

# Shear strength developments during shock loading in tantalum alloys: Effects of cold work and alloying

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**Abstract.** The development of shear strength behind the shock front in tantalum alloys of 2.5 and 10wt% tungsten has been monitored by the use of laterally mounted stress gauges. Results show that in common with pure tantalum, shear strength decreases behind the shock front. At 2.5wt%, we believe that tungsten modifies the mechanical response by mitigating the effects of interstitial solute atoms, thus easing dislocation motion, as evidenced by the smaller reduction in shear strength compared to pure tantalum. At higher tungsten levels, it would appear that this is overcome by an overall increase in Peierls stress, which renders dislocation motion more difficult, thus giving the alloy a response more in common with that of the pure metal. Cold rolling of the 2.5% W alloy also appears to increase shear strength reduction behind the shock front (compared to the annealed alloy), although at present the reasons for this are unclear.

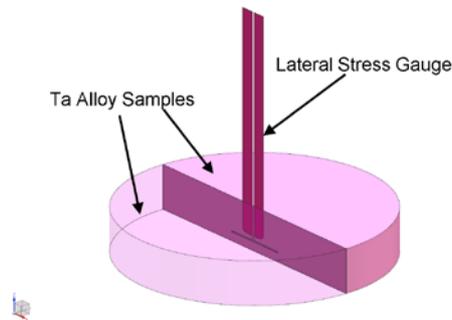
## 1. Introduction

The development of shear strength behind the shock front is of considerable interest as it has been shown to correlate closely with microstructural development. For example, in high stacking fault energy (SFE) face centred cubic (fcc) metals such as nickel, the shocked microstructure only reaches its stable dislocation cell configuration after a period of between 0.5 and 1  $\mu$ s [1]. Correspondingly, the shear strength in shock loaded nickel also increases over a similar time period before becoming stable [2]. However, as SFE drops (for example in austenitic stainless steels), the shocked microstructure becomes dominated by deformation twins [3], whilst the shear strength has been observed to be near constant behind the shock front [4]. In the case of body centred cubic (bcc) metals, it is the Peierls stress (*i.e.* the ability to generate and move dislocations) that is the main factor. This is generally high in bcc metals, as shown by only the small increases in dislocation density, seen after shock loading [5]. Little (if any) post shock hardening has been observed, and in contrast to fcc metals, the shear strength is observed to *decrease* behind the shock front [6-8]. This has been attributed to deformation occurring mainly due to the motion of existing dislocations rather than the generation of new ones. However, niobium, with a low Peierls stress, has shown significant (for bcc) dislocation density build up during shock loading [9], whilst corresponding measurements of shear strength showed it to be near constant behind the shock front [10]. In this paper we return to the shock response of tantalum, this time in terms of increasing tungsten content (2.5 and 10% by weight), and the effects of prior cold work on the 2.5% W alloy.



## 2. Experimental Procedure

All shock loading experiments were performed using the 70 mm bore, 3 m long, single stage gas launcher at AWE. Samples of each alloy (11 mm thick Ta-2.5W, 5 mm Ta-10W and 4 mm cold rolled Ta-2.5W) were sectioned in half and a manganin stress gauge (MicroMeasurements type J2M-SS-580SF-025) were introduced 2 mm from the impact surface. Target assemblies were reassembled using a low viscosity epoxy adhesive, with 25  $\mu\text{m}$  of mylar on either side of the gauge to provide extra insulation from the metallic targets. Each target assembly was held in a special jig for a minimum of 12 hours, after which the impact face was lapped. Shock stresses were induced by the impact of 6 mm thick aluminium alloy 5083-H32 or copper flyer plates in the velocity range 200 to 500  $\text{m s}^{-1}$ , generating longitudinal stress in the range 2.51 to 11.84 GPa. Longitudinal stresses were determined using impedance matching techniques, with the shock response of the flyer materials being known [11] and assuming that the Hugoniot of the two alloys under investigation is the same as pure tantalum. Lateral stresses were obtained from the raw voltage – time data using the methods of Rosenberg *et al.* [12], which takes into account the shape of the stress gauge at low impact pressures. A schematic representation of the target assembly is shown in figure 1.



**Figure 1.** Schematic of target assembly.

## 3. Materials

Two different alloys were obtained; the first was an 11 mm thick plate of Ta-2.5W. This was incrementally cold rolled from 300 mm thick, with intermediate annealing treatments of 1100°C, with a final anneal after the last rolling pass. One plate of this material, 10 mm by 100 mm by 100 mm underwent a further series of cold rolling passes to a reduction in thickness of 50%. A second alloy, Ta-10W was obtained via MST-8 of Los Alamos National Laboratories in the form of 6 mm by 125 mm by 75 mm annealed plate. The acoustic properties of the materials under investigation are presented below in table 1, with results for pure tantalum included for comparison.

**Table 1.** Acoustic properties of tantalum and its alloys.

	$\rho_0$ ( $\text{g cm}^{-3}$ )	$c_L$ ( $\text{mm } \mu\text{s}^{-1}$ )	$c_S$ ( $\text{mm } \mu\text{s}^{-1}$ )	$c_B$ ( $\text{mm } \mu\text{s}^{-1}$ )	$\nu$
Pure Ta [7]	16.69±.02	4.18±.01	2.03±.05	3.46±.06	0.346
Ta (Marsh)	16.66	4.16	2.09	3.39	0.331
Ta-2.5W	16.78±.01	4.12±.03	2.11±.03	3.32±.06	0.322
Ta-2.5W (CR)	16.79 ±.01	4.13±.03	2.06 ±.03	3.37 ±.06	0.334
Ta-10W	16.98 ±.01	4.18 ±.03	2.15 ±.03	3.36 ±.06	0.319

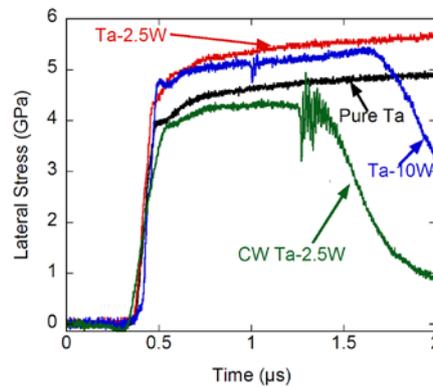
Compositions of the materials under investigation are presented in table 2.

**Table 2.** Composition of metals and alloys under investigation. Concentrations are in ppm (by weight) unless otherwise stated.

	C	Fe	Nb	Ni	Si	Ta	W	Cr	H	N	O
Ta	10	5	25			Bal	25		5	10	50
Ta-2.5W	<10					Bal	2.48%		<5	<10	24
Ta-10W	15	<5	470	<5	10	Bal	9.8%	<5	5	<10	45

**4. Results**

The lateral stress histories of all four tantalum alloys, shown in figure 2 (shocked between ~ 7 and 8 GPa) show a commonality in response, namely a rapid rise in stress as the shock front crosses the gauge location, followed by a much slower rise in lateral stress once the shock has passed and before release waves take the material back towards ambient conditions.

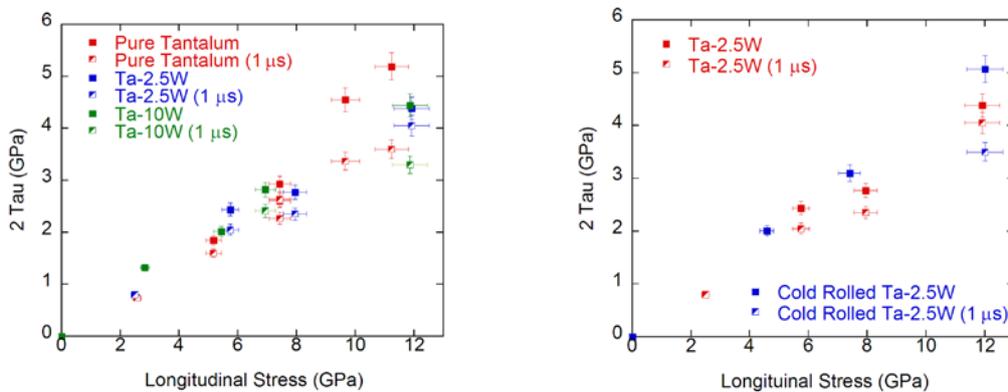


**Figure 2.** Representative lateral stress gauge traces.

From prior knowledge of the impact stress ( $\sigma_x$ ), the shear strength ( $\tau$ ) can be determined from the measured lateral stress ( $\sigma_y$ ) from the relation,

$$2\tau = \sigma_x - \sigma_y . \tag{1}$$

As it is clear that shear strength evolves behind the shock front, we have calculated shear strength at two points from each lateral stress trace; one immediately behind the shock front, and the other 1  $\mu$ s afterwards. The results are presented below in figure 3. We have separated this data into two parts to aid clarity.



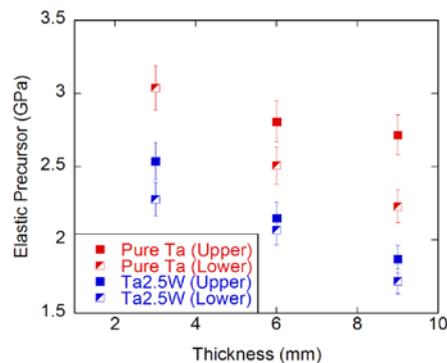
**a.** Effects of tungsten content in tantalum.

**b.** Effects of cold work in Ta-2.5W.

**Figure 3.** Shear strengths in cold rolled Ta-2.5W and Ta-10W. Data for pure tantalum from [7].

## 5. Discussion

In examining the results in this study more closely, firstly, consider the effects of increasing tungsten content. From figure 3a, it can be seen that the decrease in shear strength over  $1\ \mu\text{s}$  in pure tantalum is quite large, and increases with increasing shock stress. With an addition of 2.5% tungsten, although there is still a decrease in shear strength behind the shock front, but that reduction is significantly reduced itself. However, as tungsten content increases to 10%, the level of softening behind the shock front appears to increase again, approaching the levels seen in pure tantalum. This would seem counter intuitive, as it would be expected that increasing levels of tungsten would result in a progressive change in response. However, a number of authors [13-15] have observed that alloyed bcc metals can experience non-monotonic changes in strength as alloy content increases to the point where over a limited alloy range, the alloy can be *softer* than the pure metal. From the point of view of this investigation, Das and Arsenault [13] observed a reduction in yield strength in a Ta-2%W alloy (compared to pure tantalum) whilst a Ta-9%W alloy was significantly stronger. Nemat-Nasser and Kapoor [15] in contrast observed that the yield strength was higher in a Ta-2.5% alloy, but that the thermal stress component was reduced, resulting in a lower temperature and strain-rate dependence. Das and Arsenault [13] suggested that this behaviour may be due to low levels of solute atoms reducing the Peierls stress, although our own calculations for both pure tantalum and Ta-2.5%W suggest that there is a small increase in the alloy [10]. Other suggestions [14] have included considerations of the solute atoms (in this case tungsten) interacting with existing impurities. In essence, even low levels of impurities can cause significant strengthening. Their interaction with other solute species renders them less effective and hence overall strengthening is reduced. Whilst there are a number of explanations, these effects are real. It is interesting to note that in comparing the HELs and elastic precursor decay in both pure tantalum [7] and Ta-2.5%W [16] (figure 4), it is clear that the alloy is significantly softer than the pure metal. We have been unable to find corresponding data for Ta-10%W, but based upon the hypotheses discussed above and the trends displayed in our shear strength data, it is anticipated that the elastic precursors in this material would be higher than that of pure tantalum.



**Figure 4.** Elastic precursor decay in pure tantalum [7] and Ta-2.5%W [16].

Therefore we propose that the addition of a small amount of tungsten to tantalum has a softening effect, as shown by the reduced decrease in shear strength behind the shock front (figure 3a) and the reduction in the HEL (figure 4). We believe that there are two possible mechanisms; a) a reduction of the Peierls stress, thus making dislocation motion and generation easier. However, previous work by us [10] suggests that alloying 2.5% may actually increase the Peierls stress, although we would treat these values with caution. Alternatively, we propose b), where the addition of 2.5% tungsten interacts with interstitial solute atoms already present (especially oxygen), thus reducing its overall effect. In a previous work [7], it was shown that oxygen pinned dislocations in place, thus requiring a high initial stress to start dislocation motion, but as that motion progresses, shear stress drops. Evidence for this can also be seen in the precursor data shown in figure 4. Like many bcc metals, tantalum displays both upper and lower yield points [7,17]. Notice however, that the separation in these points is much lower

in the alloy than the pure metal, again for the same reasons. However, as tungsten content increases to 10%, the shear modulus increases (Ta, Ta-2.5W and Ta-10W have shear moduli of 68.78 GPa, 74.71 GPa and 78.49 GPa respectively). This will have a corresponding increase in the Peierls stress, and hence the highly alloyed material will have greater difficulty in moving and generating dislocations, thus having a response closer to the pure material. We would also point out that the presence of tungsten atoms on the tantalum lattice will have an effect due to size difference alone (solid solution strengthening). However, we believe that this effect is relatively small compared to the effects discussed above.

The differences between annealed and cold rolled Ta-2.5%W (figure 3b) are not so easy to explain. In contrast to pure tantalum, where cold rolling reduced the softening effect behind the shock front, due to the increase in the mobile dislocation density, cold rolling appears to have the opposite effect in Ta-2.5%W. Results suggest that the mobile dislocation density is now reduced, although the operative mechanisms responsible are not clear.

## 6. Conclusions

A series of plate impact experiments designed to probe the variation of shear strength behind the shock front have been performed on Ta-2.5%W, Ta-10%W and Ta-2.5%W, cold rolled to a reduction in thickness of 50%. As tungsten content increases, shear strength decrease behind the shock front initially reduces at 2.5% before increasing to levels seen in pure tantalum at 10%. It is believed two mechanisms are in operation. At low tungsten levels (2.5%), tungsten interacts with interstitial oxygen, thus reducing its overall effect. However, as tungsten content increases further (10%), shear modulus, and thus Peierls stress increases to the point where ease of dislocation motion is reduced to similar levels seen in the pure metal, thus resulting in similar behaviour to pure tantalum. In contrast, cold rolling appears to reduce the ability of dislocation motion. At present the reasons for this are unclear.

## Acknowledgments

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