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The Influence of Tungsten Alloying on the Mechanical Properties of Tantalum

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Abstract

In mechanical tests of tantalum-tungsten alloys with nominal tungsten contents between 0 and 10 wt% for strain rates between 0.000016 and 6800 s^{-1} and temperatures between 77 and 400 K, the addition of tungsten noticeably reduces the strain-rate dependence of the flow stress of tantalum near yield. It also subtly alters the strain-rate behavior of the work hardening, making it more like that of copper, an fcc metal. These effects are reflected in the limiting strains for uniform plastic deformation calculated from our flow curves. For unalloyed tantalum, the instability strain appears to drop dramatically for strain rates in excess of approximately 0.005 s^{-1} , whereas for tungsten bearing alloys, it remains unchanged or increases slightly. Tungsten alloys may therefore be preferable to unalloyed tantalum in applications that demand substantial ductility at high rates of strain. We briefly discuss possible mechanisms for plastic flow in tantalum and how they might be affected by tungsten additions to produce the effects we observe.

Résumé

Pour des alliages de tantale-tungsten ayant des compositions nominale de tantale entre 0 et 10% en poids, de tests mécaniques à des températures entre 77 et 400 K, et des taux d'élongation variant de 0.000016 à 6800 s^{-1} , l'addition de tungsten réduit de manière notable la dépendance du fluage du tantale sur le taux d'élongation au voisinage de la déformation plastique. Le comportement du taux d'élongation sur le durcissement de l'alliage change de manière subtile, le rendant plus proche du comportement du cuivre, un métal c.f.c. Ces effets se font sentir dans les contraintes limitantes de déformation plastiques uniformes calculées à partir de nos courbes de fluage: pour le tantale sans éléments d'alliage, la contrainte d'instabilité semble diminuer de manière dramatique pour des taux d'élongation supérieurs à environ 0.005 s^{-1} , alors que pour les alliages de tungsten, elle reste inchangée ou augmente faiblement. Les alliages de tungsten peuvent par conséquent être plus performants que le tantale sans alliage, pour des applications qui nécessitent une ductilité importante à des taux d'élongation élevés. Nous discutons brièvement les mécanismes éventuels de fluage du tantale et le rôle des additions de tungsten sur les effets qui ont été observés.

1. INTRODUCTION

As in many body-centered-cubic (bcc) metals, the mechanical behavior of tantalum displays a marked temperature and strain-rate dependence [1-3]. The yield and flow stress, for example, have been the subject of many investigations and are well known to rise dramatically when the strain rate is increased or the temperature is decreased. From these observations, it has been inferred that the early stages of deformation in tantalum are controlled by a Peierls mechanism [2,4]. In contrast, characterization of the evolution of the flow stress during deformation has received relatively little attention, and although the apparent work hardening of tantalum (the slope of the stress-strain curve) appears to decrease when the strain rate is increased or the temperature is decreased, the mechanisms or combination of mechanisms that produce this behavior are not clearly understood. By comparison, in copper, a face-centered-cubic (fcc) metal, the yield stress shows little if any temperature or strain-rate dependence, and the work hardening typically increases as the strain rate increases or the temperature decreases [5,6].

In this work, we explore the changes induced in the flow stress and the work hardening of tantalum by adding tungsten solutes. We demonstrate that, as tungsten content is increased, the mechanical behavior of tantalum-tungsten alloys acquires characteristics that are more typical of fcc than bcc metals and that such changes have important implications for the dynamic ductility of these materials. We also suggest that our observations can be explained if tungsten promotes a change from Peierls-dominated flow to flow controlled by dislocation-obstacle interactions.

2. EXPERIMENT

Alloys with nominal tungsten contents of 0, 2.5, 5 and 10 wt% were obtained from the Cabot Corporation. Triple electron-beam-melted ingots were forged, rolled, and annealed to yield materials with uniform microstructures and similar grain sizes [7]. The grain sizes of the various alloys are summarized in Table 1 and their chemistry in Table 2.

Cylindrical specimens 0.5 cm in diameter by 0.5 cm high were machined from the rolled plate, with their axes normal to the rolling plane. These specimens were tested in compression at engineering strain rates of 0.000016, 0.001, 0.005 and 0.1 s⁻¹. Although most of the tests were conducted at room temperature (298 K), a few were also conducted on selected materials at 77 K and 400 K.

In addition to the compression tests, one experiment was performed with each material in tension on a split Hopkinson pressure bar [8] at room temperature and a nominal strain rate of 6800 s⁻¹. Flat, "dog-bone" specimens for these experiments were cut with their broad faces parallel to the rolling plane.

Table 1. Grain sizes.

Alloy	Grain size (μm)
Ta	35–38
Ta-2.5W	45–50
Ta-5W	43–45
Ta-10W	43–51

Table 2. Alloy chemistry.^a

	Ta	Ta-2.5W	Ta-5W	Ta-10W
W	40	24,000	44,000	101,000
Nb	330	1,200	1,900	450
O	12	65	59	21
N	3	4	6	1
C	1	10	3	3

^a All values are in weight ppm.

3. RESULTS.

Figure 1 shows flow curves of true stress-true strain in compression for each of the materials. Figure 2, flow stress vs. logarithm of the strain rate, shows that adding tungsten substantially reduces the flow-stress dependence on rate. The slopes of the curves for the tungsten alloys (0.012 to 0.015 GPa) in Fig. 2 are about half that of the unalloyed tantalum (0.0282 GPa) and appear to be independent of tungsten content.

Figure 1. True stress-true strain compression flow curves for strain rates of 0.000016, 0.001, 0.005, and 0.1 s⁻¹ and 298 K: (a) Unalloyed tantalum, (b) Ta-2.5 wt% W, (c) Ta-5 wt% W, and (d) Ta-10 wt% W.

Figure 2. Flow stress at 5% strain as a function of the log of the strain rate for unalloyed tantalum and each of the tantalum-tungsten alloys.

Figure 3 shows the slopes of the curves in Fig. 1. At small plastic strains, yield-point phenomena dominate the flow curves; hence, only slopes at strains greater than a few percent are shown. The behavior of unalloyed tantalum appears somewhat confused. At small strains, the slope clearly decreases as the strain rate is increased from 0.000016 s^{-1} to 0.1 s^{-1} , but as deformation proceeds, the curves cross. The strain at this crossover increases as the strain rate increases. Tungsten additions, however, "resolve" the apparent confusion in the slopes of unalloyed tantalum. The initial work hardening of the 2.5% alloy (Fig. 3b) is virtually independent of strain rate up to a strain of 10%, beyond which the curves diverge. In

Figure 3. Slopes of the flow curves (apparent work hardening) as a function of true strain for strain rates of 0.000016 , 0.001 , 0.005 and 0.1 s^{-1} and 298 K : (a) Unalloyed tantalum, (b) Ta-2.5 wt% W, (c) Ta-5 wt% W, and (d) Ta-10 wt% W.

contrast to the unalloyed material, hardening beyond this strain increases with increasing strain rate. The 5% and 10% alloys also show this characteristic pattern (Figs. 3c and 3d), but for these materials, the divergence of the curves is shifted to a point very early in the deformation. Although the initial work-hardening rates appear to be independent of rate, the slopes immediately diverge as deformation progresses. All of the curves converge at larger plastic strains.

The slopes of the flow curves may also be plotted as a function of the stress (not shown here). With these curves and the flow curves, we can apply the simple criterion $\sigma = d\sigma/d\varepsilon$ to determine the strains at which uniform plastic flow becomes unstable in each alloy. Figure 4 shows the results of this calculation as a function of the logarithm of the nominal strain rate. For rates below about 0.005 s^{-1} , little change in the limiting strain occurs, and the value for unalloyed tantalum is larger than for any of the alloys. At rates higher than this, however, the limiting strain for unalloyed tantalum drops dramatically, but corresponding strains for the alloys either remain unchanged or increase. The limiting strains for the alloys thus approach, or exceed, that for unalloyed tantalum.

Figure 4. The calculated limiting strains for stable, uniform plastic flow as a function of the logarithm of strain-rate for unalloyed tantalum and each of the tantalum-tungsten alloys.

4. DISCUSSION

In previous studies [6], we showed that the yield strength of oxygen-free electronic (OFE) grade copper is insensitive to the strain rate but does depend on the grain size through a Hall-Petch relationship. We also demonstrated that work hardening, while independent of the grain size, increases with strain rate in a manner similar to what we observe for the 5% and 10% tungsten alloys (Figs. 3c and 3d). The initial work hardening of copper is independent of strain rate⁽¹⁾, and its curves converge at both very small and large strains. While this behavior implies that the instability strain must increase with grain size in copper [10,11], model calculations show [11] that it also implies that the instability strain increases with increasing rate. This is in marked contrast to the behavior of unalloyed tantalum, but similar to that of the alloyed materials (Fig. 4). The data in Fig. 4 suggest that at high strain rates ($>0.1 \text{ s}^{-1}$), tantalum-tungsten alloys should deform to substantially larger strains than unalloyed tantalum before plastic deformation becomes unstable and susceptible to necking. To investigate this, we tested one sample of each alloy in tension at a strain rate of 6800 s^{-1} to determine the engineering strain at failure⁽²⁾. Table 3 summarizes the results of these experiments and shows that the alloys all have substantially larger strains to failure than the unalloyed material. Whereas the ultimate strain is clearly a different quantity than the limiting strain⁽³⁾, the results in Table 3 seem to be in general accord with Fig. 4. The large flow stress and reduced work hardening of unalloyed tantalum at high strain rates reduce the instability strain to a small value compared with the tungsten alloys, and this is reflected in the ultimate strains of the two materials. We conclude that the dynamic ductility of tantalum-tungsten alloys exceeds that of unalloyed tantalum and that this is a direct consequence of changes in the constitutive properties produced by the tungsten solutes.

¹ At strain rates in excess of about 5000 s^{-1} , the initial hardening rate appears to increase linearly with rate, however [5,6,9].

² Ideally, we should determine the onset of necking, but it is impossible to do this with any accuracy.

³ For materials of comparable grain size, it may be reasonable to assume that instability strain and ultimate strain correlate positively. The size of inhomogeneities that promote necking will be on the order of the grain size and thus should be the same for all of the materials studied here. However, we have noted [6,10] that, for copper of widely different grain sizes in tests of rapidly expanding thin rings, the ultimate and limiting strains correlate negatively. This may be a size effect related to the rate of instability growth.

Table 3. Engineering strains at failure, 6800 s⁻¹.

Ta	Ta-2.5W	Ta-5W	Ta-10W
0.36	0.46	0.52	0.48

In copper, the Peierls stress (σ_p) is extremely small, and deformation is controlled by the interaction of mobile dislocations with obstacles. The form of the flow curves and their response to changes in rate and temperature suggest that these obstacles are other dislocations [5]. The activation energy associated with flow over such obstacles is large (7 eV per atom), and the mechanical threshold is vanishingly small at yield but rises quickly as deformation proceeds [5,6]. These characteristics ensure that the yield of copper is insensitive to strain rate and temperature and that hardening increases with rate.

The reduced rate dependence of the flow stress and the change in the work-hardening dependence on rate produced by tungsten solutes suggest, by analogy with copper, that dislocation-obstacle interactions in tantalum-tungsten alloys play a much more prominent role during plastic deformation than in unalloyed tantalum. Given that the role of the Peierls barrier in controlling the yield and initial flow stresses in tantalum is well substantiated, it appears that we must invoke a combination of mechanisms to explain our observations. The possibility of multiple mechanisms in bcc metals has been recognized for some time, and various alternatives have been suggested [12,13]. The situation is complicated by the fact that screw dislocations, which carry much of the plastic flow in bcc metals, undergo a nonplanar dissociation [3,4,14]. Hence, a simple Peierls mechanism with a constant activation energy and constant σ_p seems unlikely; it seems much more reasonable to expect that the Peierls mechanism itself will be a combination of processes. Based on these ideas, we propose that plastic flow in tantalum and tantalum-tungsten alloys is carried by a combined Peierls-type mechanism and an obstacle mechanism which operate in series. The former is characterized by a low activation energy, a large mechanical threshold (σ_p), and a relatively weak structural evolution (change in σ_p with deformation), whereas the latter has a large activation energy and a vanishingly small initial mechanical threshold that evolves rapidly with deformation.

With this model, we expect that the initial deformation of unalloyed tantalum will be controlled by a Peierls barrier, except at low rates and high temperatures. It will dominate until the obstacle evolution (work hardening) has progressed far enough to supersede it. As the strain rate increases, the Peierls mechanism will cause the flow stress to increase, and the switch to obstacle control will be delayed to larger strains. If we presume that the change in σ_p with strain is small, the work hardening will appear to decrease as the rate is increased and the crossover point of the work-hardening curves will shift to larger strains, consistent with our observations (Fig. 3a). At higher temperatures, contribution from the Peierls mechanism should be reduced, and the apparent initial work hardening should increase. This is indeed true, as Fig. 5 demonstrates. Similarly, if dislocation-obstacle interactions dominate the flow, by analogy with copper, higher temperature should decrease the work hardening, and lower temperature should increase the work hardening at constant rate in Ta-W alloys, as demonstrated in Fig. 6 for the 10% alloy.

Although this model appears to explain the qualitative features of both the flow curves and the work hardening, we have not yet demonstrated that it is capable of giving quantitative agreement. Preliminary calculations indicate that the fundamental notions are sound, but that quantitative agreement in putative transition regions may be difficult to achieve. Furthermore, it is not yet clear how tungsten produces the effects associated with it. Although tungsten appears to have a direct effect on the athermal stress, it may

Figure 5. Work-hardening curves for unalloyed tantalum at 298 and 400 K and a nominal strain rate of 0.000016 s⁻¹.

Figure 6. Work-hardening curves for Ta-10 wt% W for temperatures of 77, 298, and 400 K at strain rates of 0.001 and 0.000016 s⁻¹.

also substantially alter energies and mechanical thresholds associated with thermally activated flow. Although we expect that tungsten additions will certainly change the forces required to move dislocations, we have as yet no fundamental, quantitative relationship between the tungsten content and, for example, the Peierls activation energy, G_p . One possibility is that tungsten addition somehow modifies the manner in which screw dislocations dissociate, thereby modifying σ_p and G_p .

6. CONCLUSIONS

From this work, we conclude the following:

- Additions of tungsten solutes to tantalum impart characteristics to the constitutive properties that are characteristic of ductile fcc metals (copper). That is, the rate dependence of the yield and flow stresses is reduced, and work hardening increases with rate.
- The changes in the constitutive properties imparted by tungsten solutes are directly responsible for the greater dynamic ductility of tantalum-tungsten alloys relative to that of unalloyed tantalum at strain rates which exceed approximately 0.1 s^{-1} .
- Our observations are qualitatively consistent with a model for deformation in these alloys, which consists of at least two components that operate in series: (1) a Peierls-type mechanism characterized by a small activation energy for flow and a large mechanical threshold that evolves only weakly with deformation and (2) a dislocation-obstacle interaction mechanism characterized by a large activation energy for flow and a mechanical threshold that initially is very small but evolves rapidly with deformation.

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