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THE EFFECT OF ALLOY CONTENT, CARBON, OXYGEN, AND NITROGEN
ON THE MECHANICAL PROPERTIES OF URANIUM-2.2 wt% NIOBIUM AND
URANIUM-0.75 wt% TITANIUM WROUGHT HEAT TREATED ALLOYS

John G. Avery

DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT(29-1)-1106

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Printed in the United States of America
Available from the
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

Printed
March 1, 1973

RFP-1950
UC-25 METALS, CERAMICS,
AND MATERIALS
TID-4500 (59th Ed.)

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DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

SUBJECT DESCRIPTORS

Casting
Uranium alloys
Tensile properties

Prepared under Contract AT(29-1)-1106
for the
Albuquerque Operations Office
U. S. Atomic Energy Commission

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ACKNOWLEDGMENTS

The author wishes to thank Mr. R. Jamsay, Jr. and Mr. J. F. Norris for their valuable suggestions on casting and fabricating techniques for the experimental alloys and for performing the actual casting and fabricating work.

THE EFFECT OF ALLOY CONTENT, CARBON, OXYGEN, AND NITROGEN ON THE MECHANICAL PROPERTIES OF URANIUM-2.2 wt% NIOBIUM AND URANIUM-0.75 wt% TITANIUM WROUGHT HEAT TREATED ALLOYS

John G. Avery

Abstract. A series of uranium-niobium alloys was prepared with 1.8 wt% niobium composition and varying amounts of carbon, oxygen, and nitrogen. A similar series of uranium-titanium alloys was also prepared with the titanium content both above and below the desired 0.75 wt% level.

The final chemical compositions of the various alloys were related to their heat treated mechanical properties. It was found that carbon was detrimental to ductility in both uranium-niobium and uranium-titanium alloys, but did not affect the yield or ultimate strengths. In the uranium-titanium alloy, variations in titanium content affect the yield and ultimate strengths. The uranium-titanium alloy exhibited a "gettering" action in which part of the carbon was removed by titanium.

INTRODUCTION

Interest has been created in the dilute uranium alloys uranium-2.2 wt% niobium and uranium-0.75 wt% titanium.

These dilute alloys are heat treatable and attain high mechanical strength while retaining ductility.¹⁻⁴ Literature indicated that small variations in alloy content and/or impurity content might substantially alter the mechanical properties after heat treatment.

Three impurities are especially significant in induction cast uranium; carbon, oxygen, and nitrogen. Oxygen and nitrogen are introduced into the melt during the run, the amount depending on the leak rate of the furnace. The use of graphite crucibles, in vacuum at high temperatures, results in a partial pressure of carbon sufficient to cause pick-up in the melt. All three of these elements form compounds with niobium and titanium, and reduce the amount of alloying element available to participate in aging reactions.

It was desirable to learn what effect these chemical variations would have on the mechanical properties of the final product. This would allow a realistic production chemical specification to be written for the two alloys.

CONCLUSIONS

1. The uranium 2.2 wt% niobium alloy is susceptible to impurity pick-up.
2. In heat treated uranium 2.2 wt% niobium alloys, high impurity levels (oxygen-plus-nitrogen-plus-carbon >400 ppm) result in approximately a 50% decrease in ductility compared to uranium 2.2 wt% niobium with low (oxygen-plus-nitrogen-plus-carbon <150 ppm) impurity levels.
3. In the uranium-0.75 wt% titanium alloy a gettering reaction occurs in the melt that reduces carbon and nitrogen. Oxygen appears to stay in the melt and end up in the cast alloy.
4. The extent of carbon removal in uranium-0.75 wt% titanium is dependent on the initial titanium content. The higher the carbon, the more titanium is required to reduce the carbon to a fixed level. Carbon removal from 200 ppm down to 40 ppm by gettering with titanium results in a titanium loss of up to 0.1 wt%.
5. Ultimate tensile strength and yield strength in heat treated uranium-titanium alloys depend on the final titanium content and not on the impurity levels.
6. Elongation and reduction of area in uranium-titanium alloys heat treated as indicated in this study are dependent on carbon content. Increasing the carbon from 10 to 40 ppm decreases the ductility by about 50%. Other aging treatments may result in less sensitivity to carbon.
7. The oxygen-plus-nitrogen content cannot be significantly controlled below 50 ppm in induction cast uranium-titanium alloy.
8. Inoculation of uranium-2.2 wt% niobium alloys with 1000 ppm of titanium appears to reduce the impurity level and result in better overall mechanical properties.

EXPERIMENTAL PROCEDURE

A series of alloys was designed that covered most of the ranges of alloy and impurity content which might occur in production. They are shown in Table 1.

Table 1. Alloys Selected for Investigation.

Alloy No.	Alloy (wt%)	Carbon (ppm)	O + N (ppm)
1	1.8 Nb	150-200	Normal ^Δ
2	1.8 Nb	150-200	>300
3	1.8 Nb	Normal*	>300
4	0.60 Ti	Normal†	Normal [°]
5	0.90 Ti	Normal	Normal
6	0.60 Ti	150-200	>300
7	0.90 Ti	150-200	>300
8	0.90 Ti	150-200	Normal
9	0.50 Ti	Normal	Normal
10	2.2 Nb (+ 1000-ppm Ti)	Normal	Normal

^ΔNormal oxygen plus nitrogen content for induction cast U-Nb alloys made from virgin D-38 and using "good casting practice" is less than 150 ppm.

*Normal carbon levels in induction cast U-Nb alloys made from virgin D-38 and using "good casting practices" are 60 to 90 ppm.

†Normal carbon levels in induction cast U-Ti alloys made from virgin D-38 and using good casting practices are 10 to 30 ppm.

[°]Normal oxygen plus nitrogen content for induction cast U-Ti alloys made from virgin D-38 using good casting practice is less than 200 ppm, with the O-to-N ratio about 10 to 1.

All niobium alloys except No. 10 were on the low side in niobium. Prior work² had shown that in uranium-titanium alloys a gettering of carbon by titanium occurs; and it was hoped that the same reaction might clean carbon out of the uranium-niobium alloy. Alloy No. 10 was inoculated with 1000-ppm titanium to determine if the titanium would remove impurities.

Casting

All castings were melted and poured in an induction heated vacuum furnace. The charges for the uranium-niobium alloys were made by blending vendor supplied commercially pure depleted uranium with arc-cast uranium-2.3 wt% niobium. The charges for the uranium-titanium alloys were made by blending commercially pure depleted uranium with uranium-1.72 wt% titanium made by arc casting. To obtain a given carbon level, an induction cast depleted uranium master alloy containing 4000-ppm carbon was blended with the other feed. In alloy No. 10 the titanium was added to the induction charge as a 0.060-in.-thick strip.

Air was introduced into the furnace by hooking a flow meter to a vacuum port on the furnace and allowing a given amount of air to flow into the furnace. Initial tests determined that a furnace leak rate of 50 cfh would give around 300-ppm oxygen-plus-nitrogen in induction cast depleted uranium. For alloys which were to have high gas, this 50-cfh leak rate was used during the run. When normal levels of carbon and/or oxygen-plus-nitrogen were desired, the term "good casting practice" will be used to indicate that no additions of the impurity in question were made.

Castings were 3-in. diameter by 9-in. long. By establishing a proper thermal gradient in the mold and hot topping, directional solidification would occur. Directional solidification from the bottom to the top of the ingot should enhance the removal of impurities from the solidifying metal by floatation.

Fabricating

The castings were machined to 2.5-in. diameter by 6-in. long (the top portion being removed). At this time, chemistry samples were taken as shown in Figure 1. The extra, top-top sample from each uranium-titanium ingot was taken to determine the extent of floatation of impurities in this alloy. Previous work⁵ had indicated a tendency for titanium to react with carbon, oxygen, and nitrogen, forming solid phase compounds which floated to the top of the casting during directional solidification.

The machined billets were forged to 2-in. squares at 950°C. They were then rod rolled to approximately 0.625-in squares at 950°C. Heating was done in a salt bath to decrease oxidation. Most of the rods from each alloy were swaged at 200°C to 0.59 inch in diameter. Several intermediate anneals at 850°C were required. These were done in vacuum to allow removal of any hydrogen picked up from the salt bath. Tensile bars were machined from the 0.59-in.-diameter bars, heat treated, and tensile tested.

RESULTS AND DISCUSSION

Chemical Composition

Table 2 shows the chemical analyses of the uranium-niobium ingots and Table 3 shows the analyses for the uranium-titanium ingots.

Examination of Table 2 brings the following factors to light: With good furnace practice, carbon (Alloy 3),

Figure 1. Locations of Chemistry Samples Taken from Uranium-Niobium and Uranium-Titanium Alloy Castings.

Table 2. Chemical Composition of Uranium-Niobium Alloys Cast to Compositions Shown in Table 1.

Alloy No.	Nb wt%		C (ppm)		O (ppm)		N (ppm)	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
1	1.80	1.77	180	220	35	60	20	50
2	2.09	2.00	160	170	75	120	30	80
3	1.76	1.71	90	80	55	120	25	90

Table 3. Chemical Composition of Uranium-Titanium Alloys Cast to Compositions Shown in Table 1.

Alloy No.	Ti wt%			C (ppm)			O (ppm)		N (ppm)		O (ppm)		N (ppm)	
	Top-Top	Top	Bottom	Top-Top	Top	Bottom	Top-Top	Top	Top-Top	Top	Bottom	Bottom	Bottom	Bottom
4	—	.58	.60	—	15	25	—	—	60	15	50	14		
5	.80	.80	.80	15	30	25	60	2	60	13	60	9		
6	.75	.50	.51	40	60	40	45	10	55	10	50	15		
7	.74	.79	.79	13	32	17	60	10	40	15	60	5		
8	.84	.76	.76	10	40	40	15	8	60	1	40	2		
9	.76	.48	.46	2	40	40	40	1	60	14	40	12		

and oxygen-plus-nitrogen (Alloy 1) both fall between 70 and 95 ppm. In Alloys 1 and 2 the aimed-for-value of 150 to 200-ppm carbon was realized. In Alloys 2 and 3 (high oxygen-plus-nitrogen), the desired level of 300 ppm was not attained. However, the combined carbon, oxygen, and nitrogen in all three uranium-niobium alloys (with carbon added and/or furnace leaking) is near the values which in uranium-6 wt% niobium causes forming and machining problems.⁴

A more interesting behavior is exhibited by the titanium alloys. The titanium alloys cast with good furnace practice show the typical low values of carbon indicated in Table 1. The oxygen-to-nitrogen ratio, as calculated from Table 3, was about 10 to 1, which agrees with previous findings.⁵ The combined oxygen-plus-nitrogen values were generally about one-half that found in larger uranium-titanium castings. This indicates that the oxygen pick-up is time dependent since larger castings require longer holding times. Metallographic examination indicates that most of the oxygen is present in the form of oxides (Figure 2). That a majority of inclusions are oxides is in agreement with previous findings.¹

Figure 2. Inclusions in Uranium-Titanium Alloy which Appear to be Primarily Titanium Oxides. 100X unetched.

In the uranium-titanium alloys with carbon and/or gas additions, the removal of these impurities by titanium is shown graphically in Figures 3 and 4, respectively.

Figure 3. Range of Final Carbon Content as a Function of Initial Titanium Content.

Figure 4. Oxygen Plus Nitrogen Content as a Function of Initial Titanium Content.

Figure 3 shows the carbon content of the ingots (after casting) as a function of the initial titanium content of the feed. In ingots made with good furnace practice, the final

carbon level is the same for both 0.6 wt% titanium and 0.9 wt% titanium. When high impurity levels are introduced (oxygen-plus-nitrogen-plus-carbon >450 ppm), the 0.9 wt% titanium reduces the impurity level to that of material made with good casting practice. At the same time the titanium content drops about 0.1 wt%. Even in the case of 0.6 wt% titanium with high impurity levels, the final carbon content (40 to 60 ppm) is far below the uranium-2.2 wt% niobium alloy carbon values (150 to 200 ppm).

Table 3 does not show high titanium or impurity levels in the extreme tops of the ingots (column Top-Top). Therefore, this gettering effect is probably occurring in the melt in the crucible, with the impurities entering the skull before pouring of the melt. (The skull is a layer of light-weight solid components such as oxides which form a layer on top of the molten metal.)

Figure 4 shows the final oxygen-plus-nitrogen content of the ingots as a function of initial titanium content. It did not appear to matter whether a good or a poor vacuum was used

because the oxygen-plus-nitrogen levels for all alloys were similar (50 to 70 ppm).

Table 4 shows the chemical composition of the uranium-2.2 wt% niobium alloy made with good casting practice and inoculated with 1000-ppm titanium. Compared to the other uranium-niobium alloys, the carbon, oxygen, and nitrogen values are very low. If the titanium was acting as a getter, the residual titanium should be below the reported figure. This level of titanium has never been of interest at Rocky Flats and therefore standards were not available to accurately determine the level.

Mechanical Properties

Table 5 shows the mechanical property results for the ten alloys, along with the ranges. Table 6 shows properties for uranium-0.75 wt% titanium and uranium-2.2 wt% niobium made with good casting practice. The alloys in Tables 5 and 6 were heat treated as follows: niobium alloys were heated to 800°C and held 5 minutes followed by a water

Table 4. Chemical Composition of Uranium-2.2 wt% Niobium Alloy Inoculated with 1000-ppm Titanium.

Top	Bottom	C (ppm)		Alloy No. 10 O (ppm) N (ppm)		O (ppm) N (ppm)		Ti (ppm)
		Top	Bottom	Top	Bottom	Top	Bottom	
2.40	2.44	30	45	30	40	35	65	1000

Table 5. Heat Treated Mechanical Properties of Uranium-Niobium and Uranium-Titanium Alloys.

Alloy	UTS (ksi)		0.2% YS (ksi)		Elongation (%)		RA (%)		Modulus (ksi × 10 ⁶)	
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
1	193.5	+1.6 -3.5	121.1	+8.7 -4.1	3.2	+0.4 -0.8	2.53	+1.3 -1.2	21.6	+2.9 -2.0
2	203.5	+0.5 -0.5	125.7	+4.0 -3.3	4.3	+0.3 -0.3	3.75	+1.25 -1.25	19.75	+1.6 -1.7
3	198.4	+0.5 -1.1	122.5	+5.0 -3.2	3.1	+0.1 -0.3	2.5	+0 -0	21.8	+0.4 -0.6
4	193.1	+0.6 -1.3	126.8	+5.8 -5.2	9.3	+1.5 -1.1	9.5	+1.6 -0.8	20.8	+0.9 -1.4
5	224.8	+1.9 -1.7	151.8	+0.7 -0.6	6.0	+0.2 -0.2	6.85	+0.7 -0.65	21.8	+0.1 -0.1
6	185.4	+3.1 -3.1	103.7	+0.7 -0.7	11.9	+2.5 -2.5	10.0	+1.1 -1.3	19.45	+1.75 -0.5
7	232.1	+2.9 -2.1	147.3	+2.2 -4.5	10.5	+0.7 -1.2	8.3	+1.6 -2.0	20.5	+0.7 -1.1
8	225.8	+1.0 -1.4	145.3	+4.9 -5.7	7.6	+0.8 -0.4	6.3	+1.2 -1.3	24.6	+0.1 -3.4
9	154.2	+5.2 -4.2	85.7	+2.3 -4.1	9.4	+1.0 -2.4	8.7	+2.4 -2.5	18.3	+0.6 -0.4
10	228.0	+7.9 -9.5	154.1	+8.1 -4.8	6.1	+0.7 -1.1	6.4	+1.2 -1.1	21.8	+0.6 -0.6

Table 6. Mechanical Properties of U-2.2 wt% Niobium and U-0.75 wt% Titanium Made with Good Casting Practices.

Alloy	UTS (ksi)	0.2% YS (ksi)	Elong (%)	RA (%)	E (ksi $\times 10^6$)
2.2 Nb	195	130	8	7	20
0.75 Ti	210	130	13	13	20

quench, then vacuum-aged at 430°C for 48 hours. Titanium alloys were heated to 800°C and held 5 minutes followed by a water quench, then vacuum-aged at 350°C for 48 hours.

Examination of the mechanical property data of the uranium-niobium alloys of Tables 5 and 6 shows that the alloys which contain gas or carbon additions (Alloys 1, 2, and 3, Table 5) have ultimate- and yield-strengths similar to the uranium-niobium alloy (Table 6) which was made with good furnace practice. Ductility and reduction of area for all the alloys containing impurity additions are less than one-half that of the uranium-niobium alloy made with good furnace practice.

Alloy No. 10, the uranium-2.2 wt% niobium which had 1000-ppm titanium added, had mechanical properties slightly superior to those of the uranium-niobium alloy made with good furnace practice (Table 6). At the same time the ductility in this alloy did not significantly decrease. Whether this is due to the very low impurity levels found in the alloy, or the formation of a ternary alloy system is unknown. Further work in this area is under way.

As already discussed, the uranium-titanium alloys all have low impurity contents because of the gettering action of titanium. The ultimate tensile strength (UTS) and yield strength (YS) appear to be dependent on the final titanium content, as seen in Figure 5. As shown previously, the

Figure 5. Mechanical Properties of Uranium-Titanium Alloys as a Function of Titanium Content.

final titanium content is governed by the initial titanium content and the amount of titanium removed with impurities.

Carbon content and gas content affect the ultimate and yield strengths only to the extent that they remove titanium from the melt. The final residual level of carbon does not affect the ultimate or yield strengths. This can be seen by comparing the carbon levels of Alloys 4 through 9 of Table 5, to which impurity additions were made, with the uranium titanium alloy of Table 6, made with good furnace practice. Their respective carbon levels are found in Table 3 (page 3) and Footnote (†) (page 2).

There are not sufficient differences in the combined oxygen-plus-nitrogen-plus-carbon values of the titanium alloys with and without gas additions to determine the effect of total residual impurity level on mechanical properties.

The elongations of the uranium-titanium alloys exhibit a variable behavior as a function of carbon content. The general range of elongations in the alloys with carbon additions is about one-half that of the uranium-titanium made with good furnace practice (Table 6). The elongation as a function of carbon is shown in Figure 6. The carbon difference between the alloys containing carbon additions and the alloy made with good furnace practice is 20 to 50 ppm (40 to 70 ppm in the carbon-addition alloys, and 10 to 20 ppm in the alloy made with good furnace practice). Therefore, it appears that in uranium-titanium alloys the level of carbon has a very important effect on elongation, at least at the strength levels obtained in this heat treatment. Oxygen-plus-nitrogen, on the other hand, cannot be reduced by good casting practice. As a result, oxygen-plus-nitrogen content will affect all induction-cast uranium-titanium to the same extent.

Figure 6. Elongation of Wrought Heat Treated Uranium-Titanium as a Function of Carbon Content.

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