying with 5 per cent rhenium probably results from loss of volatile Re_2O_7 during oxidation.

A consistent and very interesting effect is that of carbon additions to alloys containing titanium, zirconium, or hafnium. Additions of 0.054 to 0.23 per cent carbon to alloys containing 1 to 10 per cent of these metals decreased the oxidation rate by an average of 16 per cent. In contrast, a carbon addition to Ta-5 per cent V increased the oxidation rate. Oxygen additions also appear to increase oxidation rates slightly. The mechanism

TABLE 14. OXIDATION OF TANTALUM AND TANTALUM ALLOYS IN AIR AT 1200 C (2190 F) AFTER VARIOUS EXPOSURE TIMES

Alloy Composition, weight per cent	Weight Gain After Indicated Time, mg/cm^2			Oxidation Rate, mg/cm^2/hr	Appearance of Scale
	0.5 Hr	1 Hr	2 Hr		
100Ta(a)	70.0	106	167		White, voluminous, porous
Ta-6.2Fe(a)			128.8	64.4	Porous, brown
Ta-8Fe(b)		50.1		50.1	Gray, thin, adherent
Ta-1Hf		154.3		154.3	White, voluminous, porous
Ta-1Hf + C (700 ppm)		75.9		75.9	Brown-white, adherent
Ta-1Hf + O (170 ppm)		119.4		119.4	White, porous, thick
Ta-10Hf + C (630 ppm)		51.6		51.6	Thin, white, flaking, partially adherent
Ta-30Hf		41.0		41.0	Thin, white, very adherent, protective
Ta-35Hf		41.9		41.9	Thin, white, very adherent, protective
Ta-7.5Mo		65.4		65.4	Adherent, gray-yellow
Ta-10Mo(a)			103	51.5	Porous gray scale
Ta-5Re		71.3		71.3	Yellow-white, thin, adherent
Ta-1Ti		104.2		104.2	White, porous, thick, nonadherent
Ta-1Ti + C (2300 ppm)		98.9		98.9	White, thick, adherent
Ta-1Ti + O (280 ppm)		128.8		128.8	White, voluminous, porous
Ta-5V(a)			111	55.5	Porous, gray-white
Ta-5V + C (580 ppm)	43.6			87.2	Brown, partially adherent
Ta-7.5V	40.0			80.0	Flaking, brown, nonprotective
Ta-15V	67.2			134.4	Thick, brown, nonprotective
Ta-20V		159.9		159.9	Brown, voluminous, porous
Ta-10W(a)			122.8	61.4	Porous, white scale
Ta-15W		89.0		89.0	Thin, adherent, white
Ta-1Zr		90.6		90.6	White, porous, thick
Ta-1Zr + C (1400 ppm)		78.7		78.7	White with gray subscale, adherent
Ta-1Zr + C (400 ppm)		88.3		88.3	Thick, porous, white
Ta-10Zr		47.7		47.7	Thin, adherent, light gray with dark gray subscale
Ta-30Cb-20Hf		133.2		133.2	White, thick, nonadherent
Ta-30Cb-7.5V	50.0			100.0	Brown, thick, nonprotective
Ta-30Cb-10V		93.7		93.7	Brown, porous, nonprotective
Ta-30Cb-5V-1Zr		94.7		94.7	Tan, flaking, nonprotective

TABLE 14. OXIDATION OF TANTALUM AND TANTALUM ALLOYS IN AIR AT 1200 C (2190 F) AFTER VARIOUS EXPOSURE TIMES (Continued)

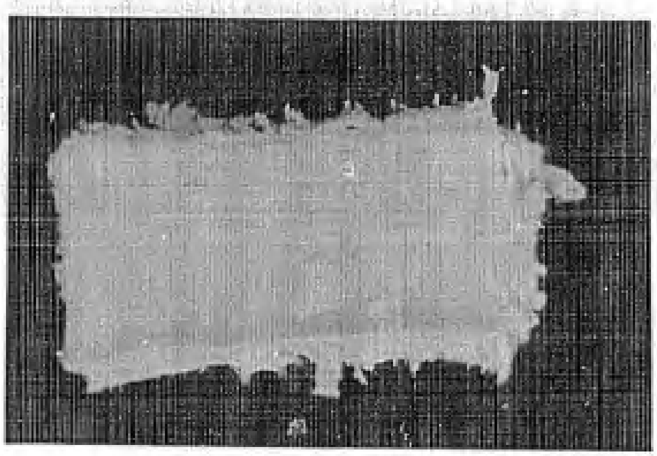
Alloy Composition, weight per cent	Weight Gain After Indicated Time, mg/cm^2			Oxidation Rate, $mg/cm^2/hr$	Appearance of Scale
	0.5 Hr	1 Hr	2 Hr		
Ta-30Cb-1Zr		126.2		126.2	White, thick, flaking, nonadherent
Ta-30Cb-1Zr		291.0		291.0	White, voluminous, flaking, porous
Ta-20Hf-2Al			67.0	33.5	White, thick, adherent
Ta-20Hf-5Al		47.4		47.4	Gray, shiny, adherent
Ta-20Hf-2Cr			35.4	17.7	White, thick, adherent
Ta-10Hf-5Mo		66.5		66.5	Yellow-tan, partially adherent
Ta-10Hf-10Ti		43.1		43.1	Yellow-white, thin, adherent
Ta-10Hf-5V		50.0		50.0	Yellow-brown, thin, flaking
Ta-5Hf-10W		92.5		92.5	White, flaking, partially protective
Ta-10Hf-5W		72.2		72.2	White, thin, adherent
Ta-10Hf-5W + C (540 ppm)		58.6		58.6	White, partially adherent
Ta-10Hf-10W		80.5		80.5	White, flaking, partially adherent
Ta-10Hf-15W		47.8		47.8	White, thin, powdery
Ta-20Hf-10W	34.1			68.2	Yellow-white, thin, partially adherent
Ta-10Hf-1Zr	35.3			70.6	Yellow-white, thin, partially adherent
Ta-20Ti-5Al		16.7		16.7	Pale-yellow, adherent
Ta-30Ti-5Al			12.5	6.3	Yellow, thin, adherent
Ta-40Ti-5Al			10.2	5.1	Yellow, thin, adherent
Ta-40Ti-10Al			3.7	1.9	Shiny, very thin, adherent
Ta-30Ti-5Al-5Cr			13.9	7.0	Greenish-brown, very thin, adherent
Ta-30Ti-5Al-1.5Si			5.6	2.8	Yellowish, very thin, adherent
Ta-30Ti-1Be			13.5	6.8	Yellow, thin, spalling
Ta-10Ti-5Cb		74.7		74.7	Tan, thick, adherent
Ta-20Ti-5Cb		28.9		28.9	Light yellow, thin, adherent
Ta-20Ti-5Cr		15.5		15.5	Tan, thin, adherent
Ta-30Ti-5Cr			12.8	6.4	Brownish, thin, adherent
Ta-30Ti-10Cr			5.8	2.9	Brown, very thin, adherent
Ta-10Ti-5Mo		43.1		43.1	Tan, thin, adherent
Ta-30Ti-1.5Si			23.0	11.5	Yellow, thin, adherent
Ta-10Ti-5V		26.3		26.3	Metallic gray, thin, adherent
Ta-20Ti-5V		19.3		19.3	Dark gray, thin, adherent
Ta-10Ti-5W		76.0		76.0	Tan, thick, adherent

TABLE 14. OXIDATION OF TANTALUM AND TANTALUM ALLOYS IN AIR AT 1200 C (2190 F) AFTER VARIOUS EXPOSURE TIMES (Continued)

Alloy Composition, weight per cent	Weight Gain After Indicated Time, mg/cm^2			Oxidation Rate, mg/cm^2/hr	Appearance of Scale
	0.5 Hr	1 Hr	2 Hr		
Ta-20Ti-5W		39.4		39.4	Light yellow, thin, adherent
Ta-20Ti-10W		42.1		42.1	Yellow, thin, adherent
Ta-10Ti-10Zr		41.4		41.4	Yellow-white, flaking
Ta-5V-5Mo		114.3		114.3	Brown-violet, thin, adherent
Ta-10V-5Mo	61.0			122.0	Dark brown, thick, nonprotective
Ta-5V-5W	31.5			63.0	Gray to brown, thin, partially adherent
Ta-5V-7.5W	31.5			63.0	Gray to brown, thin, partially adherent
Ta-5V-10W	27.0			54.0	Gray to brown, thin, partially adherent
Ta-10V-5W		122.0		122.0	Brown, voluminous, porous
Ta-5V-1Zr		67.7		67.7	Yellow-brown, thick, partially adherent
Ta-10W-5Mo		77.3		77.3	Yellow, partially adherent
Ta-10W-5Mo	49.3			98.6	Yellow-white, thick, partially adherent
Ta-10W-1Zr		85.0		85.0	White, partially adherent

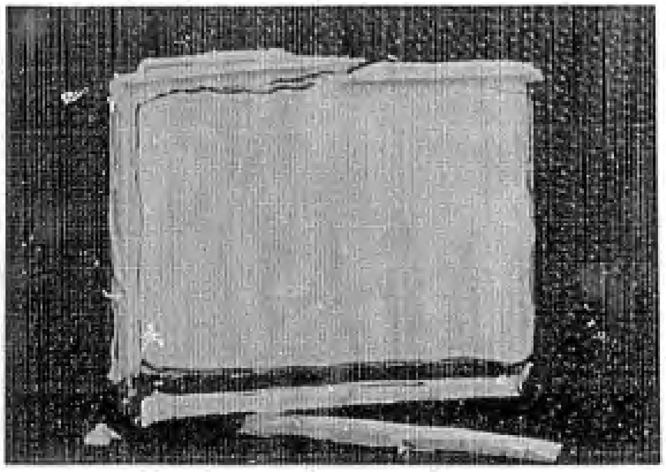
(a) Data from Reference 1 included for comparison.

(b) Sample was as cast, measuring 0.1 by 0.2 by 0.4 inch. All other samples were wrought sheet, measuring about 0.75 by 1 by 0.03 inch.



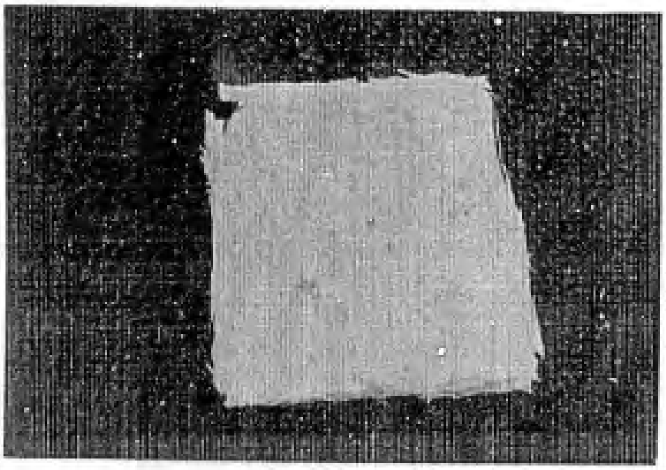
S-157

a. Ta-1Hf



S-148

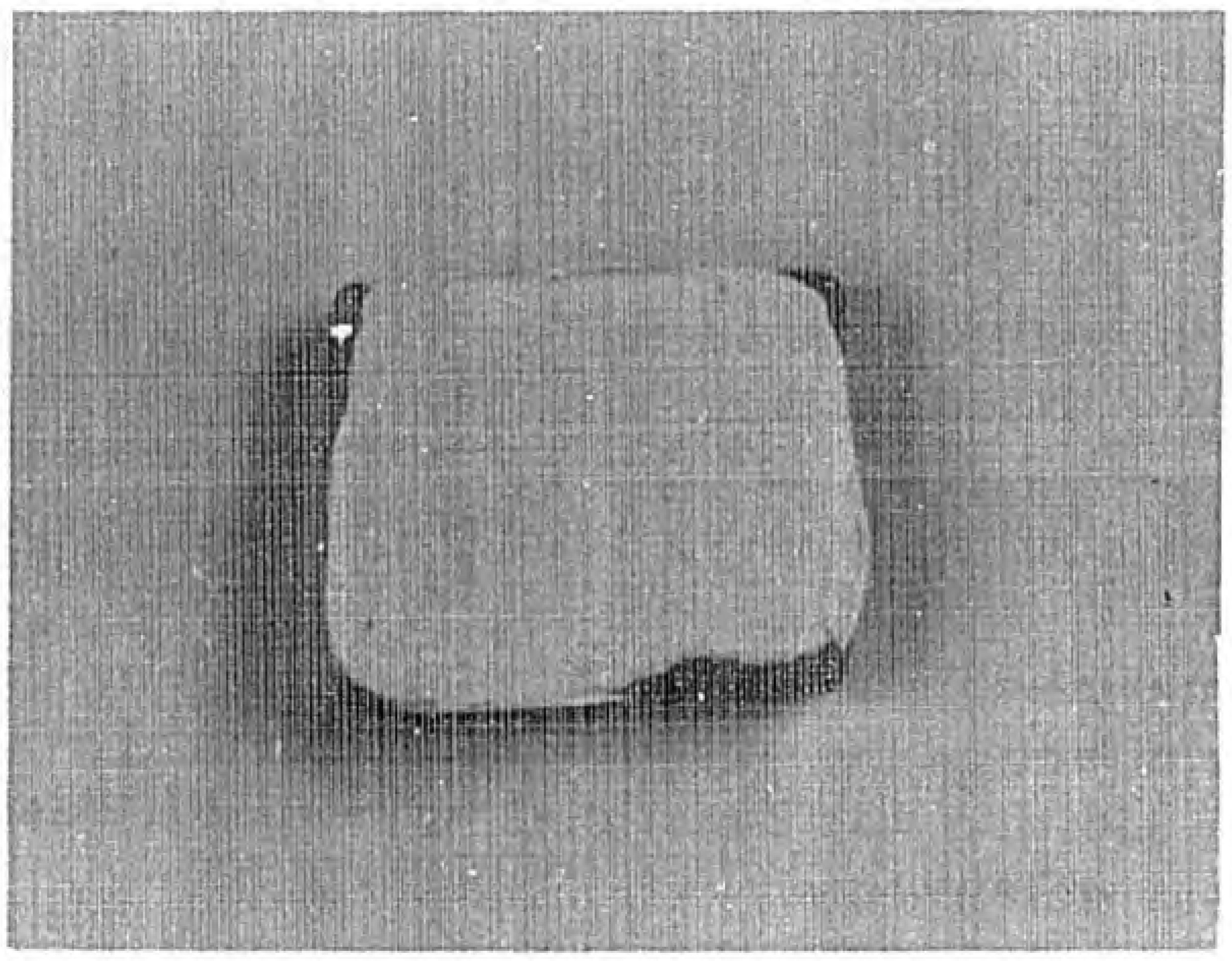
b. Ta-1Hf-0.07C



S-152

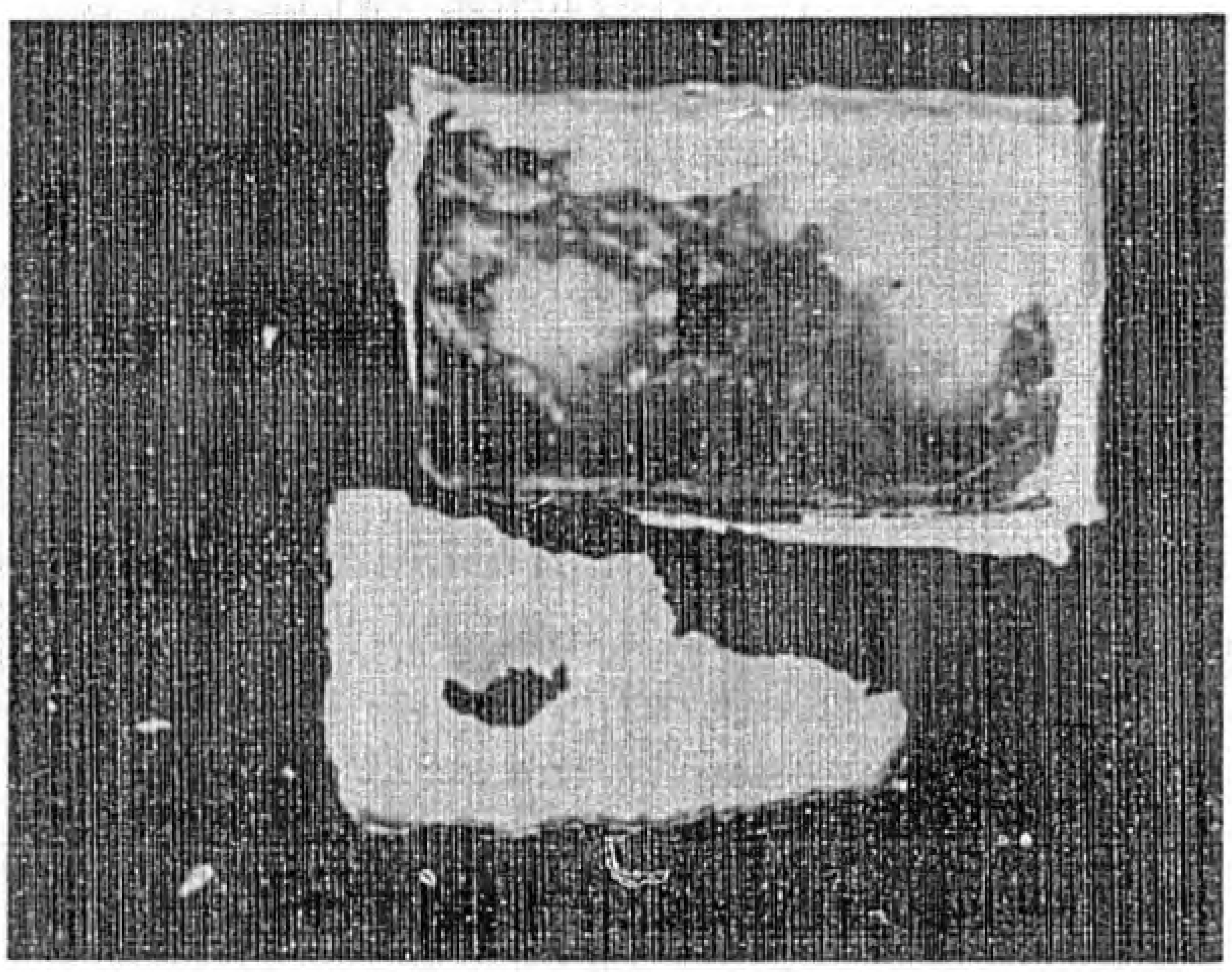
c. Ta-10Hf-5W

FIGURE 46. TANTALUM ALLOYS AFTER OXIDATION AT 1200 C (2190 F) FOR 1 HOUR



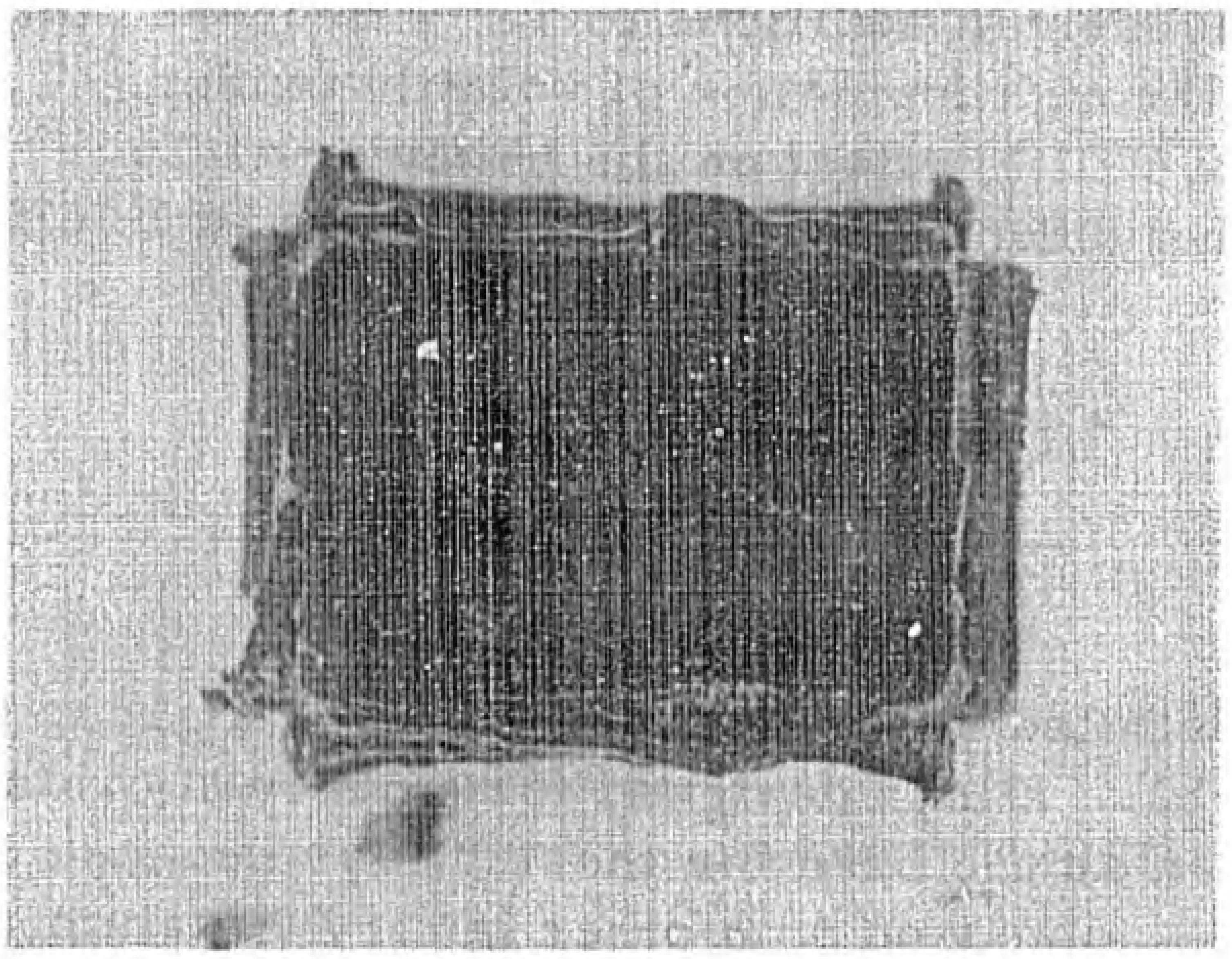
S-191

d. Ta-10Hf-5W-0.054 C



S-190

e. Ta-5Hf-10W



S-174

f. Ta-30Cb-10V

FIGURE 46. (CONTINUED)

by which carbon additions improve the oxidation behavior is not known, but the effect is doubly interesting since carbon additions also strengthen these alloys by forming dispersions.

Ternary alloys based on Ta-30Cb are less oxidation resistant than binary alloys based on tantalum alone. This is consistent with the earlier observation(1) that the addition of 30 per cent columbium increases the oxidation rate of tantalum markedly at 1200 C (2190 F).

Ternary additions of aluminum, molybdenum, titanium, and vanadium have little effect on the oxidation behavior of Ta-10 or 20 Hf. A ternary chromium addition was beneficial to oxidation resistance, while a zirconium addition was detrimental.

A number of compositions in the Ta-Hf-W system have been surveyed for oxidation resistance. Oxidation rates at 1200 C in this system are shown in Figure 47. The Ta-10Hf-5W alloy oxidizes at a rate of 72.2 mg/cm^2/hr, about 30 per cent slower than does unalloyed tantalum. The data in Figure 47 indicate that increasing the hafnium content or decreasing the tungsten content of this alloy would improve the oxidation resistance, and vice versa. Carbon additions also improve the oxidation resistance of Ta-10Hf-5W.

Aluminum, beryllium, chromium, and silicon additions to Ta-Ti generally promote superior oxidation resistance, although the strengths of these alloys are low at elevated temperatures. These alloys were studied in detail and are discussed in the next section of this report. Ternary additions of columbium, molybdenum, tungsten, and zirconium to Ta-10 and 20 Ti decreased the oxidation resistance slightly, while vanadium additions had no significant effect.

Molybdenum additions to Ta-V decrease the oxidation resistance, probably through formation of volatile oxides. Tungsten and zirconium additions have little effect on the behavior of Ta-V. Similarly, small additions of molybdenum and zirconium have little effect on the behavior of Ta-10W.

Detailed Oxidation Studies

A detailed evaluation was made on a group of complex tantalum-titanium-base alloys designed for improved oxidation. Tantalum-titanium was chosen as the base for these alloys because of its superior oxidation resistance compared with other binary tantalum alloys. The good cold fabricability of the base alloys also promoted fabricability in the complex alloys. These complex alloys might find application as high-temperature oxidation-resistant cladding materials for other refractory alloys.

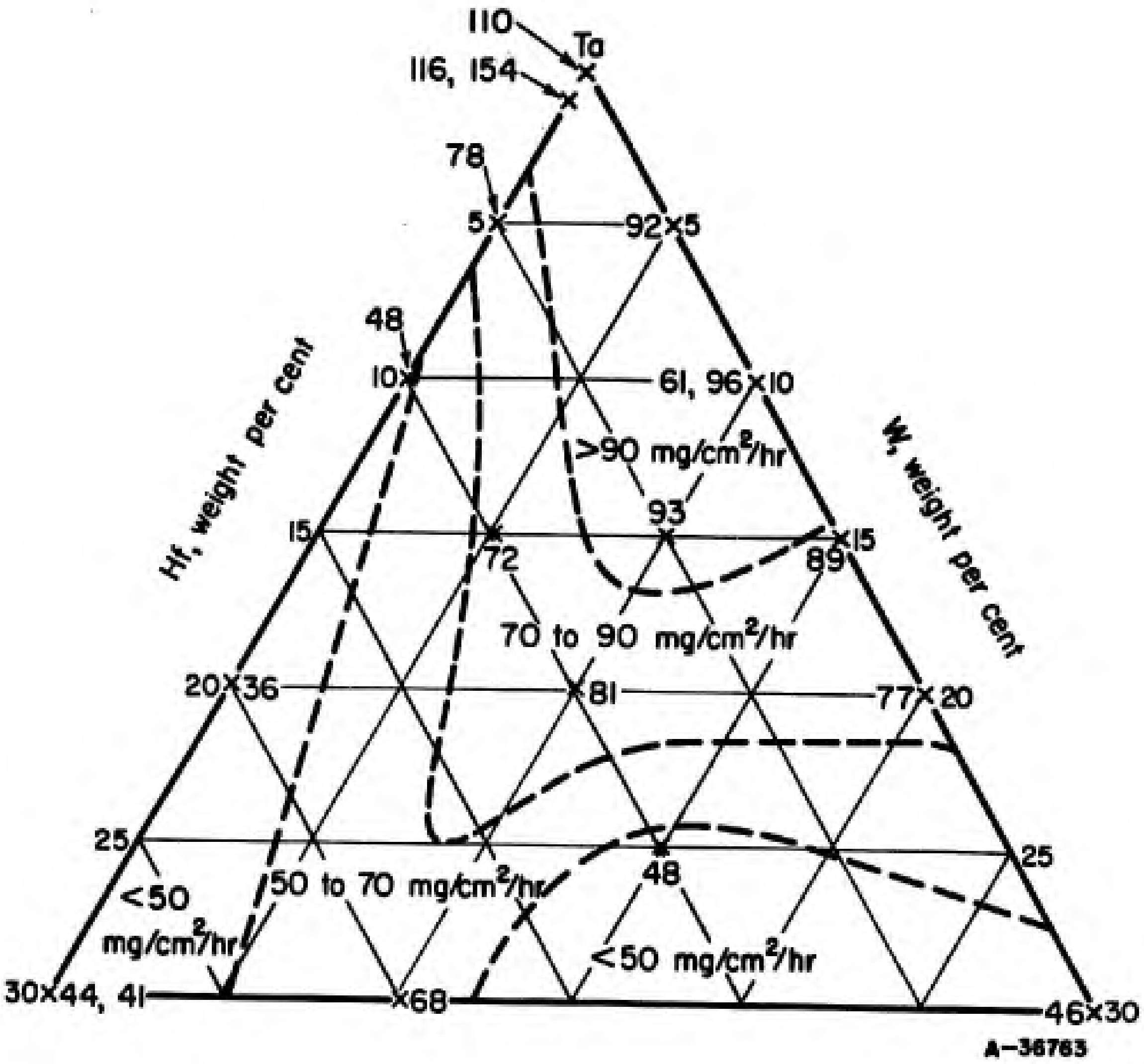


FIGURE 47. OXIDATION RATES OF Ta-Hf-W ALLOYS AT 1200 C (2190 F)

Estimated constant rate lines are shown.

The oxidation behavior of binary tantalum-titanium alloys was studied previously up to 40 per cent titanium. Evaluation of the system was completed with studies on Ta-60Ti, Ta-80Ti, and unalloyed titanium. Oxidation data on these alloys are presented in Table 15. Photographs of selected alloys after oxidation are shown in Figure 48.

The Ta-60 and -80 Ti alloys oxidize considerably slower than the tantalum-rich alloys in this system. Both alloys formed thin, protective scales and oxidized parabolically for 6 hours at 1400 C (2550 F). The 2-hour weight gains of binary titanium alloys at 1000, 1200, and 1400 C (1830, 2190, and 2550 F) are plotted in Figure 49. The weight gain versus composition curves are characterized by sharp decreases in weight gain from zero to 20Ti, and more gradual decreases to minima in the range 60 to 80Ti. The initial improvement on adding titanium is associated with formation of protective complex oxides of Ta_2O_5-TiO_2. The minimum oxidation rate in the titanium-rich alloys appears associated with the higher valence of tantalum dissolved in the TiO_2-rich scale. Titanium dioxide is classed as an oxygen-deficient semiconductor through which diffusion occurs by movement of oxygen-ion vacancies. Substitution of higher valence cations such as Ta^{5+} for Ti^{4+} reduces the number of anion vacancies, thus reducing diffusion through the oxide and improving the oxidation resistance.

The complex ternary and quaternary alloys based on tantalum-titanium exhibit significant improvements in oxidation resistance compared with the best binary tantalum alloys. Aluminum appears to be the most effective ternary addition. The addition of 5Al (14 atomic per cent Al) to tantalum-titanium improves the oxidation resistance by up to eightfold at 1000 C (1830 F) and about threefold at 1400 C (2550 F). Increasing the aluminum to 10 per cent (25 atomic per cent) improves the oxidation resistance by another threefold. The Ta-40Ti-10Al alloy is the most oxidation-resistant tantalum alloy developed to date. This alloy forms a scale which remains protective for at least 6 hours at 1400 C (2550 F), and represents about a 300-fold improvement over unalloyed tantalum at this temperature. The oxidation curve of Ta-40Ti-10Al at 1200 C (2190 F) is shown with curves for tantalum, two other tantalum alloys, and the commercial heat-resistant alloy Fecral in Figure 50.

Ternary additions of chromium also effectively improve the oxidation resistance of Ta-30Ti. Chromium additions reduce the initial parabolic rate more than do aluminum additions, but the scales are less stable and linear oxidation behavior (at low rates) is observed with the ternary chromium alloys. The weight gains of the chromium-containing alloys are comparable with those of the aluminum alloys up to at least 1400 C (2550 F).

A ternary addition of 1Be improves the oxidation behavior of Ta-30Ti at 1000 C (1830 F) but is detrimental at 1200 and 1400 C (2190 and 2550 F). A ternary silicon addition effects moderate improvements at all three temperatures studied.

TABLE 15. CONTINUOUS-WEIGHING OXIDATION BEHAVIOR OF TANTALUM AND TANTALUM ALLOYS

Alloy Composition		Parabolic Rate Constant, $(mg/cm^2)^2/hr$	Transition to Linear Behavior, min	Linear Rate Constant, $mg/cm^2/hr$	Initial Slope of Log-Log Plot, n	Weight Gain, mg/cm^2, After Indicated Time					
Weight Per Cent	Atomic Per Cent					1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours
				Oxidation at 1000 C (1830 F)							
100Ta	100Ta	--	--	39.0	0.67	38.8	62.8	(79)[a]	(94)	(107)	(119)
Ta-30Ti	Ta-62Ti	--	--	4.2	0.80	4.5	11.1	16.8	21.2	25.1	28.6
Ta-40Ti	Ta-72Ti	--	--	2.3-1.6[b]	0.79	2.1	4.3	6.2	7.1	7.9	8.7
Ta-60Ti	Ta-85Ti	5.8	>360	--	0.63	1.8	2.8	3.7	4.4	5.1	5.7
Ta-80Ti	Ta-94Ti	1.54	>360	--	0.50	1.32	1.75	2.11	2.46	2.82	2.99
100Ti	100Ti	32	500	1.0	0.51	6.1	7.8	9.4	10.9	12.2	13.7
Ta-30Ti-5Al	Ta-54Ti-16Al	2.4	>720	--	0.55	1.4	2.0	2.6	2.9	3.4	3.8
Ta-40Ti-5Al	Ta-63Ti-14Al	(3.2)	>900	--	0.58	1.4	2.2	2.7	3.3	3.9	4.6
Ta-40Ti-10Al	Ta-56Ti-25Al	0.103	>900	--	0.34-0.44[c]	0.45	0.58	0.66	0.71	0.79	0.84
Ta-30Ti-1Be	Ta-56Ti-10Be	--	--	2.2	0.74	3.2	5.3	7.5	9.8	12.0	14.1
Ta-30Ti-5Cr	Ta-58Ti-9Cr	3.9	150	0.55	0.56	1.9	2.8	3.6	4.4	5.1	5.7
Ta-30Ti-10Cr	Ta-54Ti-17Cr	1.36	660	0.21	0.47	1.37	1.76	2.16	2.45	2.75	2.94
Ta-30Ti-1.5Si	Ta-59Ti-5Si	27	120	5.0	0.65	4.4	6.9	9.5	12.3	15.4	18.6
Ta-30Ti-5Al-5Cr	Ta-51Ti-15Al-8Cr	0.194	>900	--	0.42	0.61	0.75	0.89	1.03	1.12	1.21
Ta-30Ti-5Al-1.5Si	Ta-52Ti-15Al-4Si	0.27	400	0.12	0.43	0.59	0.77	0.91	1.07	1.18	1.30
				Oxidation at 1200 C (2190 F)							
100Ta	100Ta	--	--	110	0.60	106	167	211	254	302	--
Ta-30Ti	Ta-62Ti	58	45	12.0	1.05	9.8	21.8	33.8	44.8	54.8	--
Ta-40Ti	Ta-72Ti	--	--	9.0	0.91	10.0	18.0	28.0	38.0	47.0	56.0
Ta-60Ti	Ta-85Ti	52.8	>360	--	0.55	6.6	9.7	12.1	14.2	16.0	17.5
Ta-80Ti	Ta-94Ti	20.8	>360	--	0.48	5.1	7.0	8.4	9.5	10.6	11.5
100Ti	100Ti	(27)[d]	(150)	3.8	(e)	18.1	20.3	22.7	26.0	29.5	33.3
Ta-30Ti-5Al	Ta-54Ti-16Al	21	40	3.1	0.57	5.2	9.3	12.8	15.4	17.7	20.2
Ta-40Ti-5Al	Ta-63Ti-14Al	14	60	2.3	0.57	3.9	6.2	8.6	10.9	13.0	15.1
Ta-40Ti-10Al	Ta-56Ti-25Al	3.9	>360	--	0.50	1.77	2.65	3.53	4.12	4.46	4.76
Ta-30Ti-1Be	Ta-56Ti-10Be	--	--	(13.7)	0.91	20.7	36.9	50.9	63.5	75.0	86.0
Ta-30Ti-5Cr	Ta-58Ti-9Cr	15.5	30	(3.9)	0.53	4.43	8.65	13.0	16.4	19.2	21.7
Ta-30Ti-10Cr	Ta-54Ti-17Cr	6.2	>360	--	0.51	2.48	3.40	4.3	5.04	5.58	6.15
Ta-30Ti-1.5Si	Ta-59Ti-5Si	55	100	3.3	0.50	7.2	10.7	14.1	17.2	20.6	24.3
Ta-30Ti-5Al-5Cr	Ta-51Ti-15Al-8Cr	4.1	>360	--	0.43	2.36	3.13	3.73	4.23	4.66	5.10
Ta-30Ti-5Al-1.5Si	Ta-52Ti-15Al-4Si	2.9	320	--	0.47	1.83	2.50	3.03	3.46	3.85	4.33

TABLE 15. CONTINUOUS-WEIGHING OXIDATION BEHAVIOR OF TANTALUM AND TANTALUM ALLOYS (Continued)

Alloy Composition		Parabolic Rate Constant, $(mg/cm^2)^2/hr$	Transition to Linear Behavior, min	Linear Rate Constant, $mg/cm^2/hr$	Initial Slope of Log-Log Plot, n	Weight Gain, mg/cm^2, After Indicated Time					
Weight Per Cent	Atomic Per Cent					1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hou
				Oxidation at 1400 C (2550 F)							
100Ta	100Ta	--	--	(1200)	0.87	--	--	--	--	--	--
Ta-30Ti	Ta-62Ti	--	--	(61)	0.83	60.6	90.0	--	--	--	--
Ta-40Ti	Ta-72Ti	--	--	(39)	0.77	47.0	78.0	100	--	--	--
Ta-60Ti	Ta-85Ti	87	>360	--	0.41	10.7	14.6	17.3	19.2	21.0	22.9
Ta-80Ti	Ta-94Ti	383	>360	--	0.50	17.4	28.0	34.8	39.7	44.1	48.1
100Ti	100Ti	(1200)(f)	(100)	13	(e)	63.1	79.5	92.5	--	--	--
Ta-30Ti-5Al	Ta-54Ti-16Al	--	--	(14)	0.64	26.4	41.3	53.6	64.5	74.4	--
Ta-40Ti-5Al	Ta-63Ti-14Al	(204)	(20)	8.6	0.58	18.7	30.2	40.2	49.2	57.6	65.8
Ta-40Ti-10Al	Ta-56Ti-25Al	82	--	--	0.49	9.4	12.8	15.8	18.2	21.0	23.0
Ta-30Ti-1Be	Ta-56Ti-10Be	--	--	(128)	1.04	--	--	--	--	--	--
Ta-30Ti-5Cr	Ta-58Ti-9Cr	315	20	31.6	0.54	29.2	59	83.5	104	123	139
Ta-30Ti-10Cr	Ta-54Ti-17Cr	53	110	4.7	0.42	7.7	10.6	13.4	16.6	20.5	25.0
Ta-30Ti-1.5Si	Ta-59Ti-5Si	163	60	12	0.46	13.3	22.0	32.4	44.0	55.7	68.0
Ta-30Ti-5Al-5Cr	Ta-51Ti-15Al-8Cr	144	120	5.7	0.37	14.6	18.8	23.7	29.0	34.8	40.3
Ta-30Ti-5Al-1.5Si	Ta-52Ti-15Al-4Si	32.3	110	6.0	0.47	5.8	8.3	10.9	13.8	17.6	22.8

(a) Values in parentheses are estimated.
(b) Rate decreased from 2.3 to 1.6 $mg/cm^2/hr$ after 180 minutes' oxidation.
(c) Slope increased from 0.34 (cubic) to 0.44 (parabolic) after 200 minutes' oxidation.
(d) Oxidation behavior was approximately parabolic after an initial weight gain of 13 mg/cm^2.
(e) No meaningful slope.
(f) Oxidation behavior was approximately parabolic after an initial weight gain of 30 mg/cm^2.

Complex additions of aluminum-chromium and aluminum-silicon are more effective than similar additions added in ternary combination to tantalum-titanium. The quaternary Ta-30Ti-5Al-5Cr alloy surpasses both the Ta-30Ti-5Al and the Ta-30Ti-5Cr alloys by about fourfold, and approaches the oxidation resistance of the Ta-40Ti-10Al alloy. Similarly, silicon, which was only moderately effective as a ternary addition, is quite effective as a quaternary addition in the presence of aluminum.

Contamination Studies

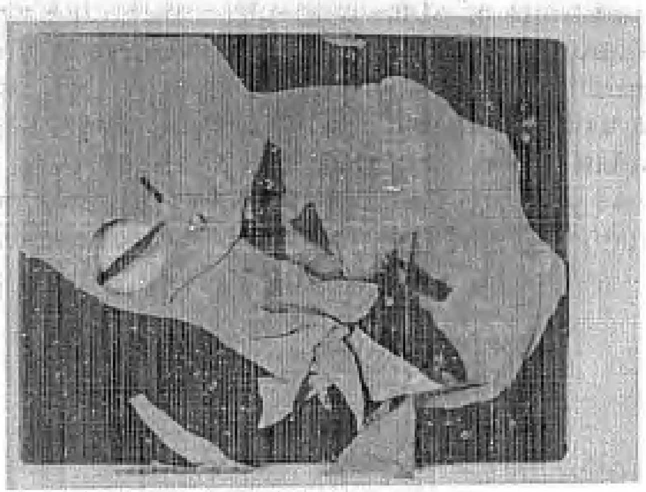
The contamination hardening accompanying oxidation of the group of tantalum-titanium-base alloys discussed in the preceding section was studied by means of Knoop hardness traverses across sections of the oxidized alloys. This technique provides simple and accurate means for measuring contamination rates in single-phase alloys, since hardness usually varies approximately linearly with oxygen content over the range of interest. However, in the tantalum-titanium alloys, oxygen induced a phase change by stabilizing the high-oxygen alpha-titanium phase. Thus, in these alloys, the hardness traverses do not vary linearly with oxygen content and cannot be employed for the calculation of contamination rates. The depth of contamination for these alloys in most cases exceeded the half-thicknesses of the samples. The traverses do, however, offer a convenient qualitative measure of the magnitude and depth of contamination hardening.

Contamination data are presented in Table 16 in terms of hardness increase over the base hardness. Figure 51 shows selected hardness traverse curves.

The contamination resistance of all nine complex alloys is superior to that of unalloyed tantalum and appears at least equivalent to that of the best binary tantalum-titanium alloy. The most contamination-resistant alloy of this group is Ta-40Ti-10Al. This alloy was hardened to a depth of about 0.02 cm (8 mils) during 14-1/2 hours' oxidation at 1000 C (1830 F). The corresponding contamination rate of 10^{-9} cm^2/sec is significantly lower than that for pure tantalum at the same temperature, 3.4×10^{-7} cm^2/sec.(1) The Ta-30Ti-5Al-5Cr alloy also exhibited relatively low hardening during oxidation but was not superior to the Ta-40Ti-10Al alloy.

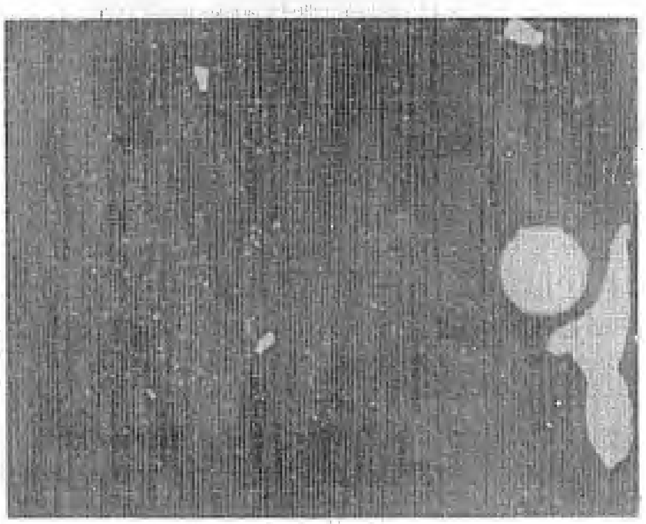
In general, the contamination data indicate that aluminum additions are most effective in reducing contamination hardening. Aluminum-chromium, aluminum-silicon, chromium, and silicon also reduce contamination hardening, with silicon being the least effective.

Microstructures of several selected alloys before and after oxidation at 1200 C (2190 F) are shown in Figure 52. In each case a surface layer of oxygen-saturated alpha-titanium is visible beneath the gray scale. The



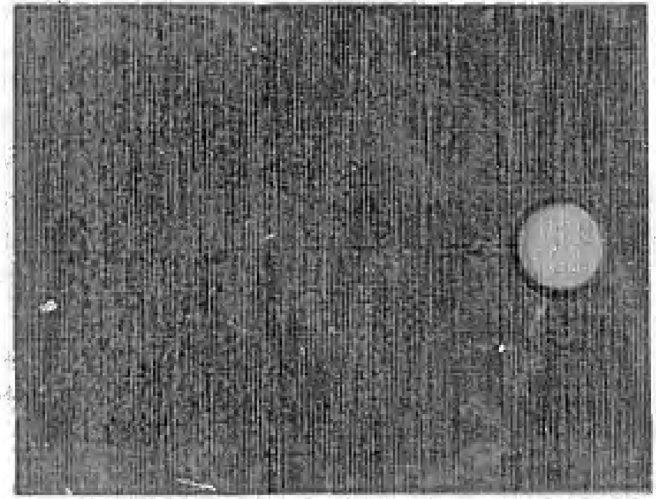
S-198

a. Ta-80Ti, 6 Hours at 1200 C (2190 F)



S-217

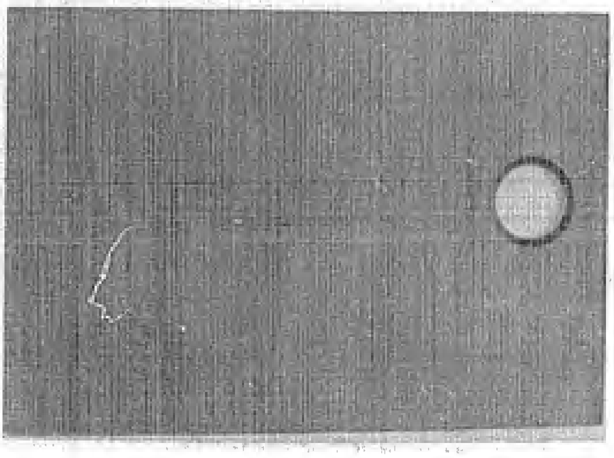
b. Ta-40Ti-10Al, 6 Hours at 1200 C (2190 F)



S-212

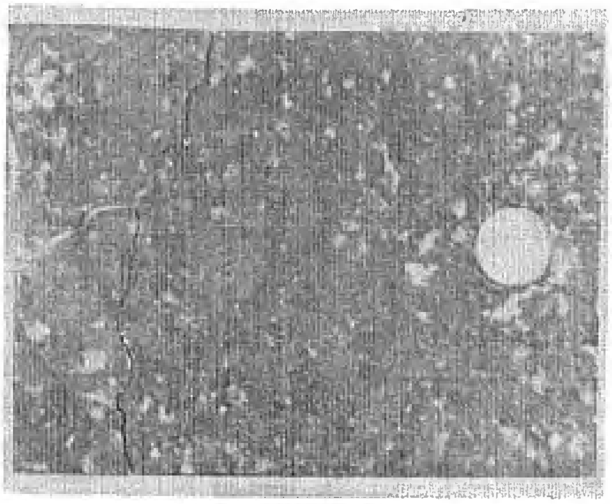
c. Ta-30Ti-5Al-5Cr, 6 Hours at 1200 C (2190 F)

FIGURE 48. PHOTOGRAPHS OF TANTALUM-TITANIUM-BASE ALLOYS AFTER OXIDATION



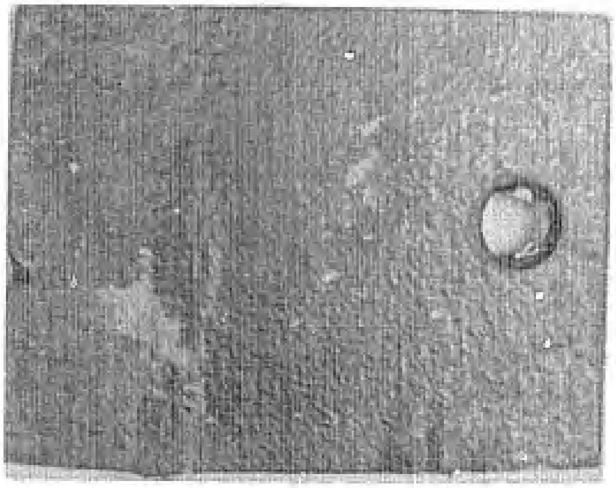
S-220

d. Ta-30Ti-10Cr, 6 Hours at 1200 C (2190 F)



S-218

e. Ta-40Ti-10Al, 6 Hours at 1400 C (2550 F)



S-219

f. Ta-30Ti-5Al-5Cr, 6 Hours at 1400 C (2550 F)

FIGURE 48. PHOTOGRAPHS OF TANTALUM-TITANIUM-BASE ALLOYS AFTER OXIDATION (Continued)

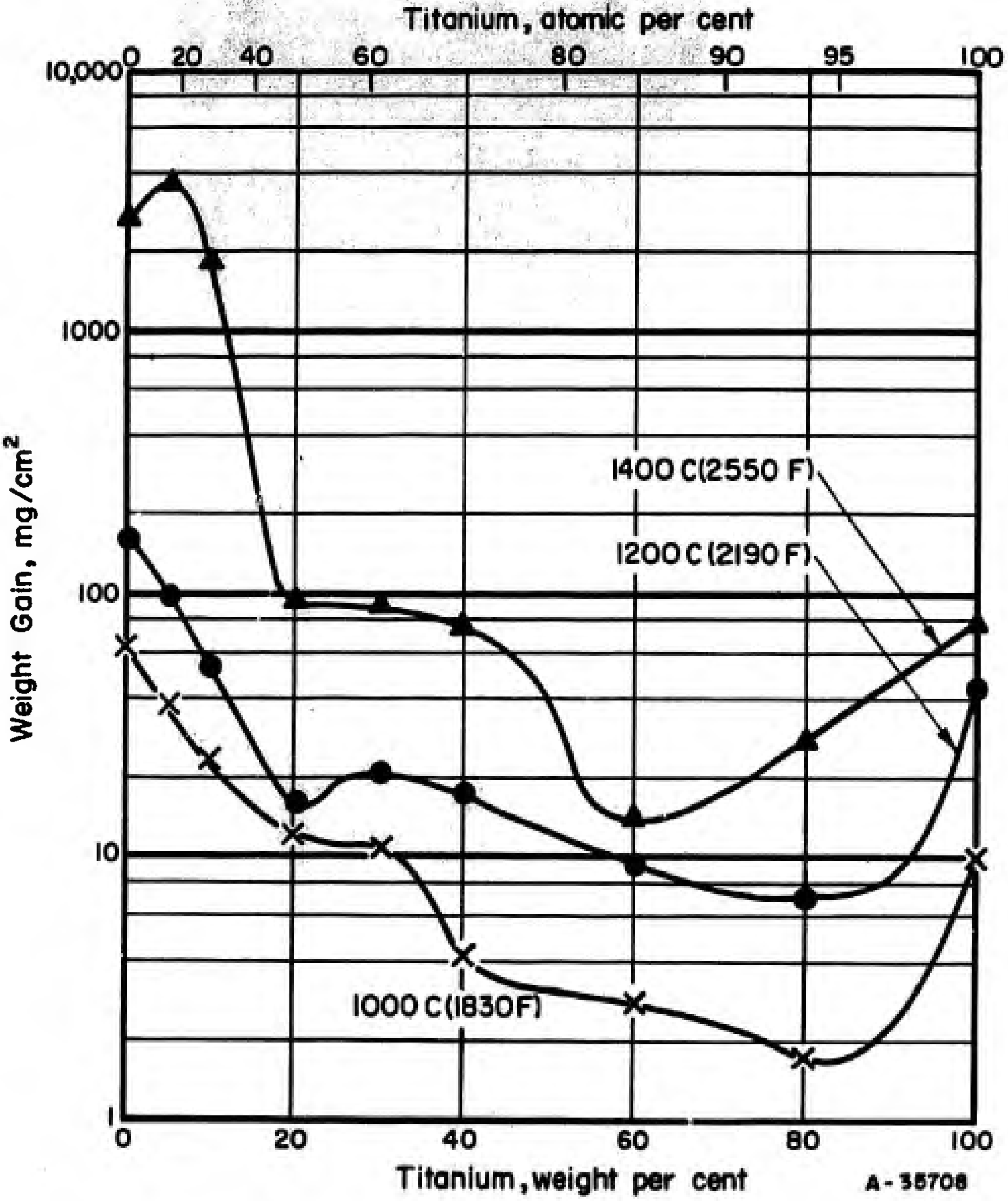


FIGURE 49. WEIGHT GAINS OF Ta-Ti ALLOYS OXIDIZED FOR 2 HOURS IN DRY AIR

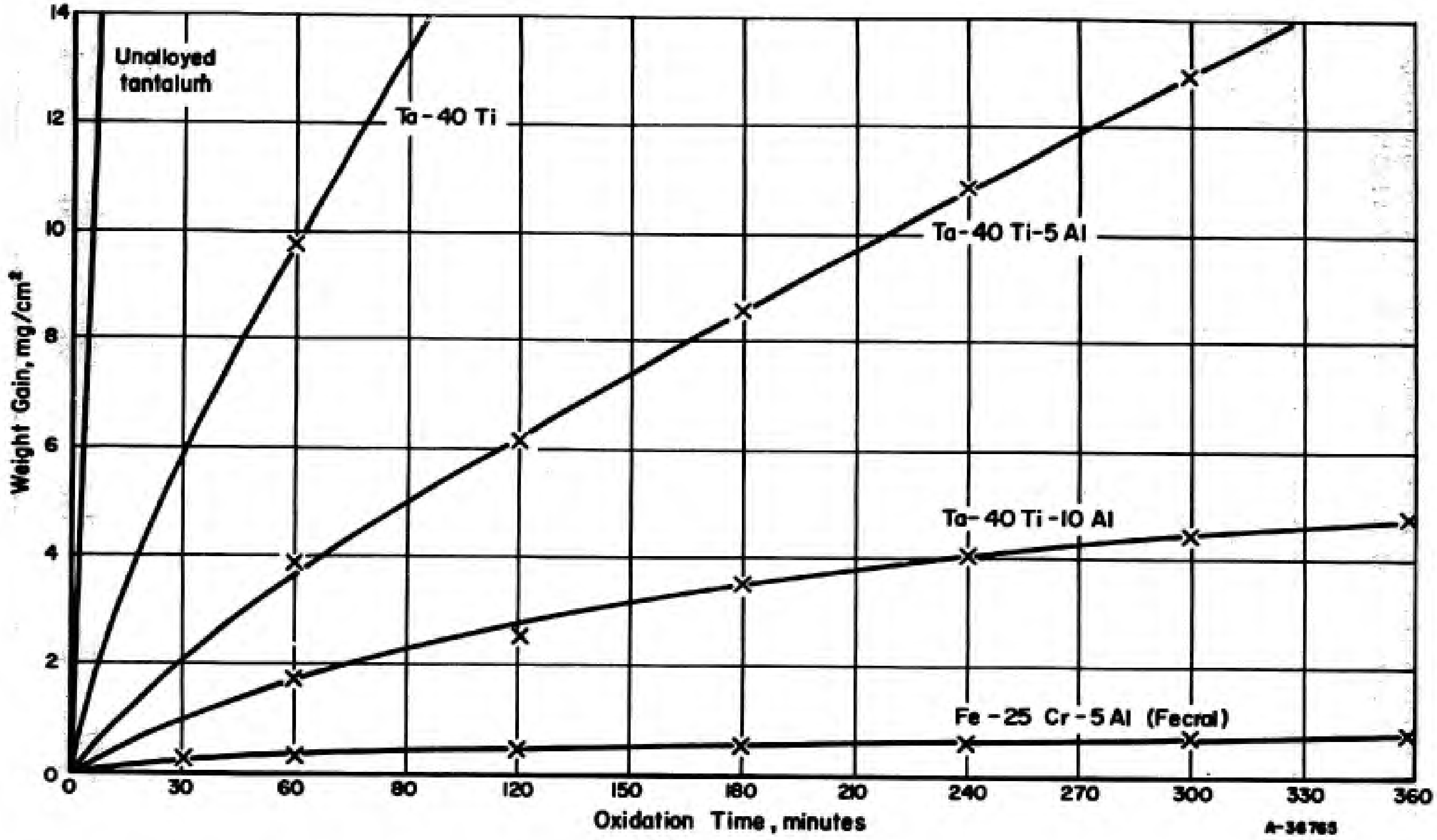


FIGURE 50. COMPARISON OF OXIDATION CURVES FOR TANTALUM, TANTALUM ALLOYS, AND FECRAL AT 1200 C (2190 F)

TABLE 16. CONTAMINATION HARDENING OF TANTALUM AND TANTALUM ALLOYS DURING AIR OXIDATION

Composition, weight per cent	Oxidation Time, hr	Hardness Increase Over Base at Indicated Depth, KHN 0.002 CM	0.01 CM	0.03 CM	Hardness of Annealed Alloy, VHN
		Oxidized at 1000 C (1830 F)			
100Ta[a]	15	286	272	246	(100)[b]
Ta-60Ti	6	450	335	204	181
Ta-80Ti	6	422	200	149	162
100Ti	15	740	493	399	(120)
Ta-30Ti-5Al	12	808	360	210	286
Ta-40Ti-5Al	15	433	175	100	257
Ta-40Ti-10Al	14.5	75	53	-2	405
Ta-30Ti-1Be	6	441	409	168	380
Ta-30Ti-5Cr	14.5	210	218	208	280
Ta-30Ti-10Cr	15	230	202	130	336
Ta-30Ti-1.5Si	16	546	274	166	370
Ta-30Ti-5Al-5Cr	15	116	93	61	373
Ta-30Ti-5Al-1.5Si	15	177	122	105	368
		Oxidized at 1200 C (2190 F)			
100Ta[a]	6	302	293	269	(100)
Ta-27Ti	2	(430)	374	(390)	210
Ta-60Ti	6	1001	561	416	181
Ta-80Ti	6	778	548	510	162
Ta-30Ti-5Al	6	726	468	339	286
Ta-40Ti-5Al	6	668	301	229	257
Ta-40Ti-10Al	6	202	143	58	405
Ta-30Ti-1Be	6	600	492	430	380
Ta-30Ti-5Cr	6	514	364	334	280
Ta-30Ti-10Cr	6	1664	354	254	336
Ta-30Ti-1.5Si	6	418	304	272	370
Ta-30Ti-5Al-5Cr	6	433	246	152	373
Ta-30Ti-5Al-1.5Si	6	370	286	286	368

TABLE 16. CONTAMINATION HARDENING OF TANTALUM AND TANTALUM ALLOYS DURING AIR OXIDATION (Continued)

Composition, weight per cent	Oxidation Time, hr	Hardness Increase Over Base at Indicated Depth, KHN 0.002 CM	0.01 CM	0.03 CM	Hardness of Annealed Alloy, VHN
		Oxidized at 1400 C (2550 F)			
100Ta[a]	6	320	314	298	(100)
Ta-40Ti-5Al	6	1273	468	692	257
Ta-30Ti-5Al-5Cr	6	1111	373	359	373

(a) Data for unalloyed tantalum are calculated from Reference 1.

(b) Hardness values in parentheses are estimated.

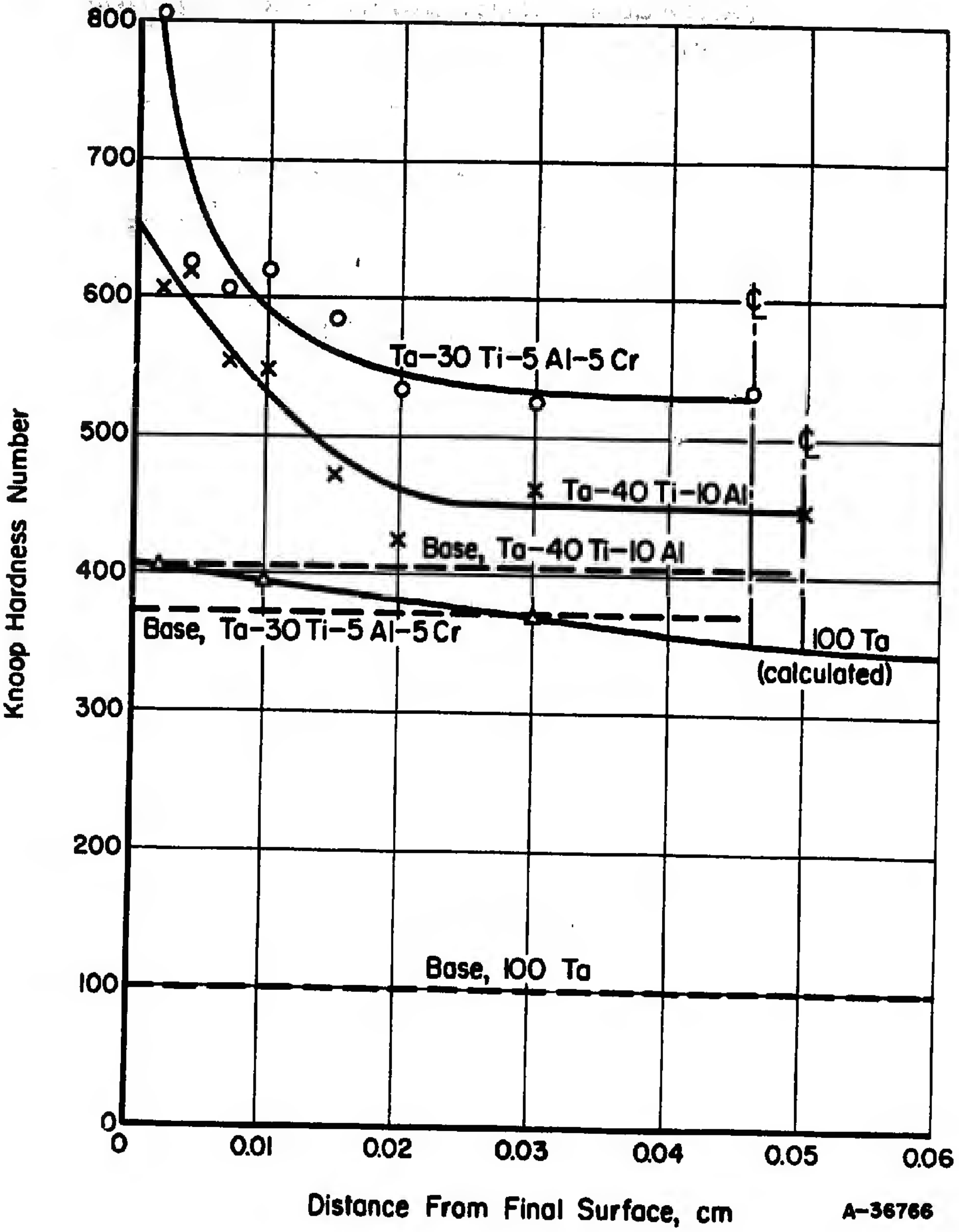
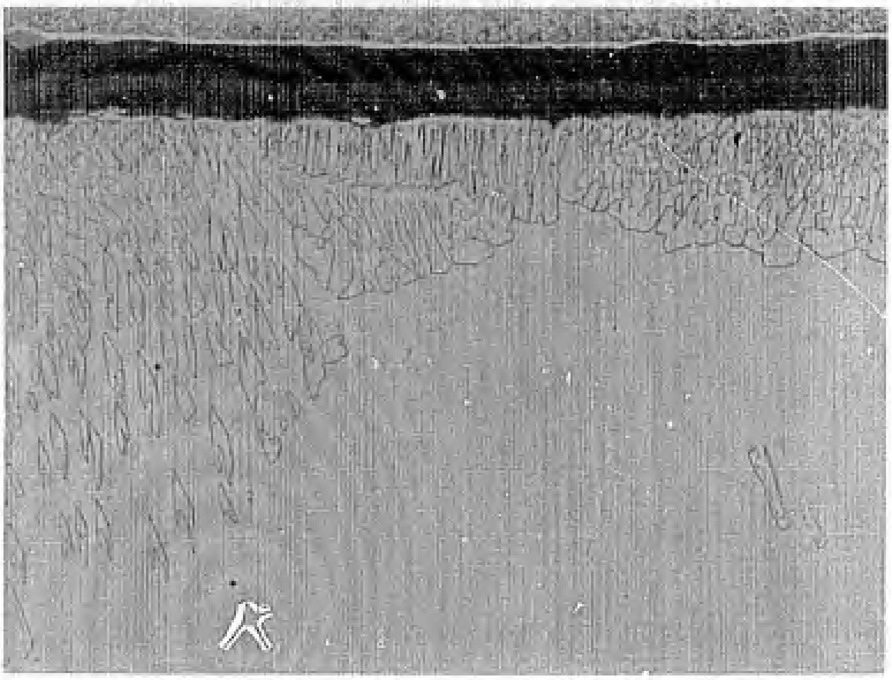


FIGURE 51. CONTAMINATION HARDENING OF TANTALUM AND TANTALUM ALLOYS OXIDIZED FOR 6 HOURS IN AIR AT 1200 C (2190 F)

500X N72575

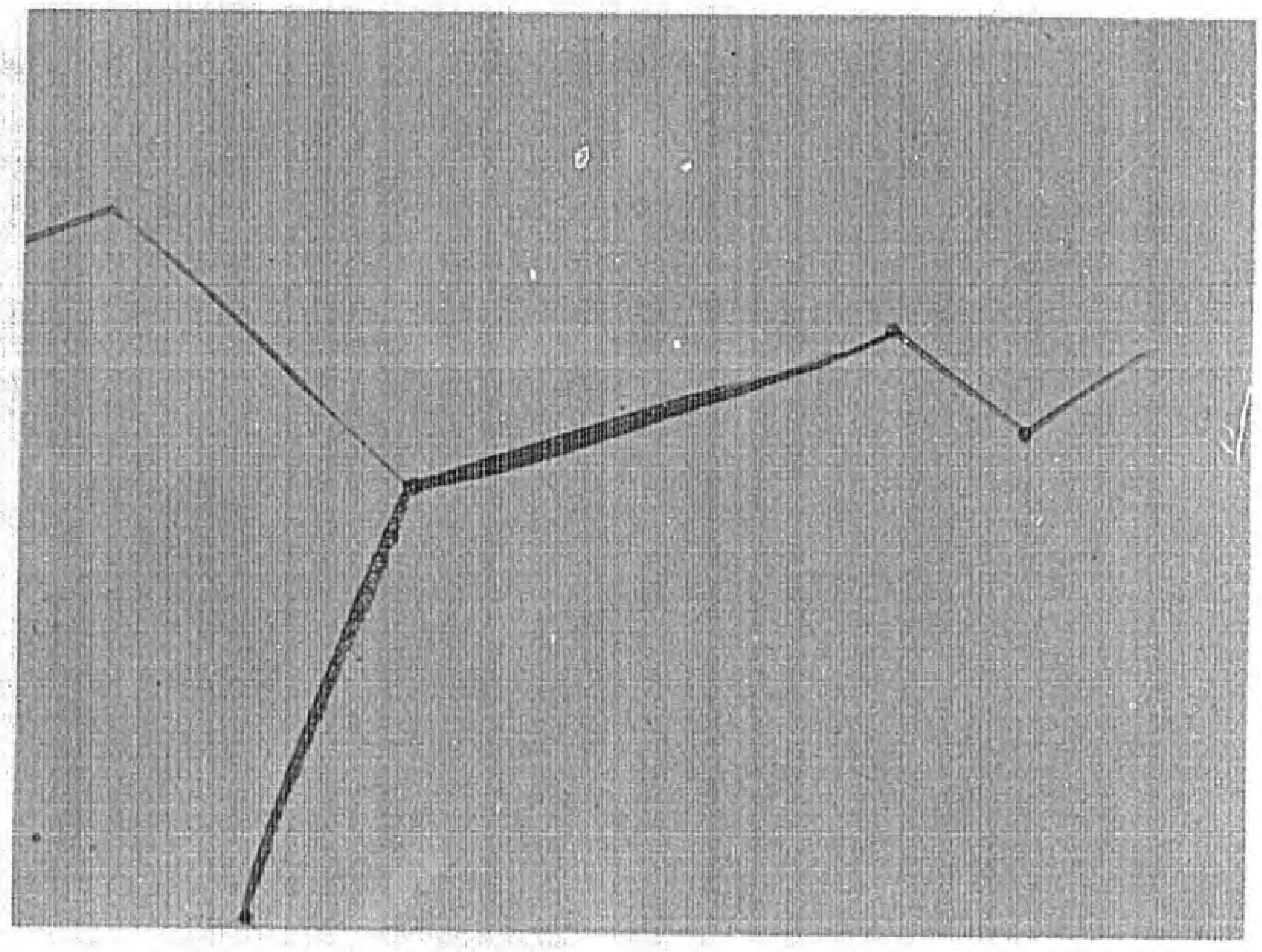
a. Ta-40Ti-10Al, Annealed 1 Hour at 1200 C (2190 F)



250X N73201

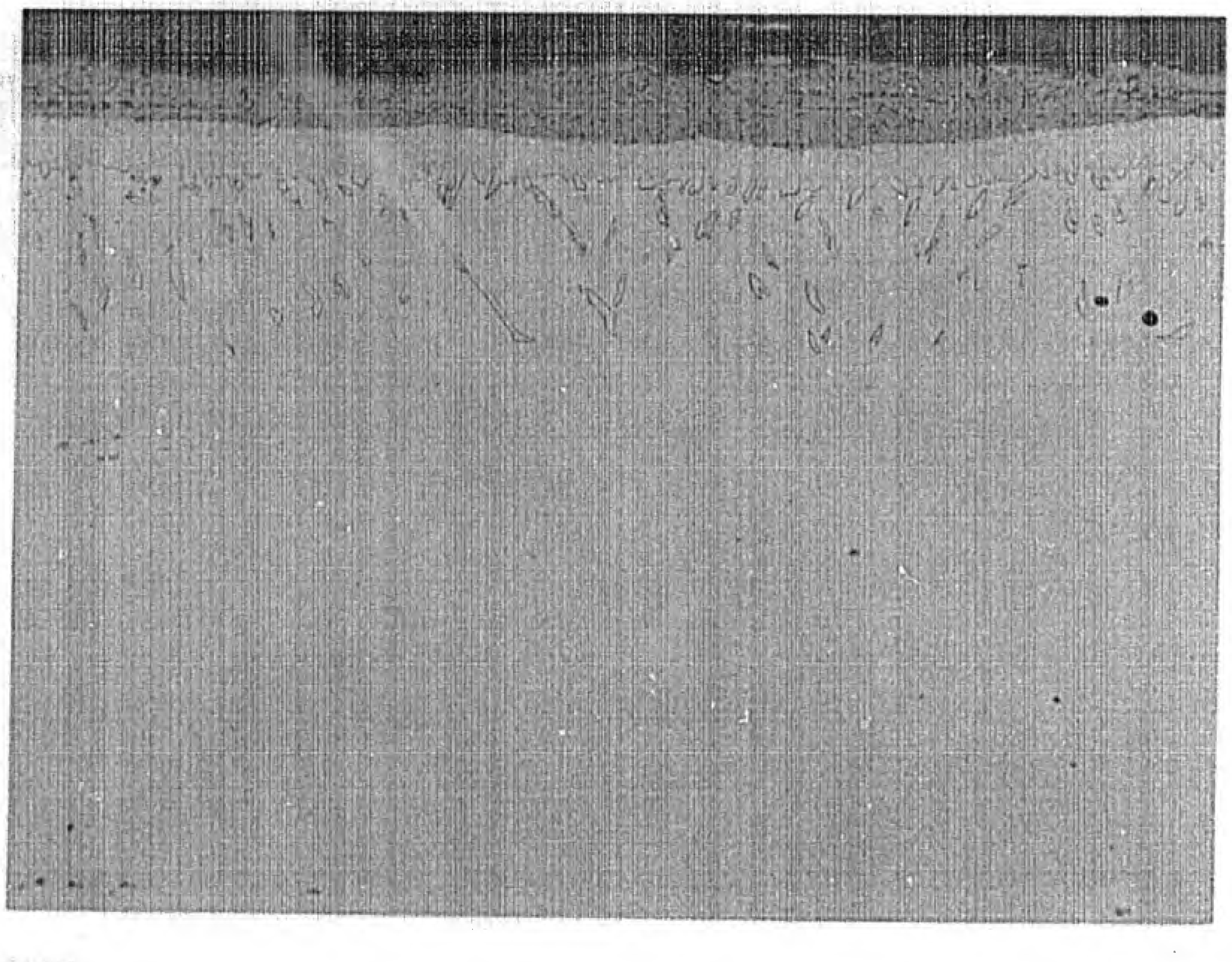
b. Ta-40Ti-10Al, Oxidized 6 Hours at 1200 C (2190 F)

FIGURE 52. MICROSTRUCTURES OF TANTALUM-TITANIUM-BASE ALLOYS AS ANNEALED AND AFTER OXIDATION AT 1200 C (2190 F)



500X N72580

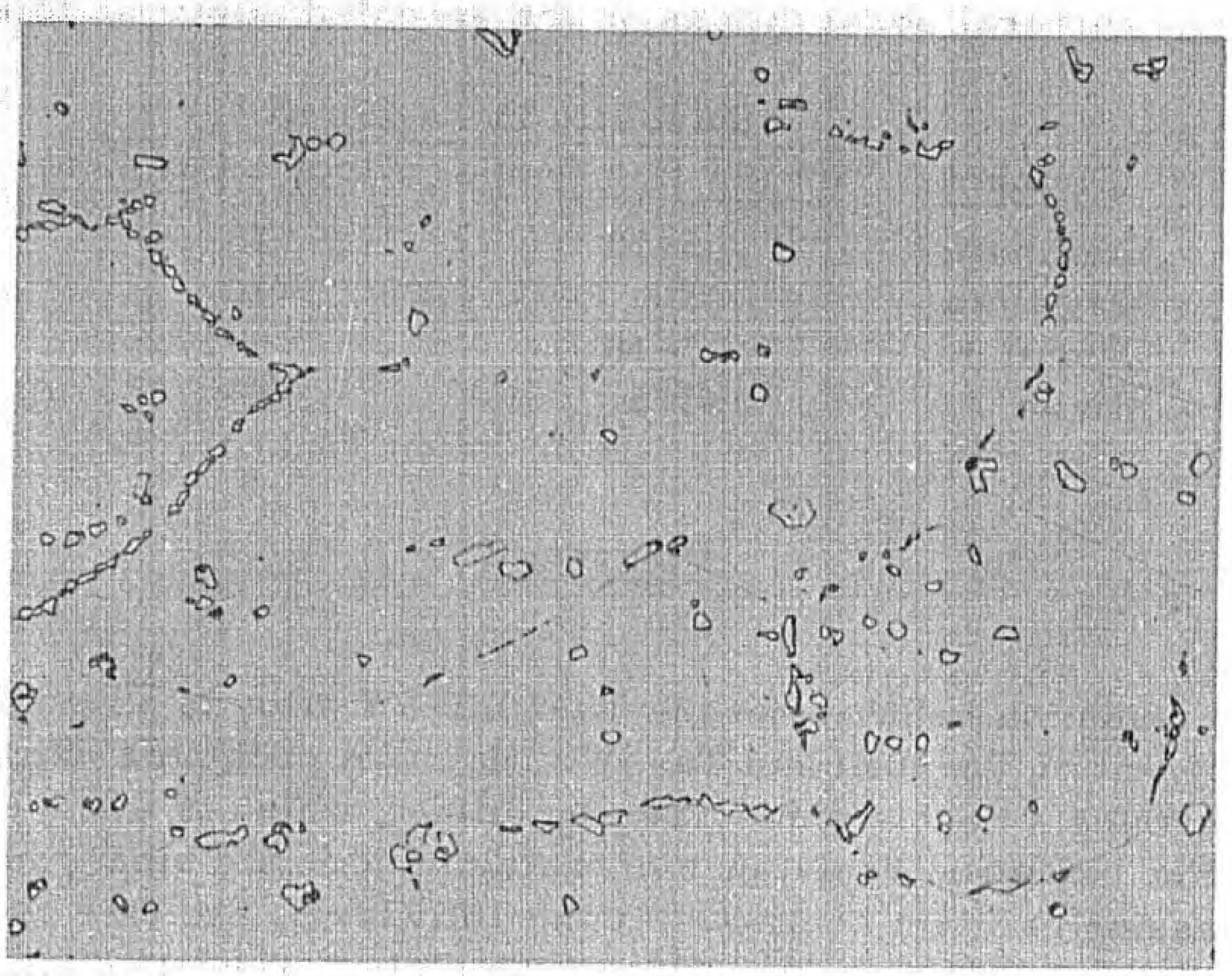
c. Ta-30Ti-5Al-5Cr, Annealed 1 Hour at 1200 C (2190 F)



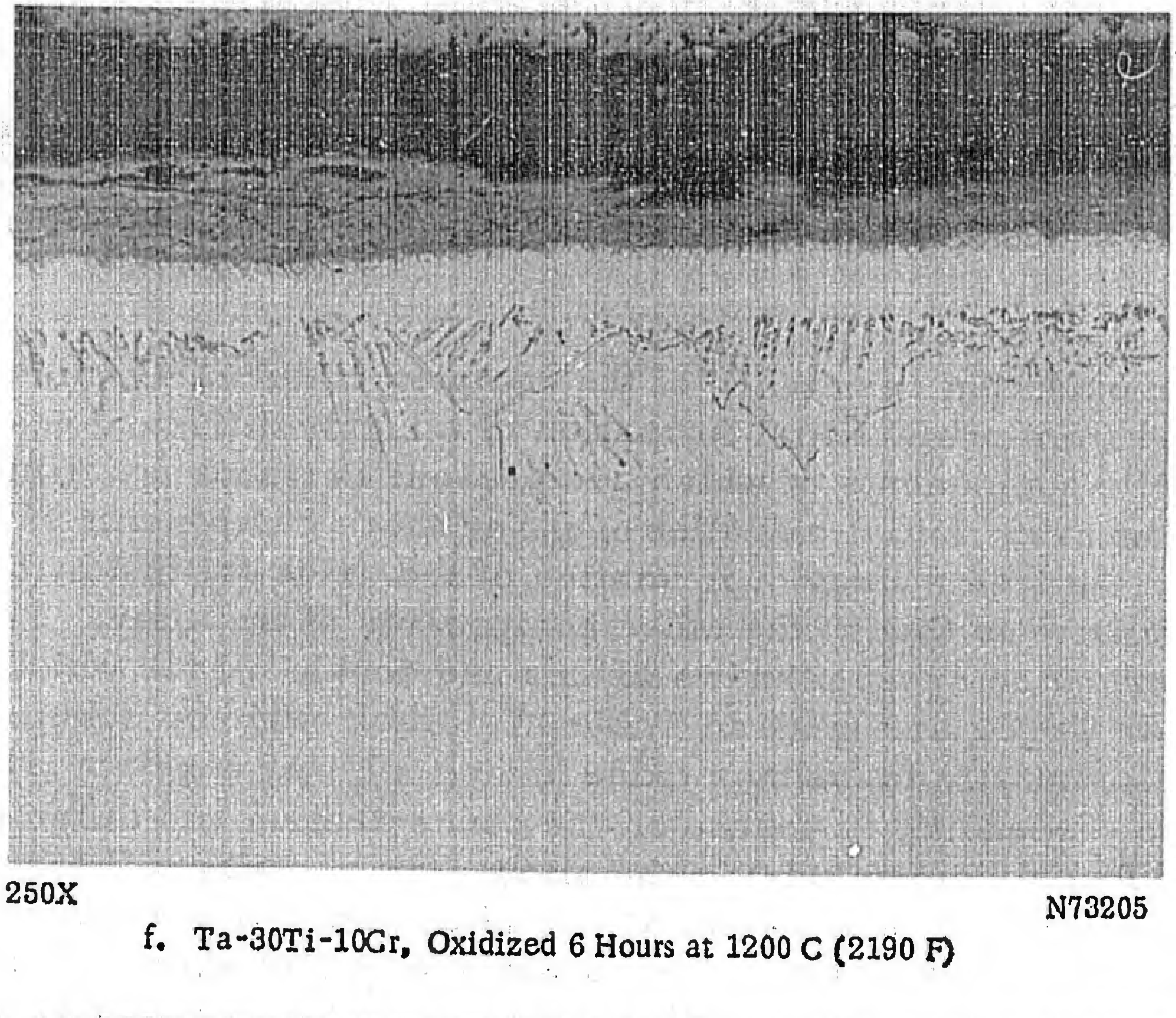
250X N73207

d. Ta-30Ti-5Al-5Cr, Oxidized 6 Hours at 1200 C (2190 F)

FIGURE 52. MICROSTRUCTURES OF TANTALUM-TITANIUM-BASE ALLOYS AS ANNEALED AND AFTER OXIDATION AT 1200 C (2190 F) (Continued)



e. Ta-30Ti-10Cr, Annealed 1 Hour at 1200 C (2190 F)



f. Ta-30Ti-10Cr, Oxidized 6 Hours at 1200 C (2190 F)

FIGURE 52. MICROSTRUCTURES OF TANTALUM-TITANIUM-BASE ALLOYS AS ANNEALED AND AFTER OXIDATION AT 1200 C (2190 F) (Continued)

solubilities for aluminum, beryllium, chromium, and silicon are estimated from microstructural observations on the annealed alloys as follows:

Element	Solubility in Ta-(30 to 40)Ti Weight Per Cent	 Atomic Per Cent
Aluminum	5-10	15-25
Beryllium	<1	<10
Chromium	5-10	9-17
Silicon	<1.5	<4

Discussion

The oxidation behavior of the Ta-10Hf-5W alloy is approximately an average of that of Ta-10Hf and Ta-5W. Hafnium promotes oxidation resistance by forming a double oxide, $Ta_2O_5 \cdot 6HfO_2$, which is more stable than Ta_2O_5. The oxidation resistance of tantalum-hafnium binary alloys increases with increasing hafnium content. At the 10Hf level, the rate at 1200 C (2190 F) is about half that of unalloyed tantalum. Tungsten, on the other hand, has only a slight effect on the oxidation behavior of tantalum up to the 30 per cent level. At 1200 C (2190 F), the ternary Ta-10Hf-5W alloy oxidizes about two-thirds as rapidly as unalloyed tantalum. Although the contamination behavior of this alloy has not yet been evaluated, the contamination rate at 1200 C (2190 F) may be expected to be about 10^{-7} cm^2/sec, compared with 10^{-6} cm^2/sec for unalloyed tantalum. This is based on the contamination behavior of the binary Ta-10Hf alloy, and would indicate a threefold reduction in the depth of contamination as compared with unalloyed tantalum.

The oxidation resistance of the complex tantalum-titanium-base alloys is derived from preferential formation of a highly diffusion-resistant scale, the metallic components of which are present as minor constituents of the alloy. The preferential oxidation of one or more components of an alloy is related to the free energy of formation of the oxide formed by the component(s) relative to that of the other components of the alloy. The free energies of formation of most known oxides and double oxides which are more stable than Ta_2O_5 are given in Table 17. Each oxide or double oxide will form preferentially to another oxide having a lower negative free energy of formation, depending of course on the concentration and diffusivity of the more stable oxide former(s) in the alloy. Thus, TiO_2 will form preferentially to Ta_2O_5 on a tantalum binary alloy containing a moderate amount of titanium. Since TiO_2 is more resistant to diffusion than Ta_2O_5 and is more stable mechanically, the oxidation behavior of Ta-Ti alloys is superior to that of unalloyed tantalum.

TABLE 17. THERMODYNAMIC STABILITIES OF OXIDES

Oxide Formula	Free Energy of Formation at 1500 K, kcal/g-atom of oxygen(a)	Melting Point	
		C	F
La_2O_3	-112.0	2320	4210
ThO_2	-112.0	3300	5970
Y_2O_3	-109.0	2400	4350
BeO	-108.3	2520	4570
$Be_3Zr_2O_5$	-107.8	2550	4620
$LaAlO_3$	-101.3	--	--
$YAlO_3$	-99.4	--	--
HfO_2	-99.0	2777	5030
$BeAl_2O_4$	-98.4	--	--
UO_2	-97.0	2800	5070
ZrO_2	-96.9	2715	4920
Al_2SiO_5	-95.5	(1815)(b)	(3300)
Al_2O_3	-95.1	2020	3670
Be_2SiO_4	-93.7	(1560)	(2840)
Al_2TiO_5	-89.3	1870	3400
Al_2MnO_4	-87.8	(1560)	(2840)
$ZrSiO_4$	-85.1	2430	4405
CeO_2	-84.8	--	--
$LaCrO_3$	-83.5	--	--
Al_2FeO_4	-81.4	(1440)	(2625)
TiO_2	-80.6	1860	3380
Al_2NiO_4	-79.0	2020	3670
Al_2CoO_4	-78.8	1960	3560
Fe_2TiO_4	-76.6	--	--
$LaMnO_3$	-76.6	--	--
$MnTiO_3$	-75.6	(1360)	(2480)
SiO_2	-73.2	1713	3120
Mn_2TiO_4	-73.1	1450	2640
$MnSiO_3$	-72.6	(1270)	(2320)
Mn_2SiO_4	-72.3	(1340)	(2445)
$LaFeO_3$	-71.3	--	--
$FeTiO_3$	-68.3	1470	2680
YVO_4	-68.0	--	--
Ta_2O_5	-66.9	1890	3435

(a) Heat of combination for double oxides included where known.

(b) Values in parentheses are estimated.

The oxides forming on the complex tantalum-titanium-base alloys most probably include Al_2TiO_5 and Al_2SiO_5, both of which are seen to be appreciably more stable than either TiO_2 or Ta_2O_5. The resistance to diffusion and thus to oxidation afforded by the aluminum-containing double oxides is related to the high electrical resistivity of Al_2O_3 and the fact that Al_2O_3 is an ionic conductor rather than a semiconductor as are both Ta_2O_5 and TiO_2.

Data upon which this report is based may be found in Battelle Laboratory Record Books No. 14736, pp 1-100; No. 14769, pp 1-100; No. 15412, pp 1-100; No. 15591, pp 1-100; No. 16057, pp 1-100; No. 16217, pp 1-100; No. 16925, pp 1-92; No. 17451, pp 1-37; and No. 17491, pp 1-65.

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