EFFECTS OF SHOCK PRESTRAIN ON THE MECHANICAL BEHAVIOR OF TANTALUM AND TANTALUM-TUNGSTEN ALLOYS

D. H. Lassila[1], M. M. LeBlanc[1], M. A. Meyers[2]
1. University of California, Lawrence Livermore National Laboratory
Livermore, CA 94550 USA

2. University of California, San Diego
La Jolla, CA 92093-0411

Abstract

The effects of shock prestrain on the mechanical behavior and microstructure of annealed tantalum and Ta-W alloys have been examined. The test material was shocked to 45 GPa for 1.8 μs and soft-recovered such that deformation that occurred during this procedure was predominantly due to the shock loading. Mechanical characterization of the annealed and shock-recovered tantalum was performed over a wide range of strain rates (10^{-3} to 7000 s^{-1}) in compression. Shock prestraining caused an increase in the yield and flow stress in all of the test materials. The test results suggest that the athermal component of the flow stress is altered and to some extent work hardening is exhausted. The effects of shock prestrain on the microstructure and substructure of the test material were examined using optical microscopy, which revealed features which may be deformation twins. The results of these examinations and how they correlate with the effects of shock prestrain on mechanical behavior are discussed.

Introduction

The effects of shock prestrain on the mechanical behavior, microstructure, and substructure of annealed tantalum [1-3] and tantalum tungsten alloys [4] have previously been examined. In general, shock prestraining where the peak shock pressure was less than or equal to 20 GPa caused an increase in the quasistatic yield strength of tantalum but had less effect on the dynamic stress-strain response. These effects have been mainly attributed to an increase in dislocation density and are in some regards equivalent to quasistatic deformation, e.g. there does not appear to be an enhanced shock hardening effect [1,4]. This is in contrast to most FCC metals which show a substantial shock hardening effect [5,6].

It has been noted that twinning in Ta occurs to greater extents as the peak shock pressure is increased [7]. The purpose of this study is to examine the effects of a 45 GPa shock with a 1.8 μs duration on the microstructure and reload behavior of unalloyed Ta and Ta-W alloys[1]. To assess the mechanical response of shock-prestrained tantalum we have tested the annealed and shock-recovered tantalum over a wide range of strain rates (10^{-3} to 7000 s^{-1}) in compression. Optical light microscopy was performed to assess the effects of shock loading on the microstructures.

Experimental

Table 1. Chemical Analysis of the Test Materials (ppm in weight percent)

	Ta	Ta-2.5%W	Ta-10%W	Ceracon Ta
O	23	21	40	425
N	20	10	19	420
C	<2	3	4	20
H	1.3	1.5	2.1	na
B	0.17	0.020	0.020	0.12
Na	0.81	0.33	0.49	20
Mg	0.007	0.005	0.010	0.17
Al	0.11	0.024	0.014	1.9
Si	0.47	0.072	0.075	4.5
P	0.13	0.052	0.085	0.020
S	0.035	0.020	0.035	0.10
Cl	0.20	0.12	0.15	1.6
K	0.017	0.010	0.018	19
Ca	0.14	0.028	0.050	2.1
Ti	<0.001	0.004	0.003	0.18
Cr	0.019	0.02	0.020	5.3
Mn	≤0.005	0.002	0.007	3.5
Fe	0.035	0.075	0.10	14
Co	<0.005	0.001	<0.005	0.024
Ni	0.020	0.047	0.025	8.4
Cu	1.2	2.5	1.0	0.18
Zn	≤0.05	0.075	0.050	0.025
As	0.017	0.02	0.020	0.05
Sr	<0.1	<0.1	<0.1	0.25
Y	0.31	0.20	0.20	<0.1
Zr	0.011	0.028	0.023	0.020
Nb	105	200	165	0.49
Mo	16	7.0	10	0.28
Sn	≤0.05	≤0.05	0.038	0.032
Sb	≤0.03	≤0.03	≤0.03	3.0
Ba	0.07	0.019	0.060	0.045
Hf	<0.020	0.022	0.060	<0.1
W	105	3.5 (wt%)	13.5 (wt%)	0.035
Re	0.020	0.05	1.7	<0.1

One powder metallurgy (PM) and three ingot metallurgy (IM) materials were studied. The IM test materials (pure Ta, Ta-2.5W, and Ta-10W) were obtained from Cabot Corporation, Boyerstown, PA and were produced using their standard triple electron-beam process. The unalloyed Ta was received from Cabot as annealed plate stock and the alloys as bar stock (25.4 mm diameter). The bar stock was forged in the axial direction to produce disks approximately 50 mm diameter and 6 mm thick. Subsequent annealing heat treatments were performed to produce an equiaxed grain structure. The PM material was nominally pure Ta and was obtained from Ceracon Corporation, Riverbank, CA. The Ceracon material was produced using a dynamic sintering technique [8]. The chemistries of the test materials are given in Table 1 and indicate that the IM materials all had on the order of 100 ppm impurities, most of which were gaseous interstitials. The PM Ta was found to be high in oxygen undoubtedly related to the high oxygen content of the powder used to make the material. Texture

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[1] It should be noted that at the time of this writing the work is in progress and is incomplete in some respects; for example, the textures of the test materials are not reported.

Tantalum
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*characterizations of the test materials are unavailable at the present time, but are underway.

A single explosively driven shock-recovery experiment was performed at the New Mexico Institute of Mining and Technology. A schematic diagram of the shock recovery setup is shown in Figure 1. Cylindrical test samples (5 mm thick, 40 mm diameter) were mounted in a Ta-10W sample holder, consisting of lateral momentum trappings and spall plates. The flyer plate (Ta-10W, 3.8 mm thick) was driven by a 25.4 mm thick charge of PBX 9501 which was initiated by a plane-wave generator. Pin data was used to determine the resulting velocity of the flyer just prior to impact. The calculated peak shock pressure and duration were 45 GPa and 1.8 μs, respectively.

Compression test samples were electrical discharge machined (EDM) from the shock-recovered disks. The compression samples measured 4.5 mm in length and 4.5 mm in diameter. Tests at strain rates less than 10^3 s^{-1} were performed using a screw-driven machine, in which case the strain measurement was made using an extensometer attached to the compression platens. Dynamic compression tests at strain rates of approximately 4000 s^{-1} were performed using the split Hopkinson pressure bar (SHPB) technique. All test results presented in this work were performed at 23 °C.

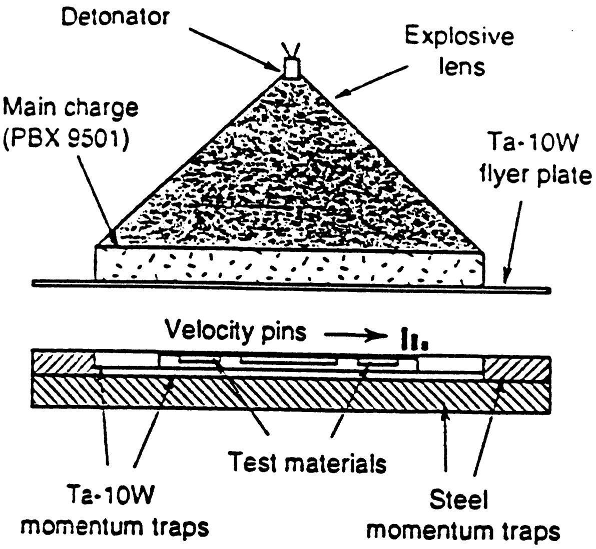


Figure 1: Schematic of the shock assembly.

Results

Optical Light Metallography

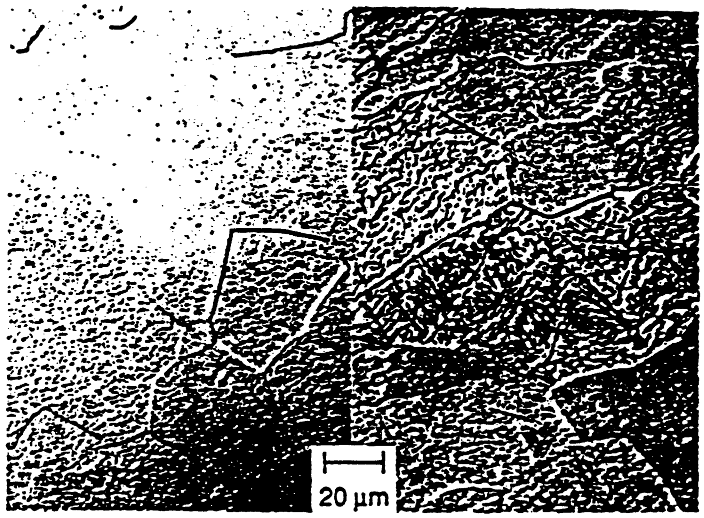
The microstructures of the test materials in the annealed and post-shock conditions were examined using optical light microscopy, as shown in Figures 2-a through 2-d. Transverse samples were mounted and mechanically polished using standard techniques. Etching of the samples was performed using a solution of equal parts nitric acid, hydrofluoric acid and glycerol.

All test materials were found to have equiaxed grain structures as shown in the optical light micrographs in Figures 2-a through 2-d. The IM materials were found to have a fairly uniform grain size of about 30 μm. The Ceracon PM material was found to have a grain size of about 10 μm and had porosity located predominately at grain boundaries and triple points.

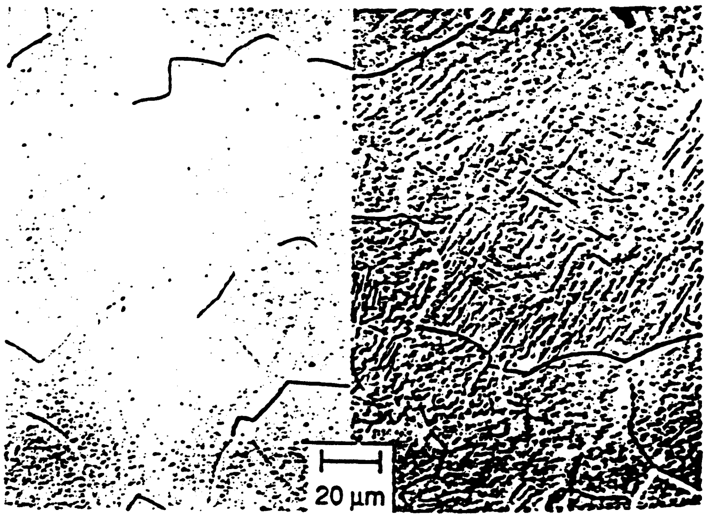
Shock loading produced two distinct changes in all of the test materials: 1) an increase in etch pitting due to the increase in dislocation density and 2) microbanding. The etch pitting is also seen in the micrographs of the test materials in the annealed conditions, consistent with the relatively high dislocation density Ta and Ta alloys have in the recrystallized state [1,9]. The microbanding due to the shock induced deformation appears to be more pronounced in the alloys and the PM Ta. It is clear that the orientations of the microbanding within an individual grain follow one or two distinct directions, consistent with deformation twinning in Ta [6]. However, at the time of this writing, it has not been determined if these artifacts are deformation twins or bands of dense dislocations related to adiabatic shear [9].

Compression Testing

Compression testing of the shocked and unshocked material was performed over a range of strain rates from 1.6 x 10^{-5} s^{-1} to 5000 s^{-1}. In Figures 3-a through 3-d we show the results of SHPB testing of the test materials in the annealed and post-shock states. From this data, it is apparent that the shock loading caused a substantial rise in the yield and subsequent flow stress in all the materials (on the order of 25% to 35%). None of the materials exhibited significant work hardening, although there appears to be a slight amount in the annealed materials and somewhat less in the shocked materials. Because these dynamic tests were adiabatic and the flow stress of test materials is known to be very temperature dependent, the apparent work hardening is expected to be less than that which occurs under quasistatic isothermal test conditions.

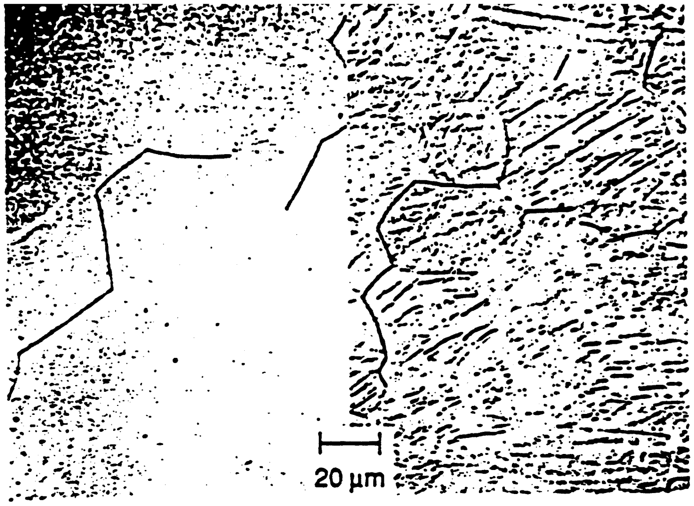


a) **IM Ta (unshocked)** **IM Ta (45 GPa shock)**

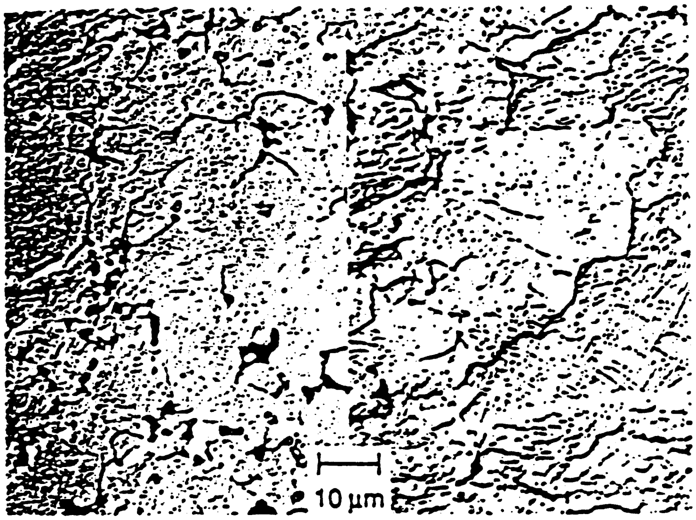


b) **IM Ta-2.5%W (unshocked)** **IM Ta-2.5%W (45 GPa shock)**

Figure 2: Micrographs of the test materials in the annealed and post-shock conditions.



c) IM Ta-10%W (unshocked) IM Ta-10%W (45 GPa shock)



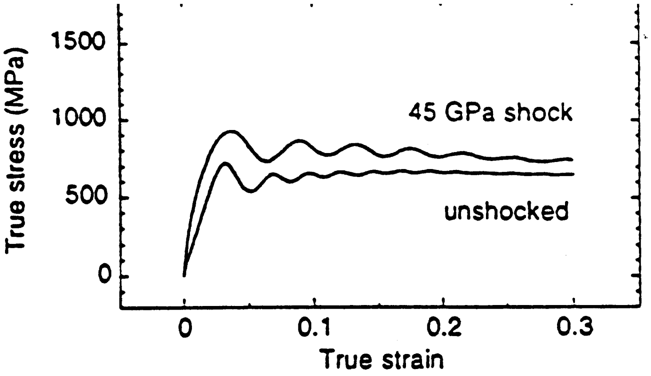
d) PM Ta (unshocked) PM Ta (45 GPa shock)

Figure 2 (cont.): Micrographs of the test materials in the annealed and post-shock conditions.

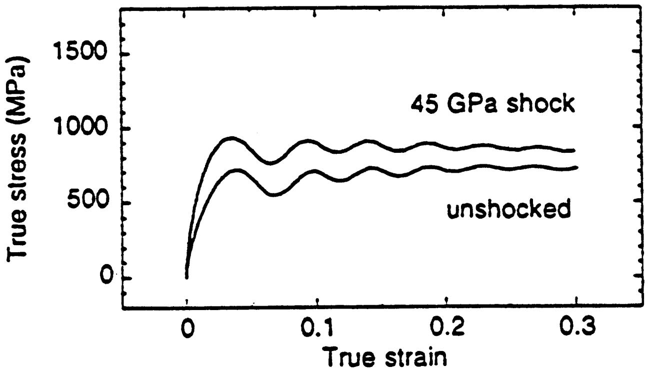
In other work [10,11] it has been demonstrated that if the dynamic tests are performed in a series of steps to very small extents of strain (referred to as quasi-isothermal dynamic testing), the work hardening of unalloyed Ta under dynamic loading is comparable to that which occurs during slow rate isothermal testing.

The compression test results of the test materials in the annealed and shocked conditions at various strain rates (10^{-1} to 1.9×10^{-5} s^{-1}) are shown in Figure 4. All of these tests are considered to be isothermal in nature. As expected, the flow stress of the materials increases with increasing strain rate. Except for some behavior at low strains at the strain rate of 10^{-3} s^{-1}, the work hardening appears to be uniform for a given material at all strain rates. It is interesting that despite the significant differences in the yield behavior, that at strains beyond 20% all of the materials exhibit similar work hardening behavior.

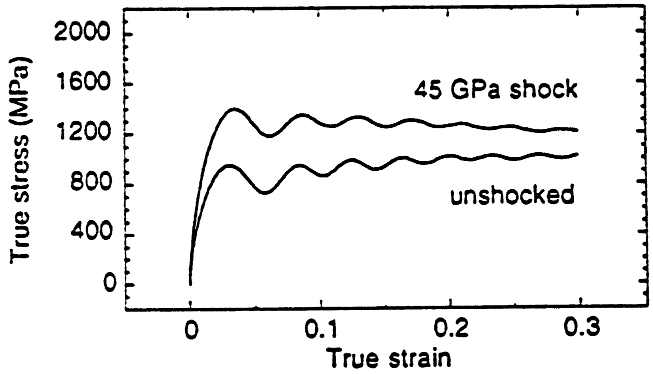
In Figure 5 we show a plot of the flow stress at 10% strain plotted against strain rate for the test materials in the annealed and shocked conditions. It appears that the shock loading resulted in little overall change in the strain rate sensitivities.



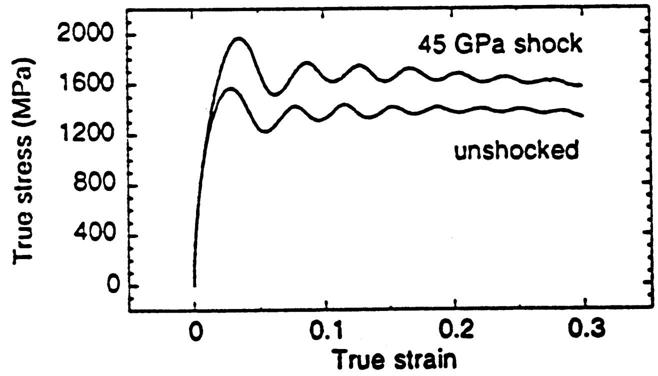
a) IM Ta



b) IM Ta-2.5%W



c) IM Ta-10%W



d) PM Ta

Figure 3: Dynamic compression tests of the materials in the shocked and unshocked conditions. ($\dot{\varepsilon} = 4 - 5 \times 10^3 s^{-1}$)

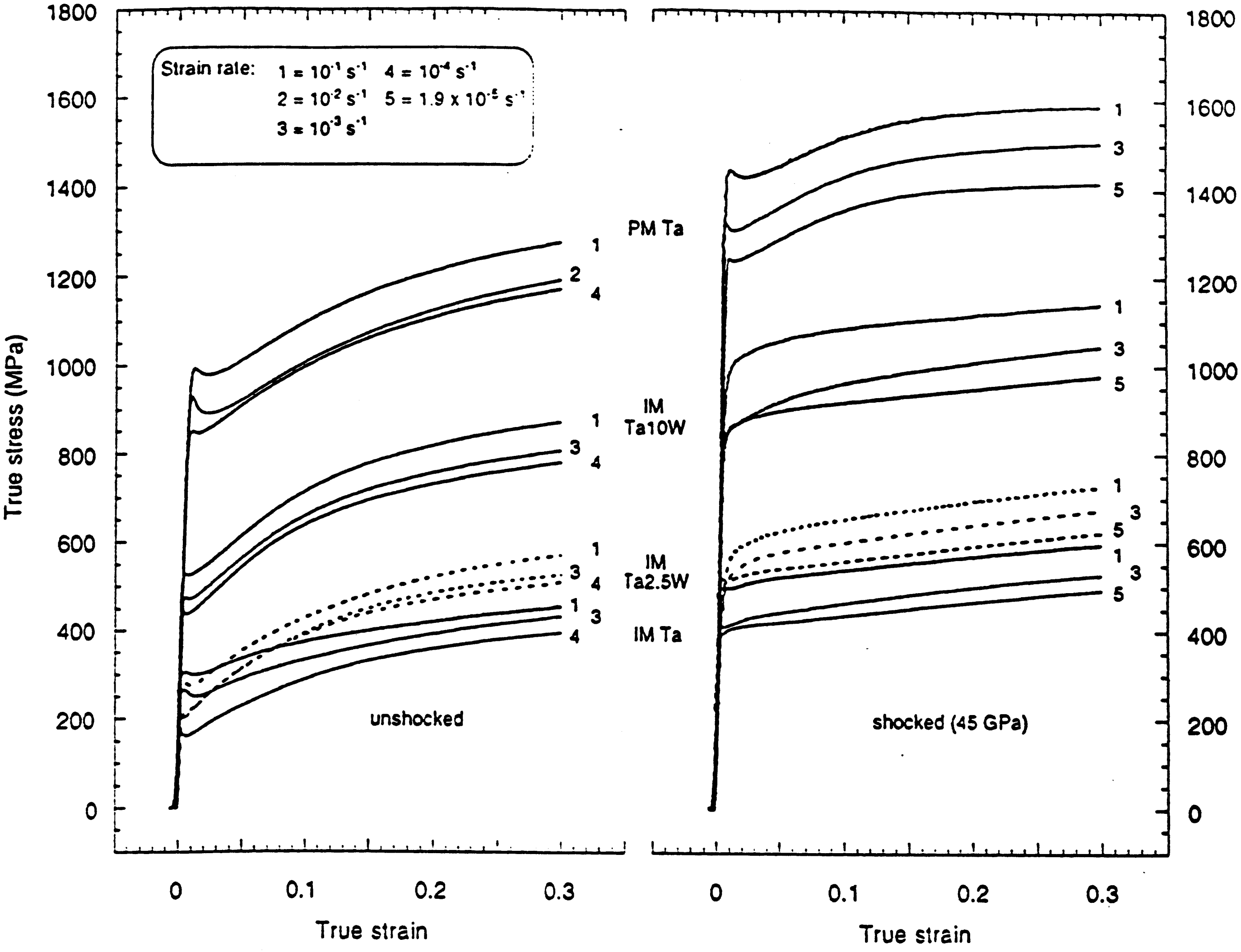


Figure 4: Engineering stress-strain behavior of the shocked and unshocked materials under quasistatic compressive loading.

Discussion

In this work we examined the effects of a 45 GPa, 1.8 µs shock on the post-shock mechanical response of unalloyed Ta, Ta-2.5%W and Ta-10%W alloys. Compression tests were performed on both shocked and unshocked material to assess the effects of the shock prestrain. The effects of the shock prestrain were qualitatively similar in all cases: an increase in the yield strength and subsequent flow stress with a slight decrease in the work hardening behavior. In Figure 5 the flow stress of the test materials at a strain of 0.10 is plotted as a function of strain rate and indicates that the strain rate sensitivity of the test materials was, to first order, unaffected by the shock prestrain. This suggests that the athermal component of the flow stress in these materials is increased [12]. In copper it has been observed that a decrease in grain size has a similar effect and results in change in the athermal component of the flow stress [13]. The observation of deformation bands that could be deformation twins in the shock recovered material (Figure 2) would seem to explain this behavior if the twins act as essentially as grain boundaries, i.e. barriers to dislocation motion which are essentially unaffected by thermal activation. This concept is explored in another paper appearing in this proceedings [14].

In a previous work by one of the authors (DHL) the effect of shock prestrain on the response of unalloyed Ta with a similar impurity content at a peak shock pressure (15 GPa) was studied [1]. In Figure 5 the flow stress at 10% strain of the annealed and shock-prestrained materials are shown for both the material shocked to 15 and 45 GPa. In comparison to the effect of the 45 GPa shock, there is very little effect of the 15 GPa shock on flow stress during reload. The metallographic observations of the material shock loaded at 15 GPa indicated very few deformation twins resulted from the shock prestrain. This appears to be consistent with the theory that the large number of deformation twins caused by the shock prestrain at 45 GPa are responsible for the substantial increase in yield and flow stress in unalloyed Ta.

Summary

We have examined the effects of a 45 GPa, 1.8 µs shock on the post-shock mechanical response of unalloyed IM Ta and PM Ta, Ta-2.5%W and Ta-10%W alloys. Qualitatively the effect of the shock prestrain was found to be similar in all of the test materials.

- The 45 GPa shock produced a high density of microstructural features which could be twins.

- The yield and flow stress of the shock-prestrained materials were substantially increased relative to the materials in the annealed condition.

- The strain rate sensitivities of the annealed and shock-prestrained materials were found to be similar. This suggests that the athermal component of the flow stress is increased in the shock-prestrained materials.

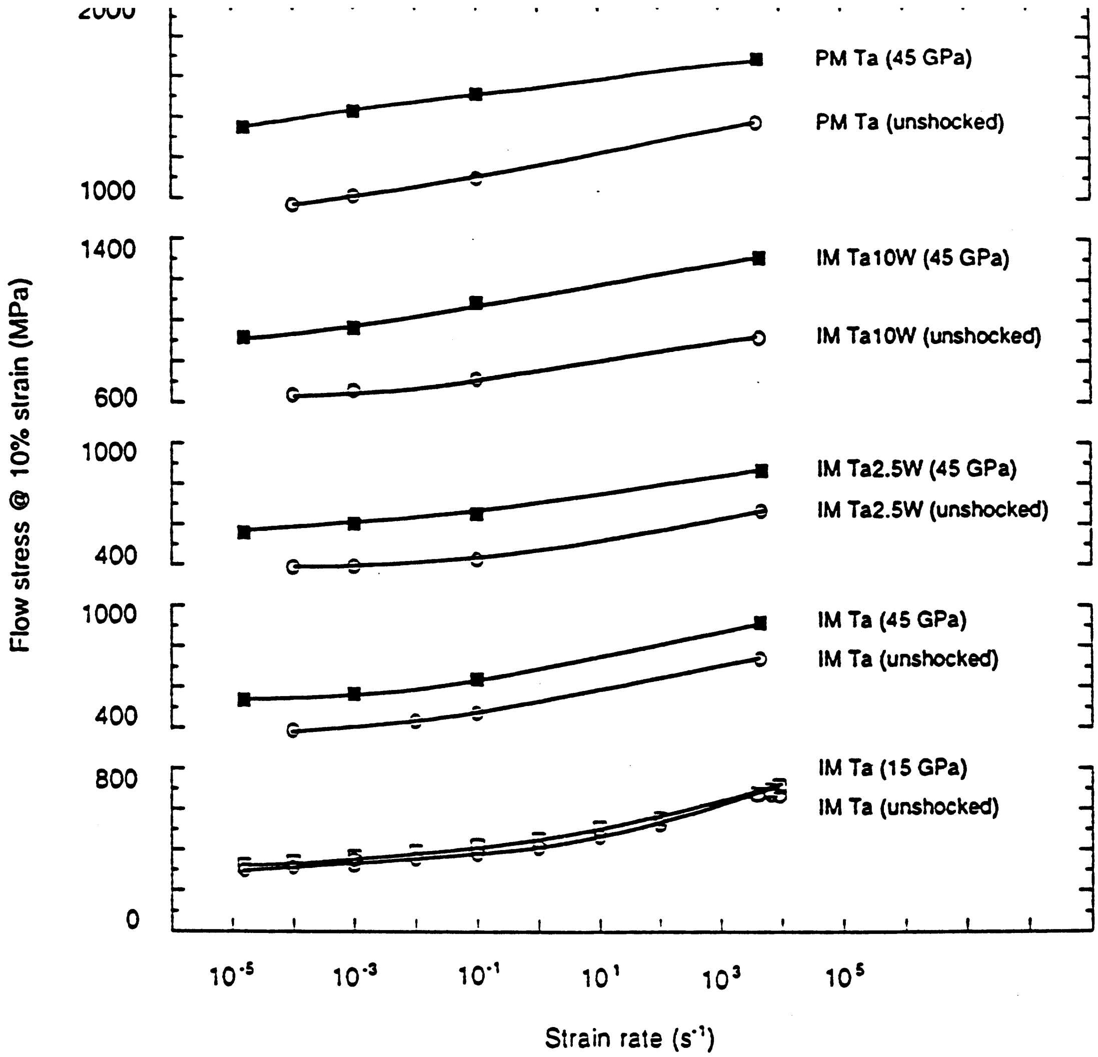


Figure 5: Plot of the strain rate sensitivities of the shocked and unshocked materials.

Acknowledgments

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