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DOI:

[10.1063/1.5044801](https://doi.org/10.1063/1.5044801)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

Millett, JCF, Higgins, DL, Whiteman, G, Pang, B, Chiu, YL & Jones, IP 2018, Contrasting the effects of cold rolling on the shock response of typical face centred cubic and body centred cubic metals. in *Shock Compression of Condensed Matter - 2017: Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter*. vol. 1979, 060004, AIP Publishing, 20th Biennial American Physical Society Conference on Shock Compression of Condensed Matter, SCCM 2017, St. Louis, United States, 9/07/17. <https://doi.org/10.1063/1.5044801>

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Published as: Millett, J. C. F., et al. "Contrasting the effects of cold rolling on the shock response of typical face centred cubic and body centred cubic metals." AIP Conference Proceedings. Vol. 1979. No. 1. AIP Publishing, 2018.
Version of Record available online at: <https://doi.org/10.1063/1.5044801>

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Citation: [AIP Conference Proceedings](#) **1979**, 060004 (2018); doi: 10.1063/1.5044801

View online: <https://doi.org/10.1063/1.5044801>

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Contrasting the Effects of Cold Rolling on the Shock Response of Typical Face Centred Cubic and Body Centred Cubic Metals

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Abstract. The response of metals to shock loading is affected by a number of factors, including the unit cell and properties that affect the motion and generation of dislocations such as stacking fault energy and the Peierls stress. In an effort to increase the understanding in this area, we have chosen to investigate the response of two near ideal materials; copper as an fcc and tantalum as a bcc. We have also investigated each material in both an annealed and cold worked to 50% reduction in thickness in an attempt to understand how differences in dislocation density affect response. Measurements have been made using standard diagnostics, including stress gauges and Photonic Doppler Velocimetry as well as analysis of the shocked microstructural and mechanical response through one-dimensional recovery.

INTRODUCTION

The behavior of metallic materials under mechanical loading, including shock loading is controlled by a number of factors, including the unit cell, level of alloying, distribution of second phases and prior dislocation density. At the most fundamental level, unit cell is likely the most important. Face centred cubic (fcc) metals such as copper or aluminium deform via dislocation motion and distribution, forming a well defined cell structure on release from shock loading [1, 2]. In contrast, body centred cubic metals such as tantalum are more likely to accommodate shock deformation via the motion of dislocations already present within the microstructure [3]. However, other factors can dominate the mechanical response. For example, a reduction in stacking fault energy in fcc metals (either in a pure metal like silver [4], or via alloying in copper alloys [5]) can result in a shift in deformation mechanism from dislocation formation to twinning, whilst in bcc metals, a reduction in Peierls stress (such as in niobium) can result in a much higher proportion of the deformation being accommodated by dislocation generation rather than motion of pre-existing dislocations [6]. The effects of increasing dislocation density before shock loading has been much less studied, although a series of papers have reported on the role of dislocation density on tantalum [7-9]. In this paper, we examine the effects of dislocation density on the shock response of two near ideal fcc and bcc metals, copper and tantalum.

EXPERIMENTAL

All experiments were performed on a series of single stage gas guns located at the University of Cambridge, Cranfield University, AWE and Imperial College, London. Copper was purchased in the form of 'half-hard' plate,

whereby the material had received cold rolling treatment to a reduction of thickness of 21% to give it a degree of strength to make handling easier. Some of this material was subsequently annealed for 1 hour at 425 °C to reduce the prior dislocation density. Tantalum was obtained in the form of 75 mm diameter bar stock in an annealed state. 25 mm thick pucks were sectioned from the bar stock, and then cold rolled at Cranfield University. This was done to an incremental reduction in thickness of 50% under a constant rolling direction. The mechanical response to shock loading was monitored using laterally mounted stress gauges [10] 2 mm from the impact face, and in the case of tantalum, Hetrodyne velocimetry (Het-V; PDV) [11] was used to measure the motion of the free surface. The microstructural response was determined using the techniques of Gray and his colleagues [12, 13], and examined using a variety of microstructural techniques (TEM *etc*).

RESULTS AND DISCUSSION

Representative lateral stress gauge traces from copper and tantalum are presented in Figure 1a. The examples shown here are for half hard copper and annealed tantalum, although the basic features are also present in annealed copper and cold rolled tantalum. Note that in the case of copper, it would appear that lateral stress drops over a period of approximately 1 μ s before reaching a near constant value. In contrast, tantalum shows a steady increase in lateral stress before releases enter the gauge location. As shear strength (τ) can be determined through the orthogonal components of stress (σ_x and σ_y), and that lateral stress can be seen to evolve with time in both materials, we have taken this parameter at specific locations from the stress-time traces in Figure 1a; where lateral stress reaches a constant level in copper and immediately behind the shock front in tantalum, as indicated by the arrows.

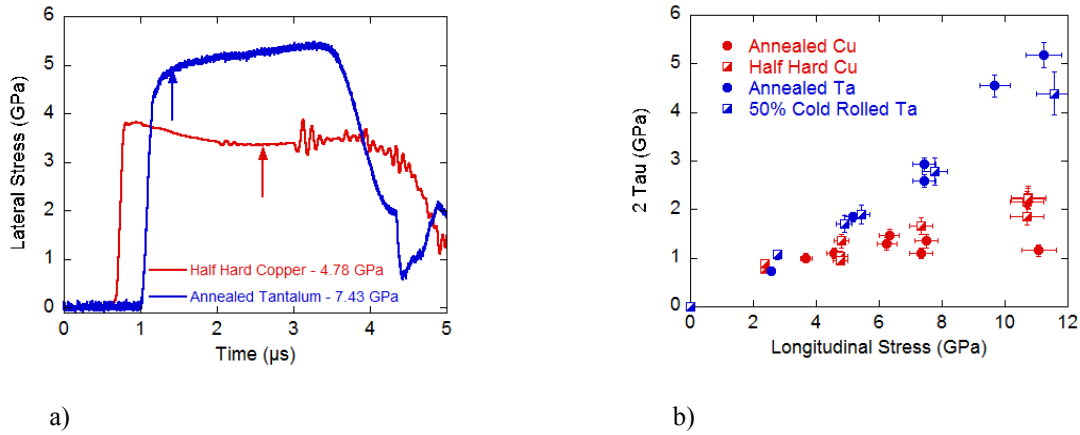


FIGURE 1. Lateral stress traces (a) and corresponding shear strengths (b) in annealed and cold rolled copper and tantalum

From these, we have calculated the shear strength behind the shock front through the relation,

$$2\tau = \sigma_x - \sigma_y \quad (1)$$

This implies that shear strength *increases* behind the shock front for copper and *decreases* behind the shock front for tantalum. In the case of copper, similar results have been observed in pure nickel [14], and seen to occur over the same time scales that the shocked microstructure takes to reach a stable confirmation [15]. In both materials, shear strength increases with shock stress, as shown in Figure 1b. In the case of copper, it would appear that a cold rolled material

has a greater increase in shear strength than its annealed counterpart. With tantalum, the dependence with prior microstructure is less significant.

We have explored these issues further by microstructurally examining shocked and recovered specimens.

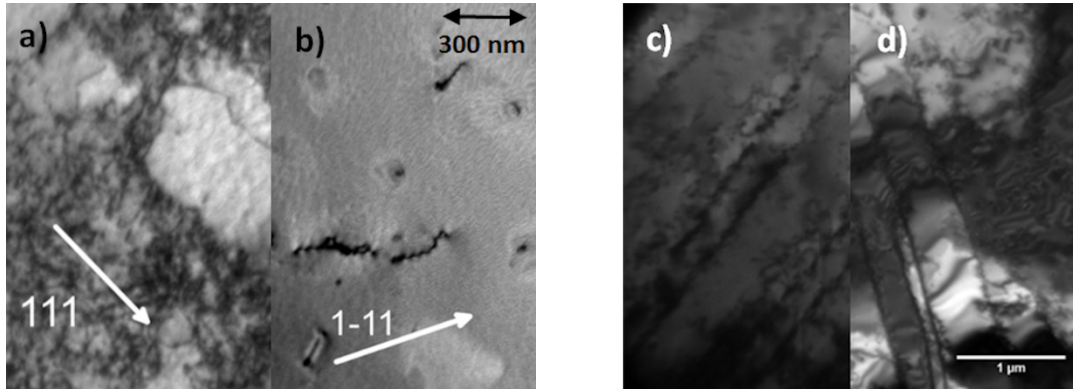


FIGURE 2. TEM micrographs for as-received copper and tantalum – a) half hard Cu; b) annealed Cu; c) annealed Ta; d) 50% cold rolled Ta.

In Figure 2, we show transmission electron micrographs of copper and tantalum prior to shock loading. In the case of copper, the as-received material in the half hard state (corresponding to a reduction in thickness of *ca.* 21%), the microstructure consists of a network of well-defined dislocation cells. After annealing at 425 °C for one hour, the dislocation density is reduced significantly to a few isolated dislocations within the microstructure. In Figure 2c, the microstructure of the as received tantalum from the original bar stock consists of dislocations lying in cell walls. After a cold rolling treatment of 50% reduction in thickness, these cell walls have tightened up to the point where they have become low angle boundaries.

The following figures show the effects of shock loading and initial microstructure on copper and tantalum. In Figure 3, we show microstructures from shock loaded copper, with 3a from an initial annealed state (shocked to 5 GPa) and 3b from a starting half-hard condition and shocked to 6 GPa. In the case of the annealed material has developed a cell structure similar to that of cold rolled copper although shock loading has led to a more loosely defined cell wall structure. This is similar to results observed by Gray and Morris [1].

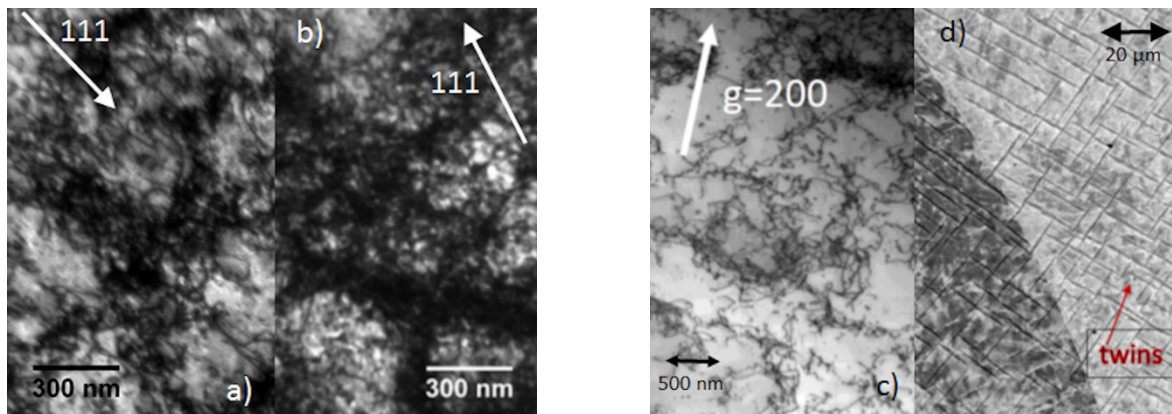


FIGURE 3. Microstructures of shocked copper and tantalum. a) TEM image of annealed Cu at 5 GPa; b) TEM image of half hard Cu at 6 GPa; c) TEM image of annealed Ta at 24 GPa; d) SEM image of annealed Ta at 24 GPa

Shock loading a microstructure already possessed of a high dislocation density, as in Figure 2a also produces a cell structure, but this time the dislocation density in the walls themselves is much higher, as well as a higher dislocation density in the cell interiors as well. This would appear to be consistent with the observations of the shear strength in Figure 1b that shows that half hard copper has a greater shear strength than annealed copper.

The effects of prior cold work on tantalum are equally significant. For annealed tantalum (Figure 3c-d), shocked to 24 GPa, deformation can be seen to consist of a mixture of dislocation motion and twin formation (the latter observed via scanning electron microscopy, the details of which are discussed elsewhere [16], similar to results shown by Gray and Vecchio [3]. Twinning was observed to become more prevalent with increasing shock stress, and in larger grains. In contrast, after a cold rolling treatment, no evidence of twinning is observed (Figure 4a-b), although the microstructure has a significant number of long, low angle boundaries present.

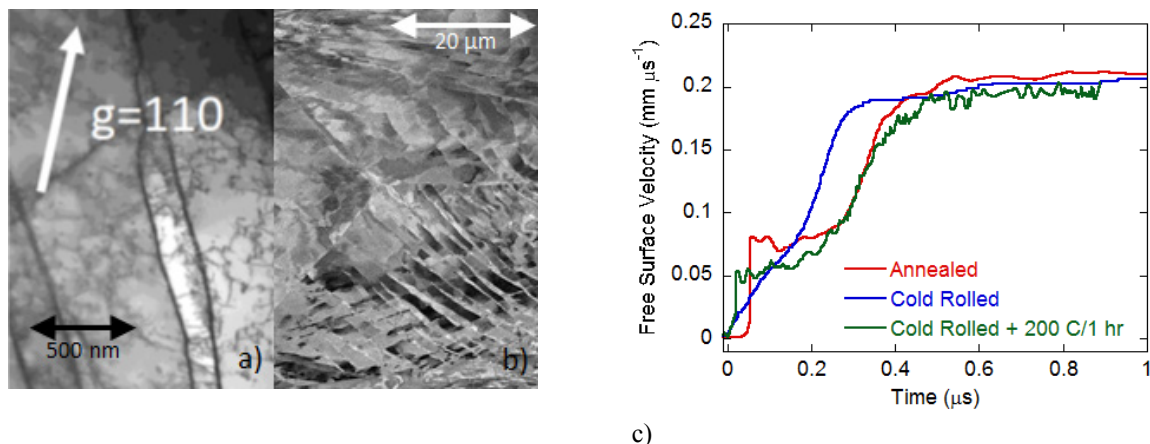


FIGURE 4. Effects of prior cold rolling on the shock response of tantalum. a) TEM and b) SEM images of cold rolled Ta shocked to 15 GPa. c) HetV traces showing the effects of cold rolling and subsequent low temperature heat treatment on the HEL.

In a previous work [8] (also noted by others [7, 9]) it was observed that the upper and low yield points at the HEL were removed by cold rolling. It was suggested that this was due to an accumulation of interstitial oxygen atoms around dislocations, effectively pinning them in place, and thus requiring a high stress to remove them. A cold rolling treatment would provide the initial stress required to move them, hence dislocation mobility would be increased by this process, and hence the requirement for plasticity to be accommodated by twinning would be reduced or even eliminated. We were able to explore this issue further by strain-aging; a low temperature heat treatment at 200°C for 1 hour of cold rolled material. The results are shown in Figure 4c. Here it can be seen that in the annealed material, there is a clear upper and lower yield point on the HEL which is clearly removed by cold rolling. Heat treating the cold rolled material at 200°C results in the return of the upper and lower yield points as the increase in temperature allows oxygen atoms to diffuse through the lattice and re-accumulate around existing dislocations.

CONCLUSIONS

The effects of a prior cold working treatment on typical fcc – copper and bcc – tantalum metals on the response to shock loading have been examined by plate impact experiments. Results indicate that in the case of copper, the shear strength behind the shock front increases after cold rolling. Microstructural examination has shown that dislocation density is significantly greater in the shocked, rolled material when compared to the shocked, annealed material. In the case of tantalum, lateral stress increases behind the shock front suggesting that shear strength decreases behind the shock front, whilst cold rolling appears to have little effect on shear strength as shock stress increases. In the annealed material, the deformation microstructure appears to be dominated by the motion of pre-existing dislocations, with twinning becoming more prevalent as impact stress increases. With a prior cold rolling treatment, dislocation motion is again dominant, although there is also the formation of long, thin sub-grains. However, there is no evidence of twin formation. It has been suggested that prior cold deformation removes dislocations from surrounding interstitial oxygen

atoms, essentially increasing their mobility and thus reducing the necessity for twinning to accommodate the applied plasticity. Such effects may also result in the removal of the upper and lower yield points in the HEL of the cold rolled material. A subsequent low temperature heat treatment appears to restore the upper and lower yield points. It has been suggested that this is due to oxygen atoms diffusing through the lattice and re-accumulating around dislocations.

ACKNOWLEDGMENTS

We would like to thanks the staff and students of the Cavendish Laboratory, Cranfield University, Imperial College London and AWE for their help and support in this project. British Crown Owned Copyright 2017/AWE. Published with permission of the Controller of Her Britannic Majesty's Stationery Office. "This document is of United Kingdom origin and contains proprietary information which is the property of the Secretary of State for Defence. It is furnished in confidence and may not be copied, used or disclosed in whole or in part without prior written consent of Defence Intellectual Property Rights DGDCDIPR-PL-Ministry of Defence, Abbey Wood, Bristol, BS348JH, England."

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