Orientation dependence of shock induced dislocations in tantalum single crystals.

B Pang¹, I Jones¹, Y Chiu¹, J Millett², G Whiteman², N Bourne²

¹School of Metallurgy and Materials, the University of Birmingham, Birmingham B15 2TT, UK,
²AWE, Aldermaston, Reading, Berkshire RG7 4PR, United Kingdom

E-mail: BXP171@bham.ac.uk

Abstract: A planar shock wave with a peak pressure of 6.2 GPa and duration of 1.7 µs followed by a lateral release wave generates profuse dislocations in single crystalline tantalum. Three orientations [100], [110], [111] were tested to examine the orientation dependence of the dislocation generation. The dislocations were characterised by transmission electron microscopy. The Burgers vectors and morphology of the primary dislocations in the specimens with different orientations showed a distinct orientation dependence and will be discussed in light of the model of slip behaviour in one-dimensional strain of C.S. Smith [1].

1. Introduction

There is a need to understand the deformation mechanism of materials in high rate shock loading-unloading phenomena. The deformation behaviour of material under one dimensional shock loading has been extensively studied over the past few decades. The tested materials were generally shock loaded by a plane wave and unloaded in the same direction with a planar release wave. The experimental data is usually taken from the shock front to investigate the material behaviour at high pressure, with less attention paid to the effect of the release wave. However, plate impact experiments by Stevens show that in some cases the plastic strain made by radial release is even bigger than that of the shock wave [2]. In a real shock loading condition like foreign object damage on aircraft, the loading cannot always be one dimensional. Therefore, for strengthening materials, we should consider the lateral release as as important as the shock wave front.

Experimental results on laser compressed tantalum single crystals have revealed that dislocation walls formed in samples with a loading axis of [001] when the local pressure is higher than 21GPa [3]. In explosive shock experiments on polycrystalline tantalum, it was found that dislocations formed a cell structure under a pressure of 45GPa but not under 15GPa [4]. Long screw dislocations, dislocation tangles and loops were detected in polycrystalline tantalum shock loaded using a gas gun recovery technique[5]. Most previous research focused on dislocation density and morphology, without much attention to the slip direction of the dislocations. As predicted by the model of Smith [1], the slip systems activated in a 1-D shock wave should tend to resolve the uniaxial principal strain into the other two directions, which means that dislocations should slip on a direction close to 45° to the loading direction[1]. In this paper, tantalum was chosen as a model material representing the body centred cubic structure. Single crystals with principal orientations [111], [011] and [001] were shocked with a planar wave and released radially. The defects generated by the shock and release wave were characterised by TEM to see if the deformation mechanisms of tantalum match with the predictions of Smith’s model.

2. Experimental procedure

Single crystal tantalum with 12mm diameter and 4mm thickness were subjected to a plate impact experiment along three directions, [111], [011] and [001] to a peak pressure of 6GPa. Instead of using a recovery assembly with momentum rings, the specimen plates were mounted in epoxy to provide a lateral release wave.
Foils for TEM examination were obtained from the as-received materials and from the front surface impacted by the projectile of the shock recovered specimens, as shown in Figure 1. The front surface of the samples are sliced by EDM spark machine and 3-4 discs were punched from each specimen. They were prepared by electropolishing at about ~25V and ~ -15°C in an electrolyte containing 86 vol. % methanol, 10 vol. % sulphuric acid and 4 vol. % hydrofluoric acid. The deformation substructures were then examined using a JEOL 2100 TEM.

![Figure 1 Sketch shows shock direction and sample position.](image)

3. Results and Discussion

3.1. Dislocation morphology and density

TEM bright field images of the as-received and the recovered materials are presented in Figure 2. The TEM foils taken from same sample reveal the same characteristics. The as-received tantalum single crystals have a dislocation density of about $6 \times 10^8 cm^{-2}$.

![Figure 2 Dislocation substructure of (a) the as-received [111] (b) as-received [011] (c) as-received [001] (d) shocked [111] (e) shocked [011] (f) shocked [001]](image)
After shock recovery, the substructures in the [111] and [011] samples are similar in that both contain dislocation walls constructed with tangled dislocations, aligned with a separation of around 1μm (A and B in Figure 2) and a low density of long screw dislocations and high density of small dislocation loops in between the walls. In the [001] loaded sample, no dislocation walls were detected. The dislocation densities calculated from the TEM images are $6 \times 10^{10} \text{cm}^{-2}$, $4 \times 10^{10} \text{cm}^{-2}$ and $2 \times 10^{10} \text{cm}^{-2}$ for samples loaded along [111], [011] and [001], respectively, which agree with the expected dislocation densities from [4] and [5].

The driving force for dislocation wall formation is recognised as arising from a reduction in the total elastic energy of the dislocations because of clustering [6]. It means the material needs a very high dislocation density with a high energy state for the dislocation wall to form. The dislocation density in the [001] sample is considered to be too low for it to decompose into dislocation walls. As shown in the TEM image it is lower than in the other two orientations [3]. The morphology of the dislocation walls is similar to those observed in fatigued specimens. A probable reason for their formation is the compression-tension cycle made by the shock and then lateral release waves. These last in the current experiment, are much stronger than the laser and explosive induced lateral release waves. The compression-tension cycle is similar to fatigue, but with fewer cycles and a higher loading stress [7].

3.2. Burgers vector analysis

The Burgers vectors of the dislocations were analysed, except the ones tangled in the dislocation walls. Figure 3 shows an example of images obtained using different reflections. The results of the analysis are shown in table 1. From the TEM images the densities of the activated slip systems are uniform in each sample. It seems that in the sample with [111] and [001] loading directions, the activated slip systems are those which resolve the strain from 1-D to 3-D as predicted by the model of Smith [1], but the dislocations in the sample loaded along [011] have their Burgers vector perpendicular to the loading direction. These dislocations are not expected to be activated in uniaxial loading. The reason for the anomalous slip in the [011] loaded sample is still unclear.

Table 1 The Burgers vectors of dislocations in the shocked specimens

| Sample | 111     | 011     | 001     |
|--------|---------|---------|---------|
| Burgers vector | $[11\bar{1}], [1\bar{1}1], [\bar{1}1\bar{1}]$ | $[1\bar{1}1], [\bar{1}1\bar{1}]$ | $[\bar{1}1\bar{1}], [\bar{1}1\bar{1}], [111], [1\bar{1}]$ |

Figure 3 Dislocation substructure obtained from [111] sample with B=111: (a) g=11̅0 (b) g=0 1̅1 (c) g= 101

Table 1 The Burgers vectors of dislocations in the shocked specimens
3.3. Twins

The twin area fractions are about 1%, 2% and 5% in samples loaded along [111], [011] and [001]. Figure 4 shows examples of twins in the three specimens. It has been reported that the twinning threshold pressure in planar shock experiments is higher than 7GPa [8].

Figure 4 TEM images showing twins in sample shock loaded along (a) [111] (b) [011] (c) [001]

Since the peak pressure employed in the current study (6GPa) is lower than the twinning threshold pressure reported, it is possible that the twins observed in this work may originate from the lateral release wave. This is different from the initial shock for various probable reasons: (i) the dislocations already present may not be the appropriate ones to accomplish the reverse strain via a lateral release wave, (ii) the dislocations present will almost certainly be tangled, raising the stress necessary for glide, (iii) the tensile strain may be higher than the compressive strain if release waves from (laterally) opposite directions arrive at the centre of the specimen together.

4. Conclusions

1. In the [111] and [011] specimens, dislocations are tangled into dislocation walls, similar to those after fatigue. This might result from the compression-tension cycle made by the shock and lateral release waves.
2. Dislocations in the samples with [111] and [001] loading follow Smith’s model. However in the [011] specimen unexpected slip in the direction perpendicular to the loading direction occurs.
3. Lateral release induced twins are found at a pressure lower than the published threshold.

5. Reference

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