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ABSTRACT

The uranium-2 weight percent molybdenum alloy was prepared, processed, and age hardened to meet a minimum 930-MPa yield strength (0.2%) with a minimum of 10% elongation. These mechanical properties were obtained with a carbon level up to 300 ppm in the alloy. The tensile-test ductility is lowered by the humidity of the laboratory atmosphere.

CONTENTS

SUMMARY

The purpose of this study was to develop minimum mechanical properties in the uranium-2 weight percent molybdenum alloy (U-2 Mo) of 930 MPa for the yield strength (0.2%) with a minimum 10% elongation. These desired properties were obtained by proper processing, alpha rolling from an argon-atmosphere furnace, then solution treating at 800° C, water quenching, and aging at 300° C. A carbon level in the alloy of up to 300 ppm was acceptable; but, at higher levels, there was a loss in ductility. Also determined was the fact that the alloy is particularly susceptible to lowered ductility caused by humidity in the laboratory atmosphere.

INTRODUCTION

The mechanical properties of uranium can be improved markedly by alloying the metal, followed by an appropriate heat treatment. In general, low-level alloys of the gamma-miscible elements in uranium can be solution treated, water quenched, and then age hardened to obtain alloys with a relatively high strength and good ductility for engineering applications. This particular study at the Oak Ridge Y-12 Plant[a] was made to examine this generality and the accompanying mechanical properties with respect to the U-2 Mo alloy. More specifically, the attempt was to provide a minimum yield strength (0.2%) of 930 MPa with a minimum elongation of 10%.

Mechanical properties of the uranium-molybdenum alloy system up to 15 wt % molybdenum have been examined at the Atomic Weapons Research Establishment (AWRE) in Aldermaston, England.[1] Tensile test results were reported on specimens that were oil quenched and mercury quenched from the gamma region. The strength level developed with the U-2 Mo alloy was high, but with an accompanying low ductility. There was no age hardening in this study. Eckelmeyer demonstrated age hardening of the U-2 Mo alloy after water quenching from the gamma range.[2] Mechanical-properties tests again showed high strength, but again with low ductility. Mechanical properties of welds of the alloy have been determined, but the heat treatments used were aimed at increasing the ductility and, therefore, provided only low strength levels.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

CHARACTERIZING THE URANIUM-2 MOLYBDENUM ALLOY

EVALUATION OF THE CARBON CONTENTS

Influence of the carbon content of the U-2 Mo alloy upon the age-hardening response was examined in the first part of this study. The alloy picks up carbon in the usual vacuum-induction melting process in coated graphite crucibles. Keeping the carbon level below a specification maximum of 130 ppm requires an additional effort and cost, so it was desirable first to establish whether or not a more readily obtained 300-ppm carbon alloy would be satisfactory. For this purpose, the alloy was prepared at four carbon levels for comparison of its tensile test results after solution treating, water quenching, and age hardening.

Alloy ingots were prepared by vacuum-induction melting in graphite crucibles coated with plasma-sprayed zirconia and poured at 1450° C into graphite molds washed with Zirconite A. To obtain the different carbon levels, four ingots (38 x 137 x 178 mm) were prepared by comelting molybdenum powder (60 ppm C) with a special high-carbon uranium for two of the ingots and with a low-carbon, Derby-grade uranium(b) in the other two. Portions of one high-carbon ingot and one low-carbon ingot were then recast in the proper ratios to obtain the U-2 Mo alloy at the other two carbon levels. Chemical analysis of the ingots showed 1.9% molybdenum, with average carbon levels of 70, 290, 660, and 880 ppm. Tensile-test blanks were cut from each plate, solution treated at 800° C, water quenched, and then age hardened at selected temperatures.

Hydrogen is detrimental to the tensile-test ductility of uranium and uranium alloys, but it is readily removed by heating in a vacuum at elevated temperatures. For this reason, all solution treatment in the study was performed in a vacuum environment. As with other age-hardening alloys, the mechanical properties developed on age hardening are related to specimen thickness on quenching, so the properties reported herein are for 13-mm-square test blanks only.

Tensile-test results from age-hardened specimens from the alloy at each carbon level are reported in Table 1. In general, results from the 70 and 290-ppm carbon specimens were about the same within each of the three conditions of heat treatment. From these data it was concluded that a carbon content up to 300 ppm would be acceptable. On the other hand, the 660 and 860-ppm carbon specimens did show lower ductility values than those from the 70 and 290-ppm carbon alloy. The aging treatment of 100° C for six hours showed little hardening, as could be expected, while aging at 400° C for six hours showed considerable hardening, much more than was needed for this study. In all of these tests, the ductility values were low, and much below the desired minimum of 10%.

EVALUATION OF THE PROCESSING CHANGES

The low ductility in the tensile tests just described was comparable to that in the literature and not entirely unexpected. Two metal processing changes were made to obtain higher

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(b) Derby-grade uranium—uranium as received from the metal-reduction plant.

Table 1

TENSILE TESTS OF THE URANIUM-2 MOLYBDENUM ALLOY
AFTER SELECTED AGING TREATMENTS
(Average of 2 Tests)

Carbon Content, (ppm)	Tensile Strength (MPa)	Yield Strength(1) (MPa)	Elongation(2) (%)	Reduction in Area (%)
		As Quenched		
70	1385	694	7.0	5.7
290	1350	712	5.0	6.6
660	1250	626	4.3	3.7
860	1181	644	4.0	4.7
		Aged at 100° C for 6 Hours		
70	1389	786	6.8	6.7
290	1415	816	6.3	6.8
660	1247	804	3.8	3.9
860	1270	762	4.0	2.6
		Aged at 400° C for 6 Hours		
70	1505	1453	1.0	1.0
290	1785	1531	2.5	3.9
660	1789	1769	3.0	3.5
860	1756	1517	2.5	3.0

(1) At a 0.2% offset.
(2) In 25.4-mm gage length.

ductility values with this alloy: The rolling temperature was changed from 800° C (the gamma region) to 540° C (the high alpha region); also, the ingots were heated for rolling in an argon-atmosphere muffle furnace, rather than in a salt bath. Such processing changes had improved the tensile-test ductility of age-hardened, uranium-2.25 weight percent niobium alloy in an earlier study.[4]

Two U-2 Mo alloy ingots (38 x 137 x 178 mm) were prepared by comelting molybdenum powder with Derby-grade uranium in one case and with a higher-carbon uranium in the other case. Average chemical analyses of the ingots showed 2.2% molybdenum, with carbon at 130 ppm in one and at 340 ppm in the other. These carbon levels were slightly higher than anticipated, but still adequate for the experiment. Both ingots were vacuum homogenized at 1000° C (for 4 hours) prior to alpha rolling to 13-mm plates from an argon-atmosphere muffle furnace. Tensile test blanks were cut from the plates, solution treated in vacuo at 800° C, and age hardened at selected temperatures.

Table 2 lists the test results from the low-carbon alloy in the aged condition. The processing changes of rolling temperatures and heating atmosphere did provide the alloy with a higher tensile-test ductility than was obtained in the earlier test series. In fact, the mechanical properties meet the 930-MPa minimum yield strength with the desired 10% minimum elongation. The 450° C treatment obviously overaged the alloy.

Comparable tests of the 340-ppm carbon alloy are reported in Table 3. Here, the tensile tests show slightly less ductility than those of the low-carbon alloy in Table 2, but still

Table 2

TENSILE TESTS OF LOW-CARBON URANIUM-2 MOLYBDENUM ALLOY AFTER SELECTED HEAT TREATMENTS

Heat Treatment (° C)		Tensile Strength	Yield Strength(1)	Elongation(2)	Reduction in Area
Quench	Age	(MPa)	(MPa)	(%)	(%)
800	275	1298	903	9.0	10.8
		1309	781	9.0	13.4
	300	1356	1014	11.0	11.5
		1326	1076	10.0	17.4
	325	1372	1082	10.0	15.9
		1384	1089	Broke in the Punch Mark	
	450	1049	801	-	30.0
		1090	785	10.0	27.4

(1) At a 0.2% offset.
(2) In 25.4-mm gage length.

Table 3

TENSILE TESTS OF HIGH-CARBON URANIUM-2 MOLYBDENUM ALLOY AFTER SELECTED HEAT TREATMENTS

Heat Treatment (° C)		Tensile Strength	Yield Strength(1)	Elongation(2)	Reduction in Area
Quench	Age	(MPa)	(MPa)	(%)	(%)
800	250	1370	808	8.0	6.8
	300	1410	1029	8.0	8.6
	350	1531	1316	5.0	5.9
	400		Broke in Grips		
680	300	1420	1039	9.0	9.3
	300	1707	1464	-	6.7
600	300	1061	785	14.0	22.7
	400	1109	854	16.0	36.3

(1) At a 0.2% offset.
(2) In 25.4-mm gage length.

higher than those reported in the first part of this study. Apparently, the 340-ppm carbon level is the significant factor that prevented realization of all of the benefit from the alloy processing changes. The data further justify a 300-ppm carbon specification maximum for the U-2 Mo alloy. The alloy water quenched from the gamma region (800° C) and from the beta-plus-gamma region (680° C) responded on age hardening to produce the same mechanical properties. A comparable phenomenon had been found with the U-2.25 Nb alloy.

Tensile-test ductility of low-level alloys of uranium is lowered by increasing the relative humidity of the test atmosphere of the laboratory. The effect has been demonstrated with U-2.25 Nb and U-0.75 Ti alloys, but it was a negligible influence below 45 - 50% relative humidity. To determine whether or not this particular phenomenon was a significant factor in producing low ductility in the U-2 Mo alloy tested in ambient laboratory air, two blanks were solution treated at 800° C, water quenched, and age hardened at 300° C (for 6 hours).

These blanks were tested in flowing argon to obtain a low relative humidity in the test atmosphere. The average elongation was 18.0% and the average reduction in area was 38.3%, with a 1080-MPa yield strength. Thus, a marked increase in ductility in a dry test atmosphere indicated that the alloy is very susceptible to the relative humidity effect. Lowered ductility from the relative-humidity effect is hydrogen related. On the basis of hydrogen solubility in the alpha phase of the U-2 Mo and U-2.25 Nb alloys, the molybdenum alloy would require less hydrogen than would the niobium alloy to produce a comparable ductility loss. This observation then would explain just why comparable process changes in the U-2 Mo alloy were not as effective as they were with the U-2.25 Nb alloy.

METALLOGRAPHY

Figure 1 is a photomicrograph of the alloy in the age-hardened condition (300° C). The grain size is small and there is some transformation banding within the individual grains. Figure 2 is a photomicrograph of a specimen of the U-2 Mo alloy in the overaged (450° C) condition.

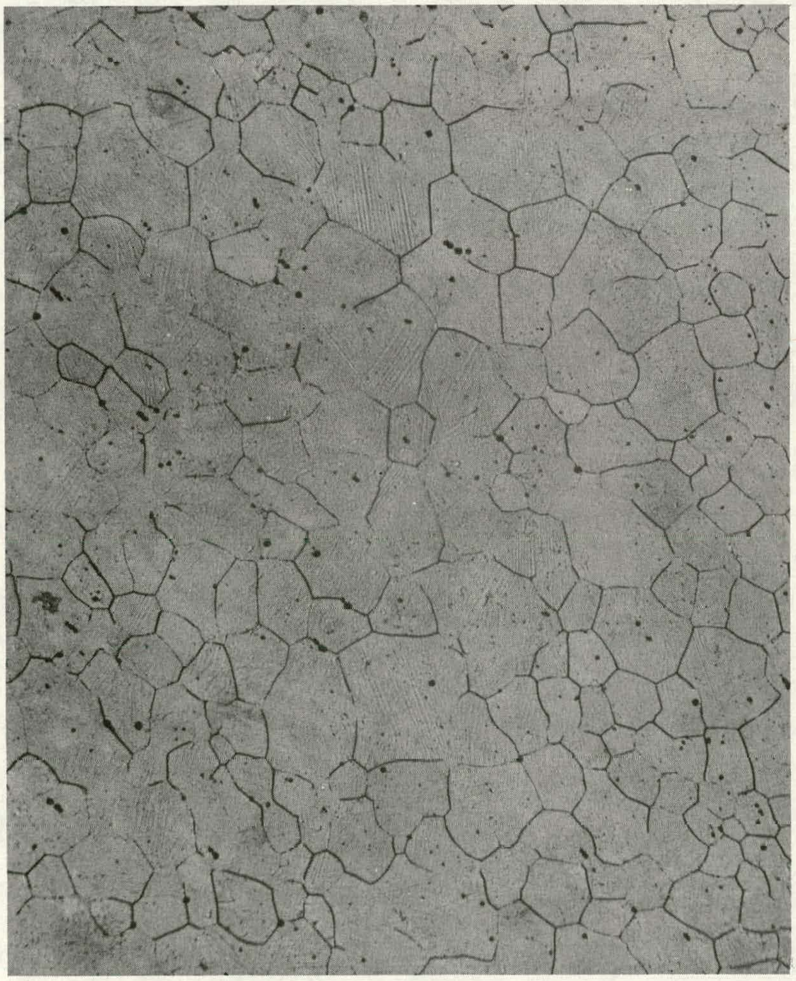

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Figure 1. AGE-HARDENED URANIUM-2 WEIGHT PERCENT MOLYBDENUM ALLOY. (Bright Field Illumination; 100X)

L383-2
Figure 2. OVERAGED URANIUM-2 WEIGHT PERCENT MOLYBDENUM ALLOY. (Bright Field Illumination; 100X)

Conclusions

As a result of this study, the following conclusions can be stated:

1. A technique was developed and demonstrated to provide a minimum yield strength (0.2%) of 930 MPa and a minimum 10% elongation with the U-2 Mo alloy.

2. In the U-2 Mo alloy, carbon contents up to 290 ppm did not affect the hardening response on aging. However, at 340 ppm and above, tensile-test ductility was reduced.

3. The alloy, solution treated in either the gamma or in the gamma-plus-beta range, produced the same age-hardening response.

4. The basic reason for the low ductility of the U-2 Mo alloy in the age-hardened condition is because of the relative humidity effect and can be associated with the presence of molybdenum.

5. The report data suggest one more processing change to be evaluated—rolling the U-2 Mo alloy in cans to eliminate completely the reaction between air and metal.

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