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Shock Driven Twinning in Tantalum Single Crystals

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SHOCK DRIVEN TWINNING IN TANTALUM SINGLE CRYSTALS

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Abstract. Recovery based observations of high pressure material behavior generated under high explosively driven flyer based loading conditions are reported. Two shock pressures, 25, and 55 GPa and four orientations {(100), (110), (111), (123)} were considered. Recovered material was characterized using electron backscatter diffraction along with a limited amount of transmission electron microscopy to assess the occurrence of twinning under each test condition. Material recovered from 25 GPa had a very small fraction of twinning for the (100), (110), and (111) oriented crystals while a more noticeable fraction of the (123) oriented crystal was twinned. Material recovered from 55 GPa showed little twinning for (100) orientation slightly more for the (111) orientation and a large area fraction for the (123) orientation. The EBSD and TEM observations of the underlying deformation substructure are rationalized by comparing with previous static and dynamic results.

Keywords: Shock, twinning, tantalum
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INTRODUCTION

The deformation behavior of tantalum has been studied extensively for both single [1-15] and polycrystalline [16-25] materials over a wide range of loading conditions. Carefully conducted single crystal compression experiments using a range of orientations have shown that twinning occurs at cryogenic temperatures (4.2°K) for most orientations persisting for a subset of orientations up to 77°K. The conditions for twin formation under these circumstances depend on both orientation relative to the compression axis and impurity content. Twinning in polycrystal tantalum has been seen sporadically at 77°K under high rate compressive loading conditions [26, 27].

Limited information has been obtained for shock loaded tantalum [28-33] and generally shows that twinning begins somewhere between 7 and 14 GPa and with twin frequency increasing up to the highest pressure recovered, 45 GPa. The only observations of shock recovered single crystal material [33], in the (001) orientation, reported significant numbers of both twins and metastable omega phase in roughly equal proportion.

EXPERIMENTAL PROCEDURE

Tantalum single crystals in four orientations, (001), (011), (111), and (123) were recovered after shock loading to 25 and 55 GPa on a two stage gas gun. Details of the recovery apparatus will be presented in a future publication.

In preparation for electron backscatter diffraction orientation imaging (EBSD), recovered samples were polished metallographically on the face perpendicular to the shock, or compression loading, direction ending with 0.05µm SiO_2 in a caustic colloidal solution.

Subsequent to EBSD analysis the samples were sectioned, ground with 800 grit SiC paper (under water) to a thickness of ≈ 200 µm, and cut into 2 mm diameter disks using electrical discharge machining. The 2 mm disks were thinned by dimpling and the final perforation was made with an ion mill.

EBSD orientation mapping was carried out in a Philips XL30S FEG-SEM operated at 20 keV. All scans were at a magnification of 1,000X with a raster step size between 170 and 200 nm. The probe beam was ≈ 5 nm in diameter and, given the sample inclination the probe dimensions would have been roughly elliptical (5 nm x 15 nm). The data then was parsed for information, such as misorientation distributions, to get a picture of the extent of deformation twinning. Subsequently, orientation maps were generated based on the inverse pole figures in the fundamental zone.

RESULTS AND DISCUSSION

Results of EBSD scans of material recovered from 25 and 55 GPa shocks are presented in figures 1-2 for each of the 4 orientations considered. Note that the scans cover areas of about 25,000 μm^2, an area approximately 2 orders of magnitude larger than is typically available during TEM examination. Coupled with the probe and step size (see above) the EBSD scans are likely to better identify infrequent twin formation but only at a size scale matched to the probe and scanning parameters.

Results for materials recovered from a 25 GPa shock show that twin formation is rare with a very small number of twins identified in the (001), (111) and (123) orientations while none are identified in the (011). These results are most easily seen in the accompanying pole diagrams for each orientation which indicate that one or two twin systems are operative for (001), (111) and (123).

Table I summarizes the number of slip systems available for each orientation and the corresponding Schmid Factors. Given the scarcity of twin formation it is difficult to draw a conclusion as to the correlation between Schmid factor or availability of multiple independent slip systems and twin occurrence.

For material recovered from the 55 GPa shock a number of interesting results can be seen in the EBSD scans.

It is clear that twinning is occurring with regularity in all orientations except the (001) direction, where there are very few identified twins in the scan area. The pole figure results indicate that at least 3-4 twin systems are operative in the remaining three orientations.

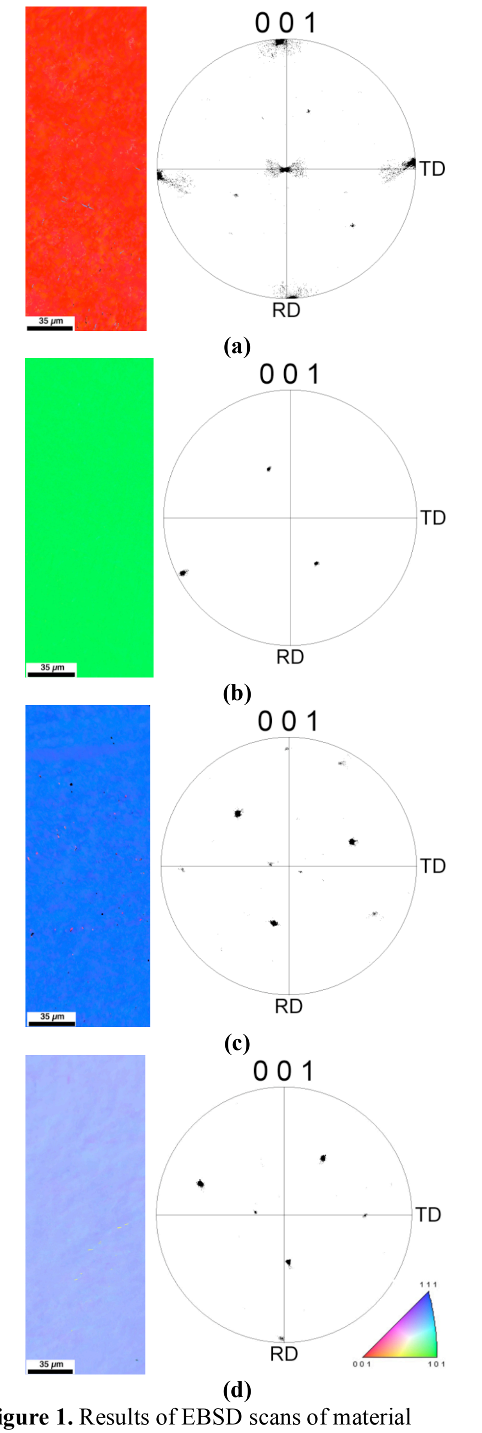

Figure 1. Results of EBSD scans of material recovered from 25 GPa for (001), (011), (111), (123) in (a)-(d) respectively. Left side shows orientation keyed to legend in (d), right side is the corresponding pole figure.

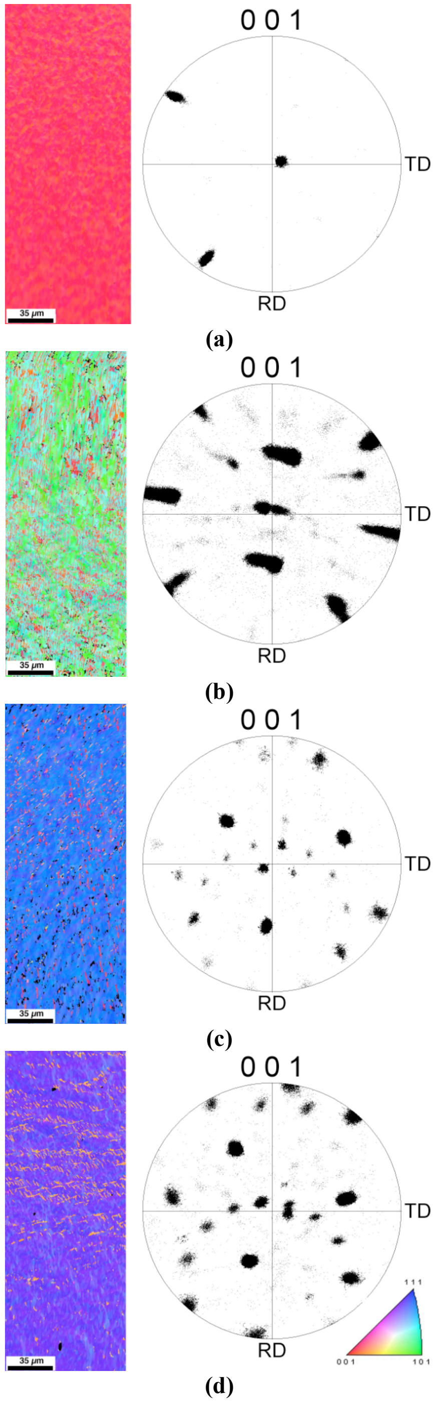

Figure 2. Results of EBSD scans of material recovered from 55 GPa for (001), (011), (111), (123) in (a)-(d) respectively. Left side shows orientation keyed to legend in (d), right side is the

A comparison of the area fraction of twins, also given in Table I, shows the most twinning occurred in the (011) oriented material while (111) and (123) orientations had approximately the same amount of twinning. These results appear to be consistent with the Schmid factors and availability of slip systems.

Table I. Twinned area fraction in 55GPa recovered material

Orientation	Area Fraction twinned	Slip Systems	Primary Schmid Factor*
(001)	≈ 0	8	0.41
(011)	0.18	4	0.41
(111)	0.06	6	0.27
(123)	0.06	9	0.12-0.47**

* For cases where there are multiple families
** (123) has 4 system with Schmid factor > 0.29 and 5 others with less favorable orientations

Preliminary TEM based observations are presented in figures 3 and 4 for (001) and (111) orientations recovered from 55 GPa. Significant residual dislocation density is present in both orientations. Both orientations also display residual twins and possibly Omega phase, the latter requiring additional analysis for confirmation. It is

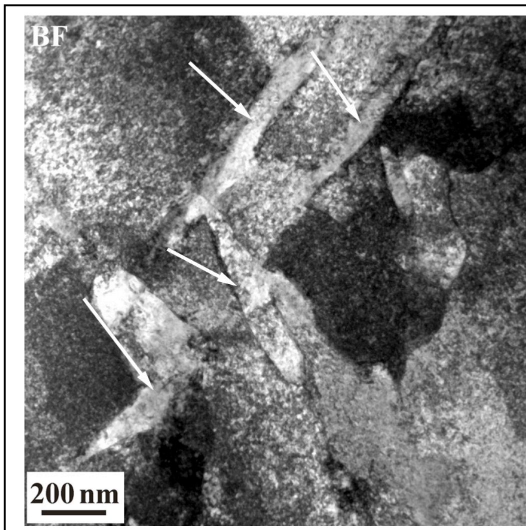

Figure 3. Bright field TEM micrograph of (001) material recovered from 55 GPa. Twins marked by arrows were confirmed using diffraction and dark filed imaging.

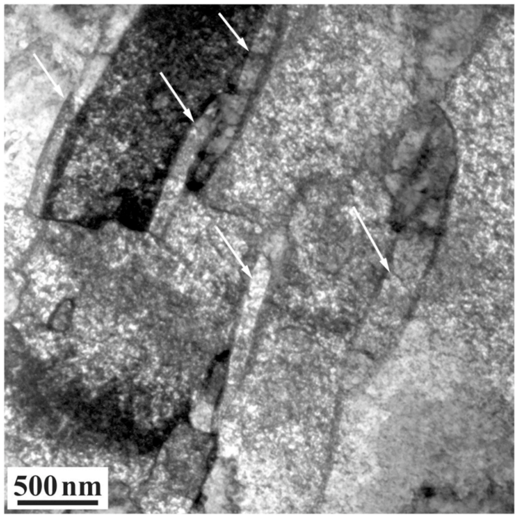

Figure 4. Bright field TEM micrograph of (111) material recovered from 55 GPa. Twins marked by arrows were confirmed using diffraction and dark filed imaging.

interesting to note that the TEM results are consistent with the EBSD for (111) but not for (001) where, as presented above, no twins were seen in EBSD. One possible explanation for this is that the TEM observations are sensitive to the finer scale twins in both cases and that the larger twins seen in the EBSD are not present in the (001) oriented material.

CONCLUSIONS

EBSD observations of single crystal tantalum recovered from shock loading at 25 and 55 GPa indicate that:

- Virtually no twinning is present for material recovered from 25 GPa
- For material recovered from 55 GPa twinning increases from essentially none for (001) to heavily twinned in (011)
- Results are consistent with trends expected from crystal orientation

Preliminary TEM observations for (001) and (111) at 55 GPa indicate twinning and omega phase formation

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