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INFLUENCE OF TUNGSTEN ALLOYING ADDITIONS ON THE MECHANICAL PROPERTIES AND TEXTURE OF TANTALUM

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ABSTRACT

Tantalum, like all bcc metals exhibits deformation behavior which is substantially influenced by alloying, temperature, and strain rate. Recently, the mechanical response, in particular the high-strain-rate response, of tantalum and tantalum alloys has received increased interest for ballistic applications. In this paper recent results on the influence of tungsten alloying additions on the mechanical response and starting crystallographic texture of tantalum-tungsten alloys are presented. The stress-strain behavior of three tantalum alloys containing 2.5, 5, and 10 wt.% W has been investigated as a function of loading path, tension and compression, and strain rate, 10^{-3} to 8000 s^{-1} . The yield strength and work-hardening rate were found to increase with increasing tungsten alloying content compared to unalloyed-Ta. Based on measurements of the surface and centerline textures of the Ta-W alloys, no systematic effect of tungsten content on texture was documented. However, due to variations in mechanical behavior between through-thickness and in-plane properties the need for complete through-thickness texture measurements is indicated.

INTRODUCTION

The microstructure / property relationships of tantalum and tantalum-based alloys continue to attract scientific and engineering interest due to their high density, melting point, excellent formability, good heat conductivity, good fracture toughness (even at low temperatures), corrosion resistance, and their weldability[1]. Since 1950 numerous studies have probed the microstructure-chemistry/property response of a large number of tantalum and tantalum-based alloys, both in single-crystal and polycrystalline form[1-5]. Tantalum, like all bcc metals exhibits deformation behavior which is markedly influenced by impurities, alloying additions, crystallographic texture, temperature, and strain rate[2-5]. Recent efforts have been focused on the optimization of tailored and reproducible microstructure / property relationships for a given application of tantalum. This emphasis has led to changes in the chemistry and processing controls used to produce current tantalum mill products, including control of crystallographic texture to affect in-plane homogeneity. Concentrated studies of the influence of texture on the deformation response of tantalum alloys have been fostered by recent code simulations and experiments revealing an influence of anisotropy on material response in ballistic applications[6]. The purpose of this paper is to report recent findings on the influence of tungsten alloying additions on the mechanical properties, as a function of loading direction and strain rate, and starting texture of tantalum alloys representing current plate materials.

EXPERIMENTAL PROCEDURE

The materials used in this investigation were commercially-pure (triple electron-beam) annealed unalloyed-Ta, Ta-2.5W, Ta-5W, and Ta-10W supplied by Cabot Corporation with compositions as listed in Table I. The unalloyed-Ta, Ta-2.5W, and Ta-10W materials were prepared by melting 25.4 cm-dia. or greater ingots. The Ta-5W in contrast was cast in a smaller research scale electron beam melter; triple melted similar to the other ingots. All the ingots were forged into billets, the billets were annealed, and then cut prior to cross rolling. The plates were straight rolled in the final finishing passes. Each material was supplied in 6.35-mm-thick plate form; in addition the unalloyed-Ta was also studied in 10.2-mm-thick plate form. The as-tested

microstructures of the 6.35-mm-thick unalloyed-Ta, Ta-2.5W, Ta-5W, and Ta-10W plates were all equiaxed grains with average grain sizes of 42 μm , 45 μm , 48 μm , and 42 μm , respectively. The 10.2-mm-thick unalloyed-Ta plate had an equiaxed 43 μm grain size.

Table I - Alloy Compositions (in ppm wt. %)

Metal (thickness)	C	O	N	H	W	Nb	Si	Ta
Ta (10.2 mm)	10	<50	<10	<5	<25	<25	<5	bal.
Ta (6.35 mm)	12	<50	<10	<5	60	250	5	bal.
Ta-2.5W (6.35 mm)	18	98	<10	<5	2.4%	330	<5	bal.
Ta-5W (6.35 mm)	15	<50	<10	<5	5.2%	65	<5	bal.
Ta-10W (6.35 mm)	11	63	<10	<5	9.6%	385	5	bal.

The mechanical responses of the tantalum materials were measured in compression using solid-cylindrical samples 6.35-mm in diameter by 6.35-mm long, lubricated with molybdenum grease. Compression samples were machined from the plates in both the through-thickness and in-plane longitudinal orientations. Sheet tensile samples were machined with square gage sections 5.56 mm by 5.56 mm by 25.4-mm gauge length from the alloys in the plane of the plates. The starting cross sectional area is comparable to that of specimens machined to ASTM E8-82[6.2 mm rounds]. Quasi-static compression and tension tests were conducted at a strain rate of 0.001 s^{-1} . Dynamic tests, strain rates of 1000-8000 s^{-1} , were conducted utilizing a Split-Hopkinson Pressure Bar. The inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens at low strains make the determination of yield inaccurate at high strain rates. The texture of the tantalum and tantalum alloys was characterized using X-ray diffraction. (110), (200) and (211) X-ray pole figures were measured at the surface and centerline of samples from each plate. The corresponding orientation distributions were determined from the experimental pole figures using the WIMV[7] algorithm as implemented in *popLA*[8], a texture analysis software package. Orthorhombic sample symmetry was enforced during the calculations. The orientation distribution was then used to generate (111) and (100) pole figures.

RESULTS AND DISCUSSION

The quasi-static compressive and tensile stress-strain responses of the 6.35-mm-thick plate tantalum materials as a function of Ta-alloying content are shown in Figures 1. The dynamic compressive stress-strain response is shown in Figure 2. The yield and flow stress levels in the tantalum and tantalum alloys beyond yield are seen to increase with increasing tungsten alloying additions. Increasing the alloying content to 10 wt.% in the Ta-10W alloy results in a factor of 2 increase in the yield and flow stress levels attained compared to the unalloyed Ta. This observation is consistent with well established solute strengthening effects of tungsten alloying additions on Ta[2,3]. This strengthening effect is further observed to prevail under both quasi-static[Figure 1] and dynamic loading[Figure 2] conditions. Comparison of the flow strength levels between quasi-static and dynamic loading for all the tantalum materials reflects the pronounced temperature and rate sensitivity of Ta[3]. At 2% strain the flow stress increases from ~200 to 575 MPa for unalloyed-Ta and from ~520 to 820 MPa for Ta-10W with a increase in strain rate. In addition to the increase in yield response linked to tungsten content the compressive stress-strain response is seen to exhibit a higher flow stress response than displayed under tensile deformation. This observation is also consistent for the unalloyed Ta, Ta-5W, and Ta-10W. Analysis of the textures of the three tantalum materials, detailed below, shows this observation to be wholly consistent with established textural effects on flow behavior.

In addition to yield, flow strength, and strain-rate variations tungsten alloying is also seen to have a pronounced influence on work-hardening behavior in Ta alloys. Under quasi-static loading, the stress-strain curves measured in both compression and tension are seen to be parallel after ~2%

Figure 1: Compressive and tensile stress-strain response of Ta, Ta-2.5W, Ta-5W, and Ta-10W at a strain rate of 0.001 s^{-1} at 298K.

Figure 2: Compressive stress-strain response of Ta, Ta-2.5W, Ta-5W, and Ta-10W at a strain rate of $\sim 2000 \text{ s}^{-1}$ at 298K.

plastic strain. The average strain-hardening rate is, however, seen to increase slightly in the quasi-static tests following the elastic-plastic transition as a function of increasing tungsten content; from nominally 830 MPa/ unit strain for unalloyed-Ta to 1330 MPa/ unit strain for Ta-10W calculated over the strain range of 0.05 to 0.2. This effect is more clearly evident under dynamic loading[Figure 2] where the average rate of strain hardening is seen to increase from nominally 1440 MPa/ unit strain for unalloyed-Ta to 2300 MPa/ unit strain for Ta-10W, calculated over the strain increment of 0.025 to 0.15. Comparison of these nominal hardening rates as a function of loading rate also reveals how increasing the strain rate to dynamic levels results in hardening rates in unalloyed-Ta equivalent to those exhibited during the quasi-static response of Ta-10W. Increasing levels of work-hardening with increasing strain rate or tungsten-alloying additions is consistent with the suppression of dynamic recovery processes, including reduced cross-slip during deformation[9].

The textures of the tantalum materials were found to vary with tungsten alloy content and with plate thickness in the case of the pure tantalum plates as shown in Figure 3. The thicker pure tantalum plate exhibits very little texture gradient between the plate surface and centerline; whereas, the pure and alloyed tantalum 6.35-mm-thick plate samples exhibit pronounced through-thickness texture gradients. Texture gradients have been frequently observed in tantalum plate materials[6]. The results of the current study on 6.35-mm-thick plate suggests that there is no systematic effect of tungsten alloying on the texture of the tantalum plate, except that the alloying seems to reduce the propensity of (111) planes to lie normal to the through-thickness direction. However, no investigation of the distribution of the "surface" and "centerline" textures through the thickness of the plate has been made to see if the measured textures truly represent the real textures of significant volumes of material. The mechanical tests also suggest that the measured textures are not representative of the bulk of material in the plates studied.

For example, in the case of the Ta-10W, the longitudinal compression stress-strain curve falls below the through-thickness curve (see Figure 1). This behavior is consistent with a (111) fiber texture, however, it is not consistent with either the measured centerline texture or the measured surface texture. The effect of texture on the stress-strain response was modeled using a Taylor polycrystal plasticity model[10] where strain is assumed to be uniform throughout the polycrystal. Using this approach, the predicted through-thickness stress-strain curve fell below the predicted longitudinal curve, just opposite of the observed trend. Thus, it is likely that the texture of the bulk of the material is more (111) fiber-like than was captured from the measured planes. Prior work has shown that the spatial distribution of texture in tantalum is not always uniform and can have significant effects on the mechanical properties[11]. Thus, the texture of Tantalum and Ta-W alloy plates should not be measured in the conventional manner where planes normal to the through-thickness are measured, but rather, textures should be measured from planes normal to either the longitudinal or the transverse directions.

CONCLUSIONS

The current study of the influence of tungsten alloying additions on the mechanical properties and texture of tantalum plate indicates:

- a) Tungsten alloy additions significantly increase the yield and flow stress levels attained and increase the rate of work-hardening compared to unalloyed tantalum, under both quasi-static and dynamic strain rates.
- b) The results of the current study on 6.35-mm-thick plate suggests that there is no systematic effect of tungsten alloying on the texture of the tantalum plate, except to reduce the propensity for (111) fiber-type textures to form. However, the existence of strong texture gradients through the thickness of the plates and inconsistencies between the measured textures and the observed mechanical anisotropy suggest that the measured textures presented here are not completely

Figure 3: (100) and (111) pole figures of Tantalum alloys measured at the surface and centerline of the plates.

representative of significant volumes of material. Textures should be measured from planes containing the through-thickness direction not planes normal to the throughthickness direction.

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