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Influence of Peak Pressure and Pulse Duration on Substructure Development and Threshold Stress Measurements in Shock-loaded Copper

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Introduction

Systematic shock recovery experiments, in which microstructural and mechanical property effects are characterized quantitatively, constitute an important tool to investigate the response of materials to shock-wave deformation. The micro-mechanisms of shock deformation are beginning to emerge through studies of the effects of variations of metallurgical and shock-loading parameters on structure/property relationships.(1) Considering the parameters of shock deformation studied to date, peak pressure, and to a lesser extent pulse duration, are generally agreed to be the major parameters influencing post-shock mechanical behavior through the development and extent of dislocations, stacking faults, twins, and point defects(1). In high stacking fault energy FCC metals, such as copper, extensive research has shown that as the peak pressure is increased, the dislocation density increases and the observed dislocation cell size decreases.(2) The occurence of deformation twinning is also seen to increase with pressure.(2) The exact influence of pulse duration on substructure development and mechanical response, however, has not defined a self-consistent pattern in the literature.(3-8) In general, the effect of pulse duration has been qualitatively explained as related to the time interval available for dislocation reorganization. Consistent with this rational, cell walls are observed to become better defined as the pulse duration is increased.(3) The concepts of reorganization however, which are postulated to encompass a recovery or stress relaxation event, during the pulse duration time interval is directly opposite to experimental observations of an increase in hardness and yield strength with pulse duration. Twin density is also seen to increase with increasing pulse duration, explained by a threshold time needed for twinning. Overall, these experimental observations present an incongruous picture of the pulse duration stage of the shock process that is thermodynamically considered to be in "steady-state equilibrium".(9)

The object of the present study was to systematically investigate the effect of peak pressure and in particular, pulse duration on the structure/property relationships of OFE copper. The effect of peak pressure and pulse duration are discussed in terms of substructure development and their

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corresponding mechanical threshold stresses(10) as a function of applied shock-wave parameters.

Experimental Procedure

Oxygen-free-electronic (OFE) copper was selected for this study since its shock-deformation behavior has been extensively studied. Specimens for the shock recovery experiments were machined from as-received starting plate and recrystallized in vacuum at 600 ^{0}C for one hour yielding an equiaxed grain structure of nominally 40 μm. Shock recovery experiments were performed utilizing a 40-mm single-stage gas gun. The specimen shock assembly consisted of a 4.76 mm thick, 12mm diameter sample tightly fitting into a similarly sized bored recess in the inner momentum ring/spall plate(25.4mm diameter). This central cylinder is inturn surrounded by two concentric momentum trapping rings with outside diameters of 31.7 and 44.5mm. The sample surface was protected from impact and the entire sample from spallation by a close-fitting cover plate (2.54mm) and spall plate support(12mm), respectively. All sample assembly components were made of copper to ensure impedance matching during shock-loading.

Copper samples were shocked to pressures of 5,10,and 20 GPa for pulse durations of 0.1 to 2.0 μsec by impacting various thickness copper flyer plates with the specimen assembly in vacuum. Samples were "soft" recovered to minimize residual plastic strain by decelerating the sample/inner momentum ring in a water catch chamber positioned immediately behind the impact area. All of the shock-loaded samples investigated in this study were shock-recovered possessing fixed residual plastic strains of less than or equal to 1.5 percent. Compression specimens were electro-discharge machined (EDM) from the recovered shock-loaded sample and reloaded at a strain rate of 0.0015 s^{-1} with a screw-driven mechanical testing machine. Two specimens were reloaded at room temperature (297K) and two were reloaded at liquid nitrogen temperature (76K). Samples for optical and transmission electron microscopy (TEM) were sectioned from the pieces of the shock deformed disc which remained after the compression specimens were removed. Discs 3mm in diameter were punched and electropolished in a solution of 25% H_3PO_4 and 75% H_2O at 0^0C utilizing a current density of 80 mA/mm^2. Observation of the foils was made using either a Philips 400 at 120KV or a JEOL 2000EX at 200KV utilizing goniometer-tilt stages.

Experimental Results

The substructure and mechanical thresholds of copper following shock-loading was found to depend on both the peak pressure and pulse duration of the shock. Figure 1 presents a normalized plot of reload yield stress versus test temperature illustrating the increase in yield strength with increasing peak pressure or pulse duration. The intercept at zero temperature in this plot gives the mechanical threshold stress normalized by the shear modulus while the slope is inversely related to the normalized activation energy.(10) Increasing the peak pressure from 5 GPa, 1μsec to 10 GPa, 0.1μsec and 10 GPa, 1μsec shows an increase in the yield strength at both temperatures, with a similar slope to the data. Changing the pulse duration from 1 to 2 μsec at 10 GPa is observed to significantly increase the yield strength response of shock-recovered copper at a steeper slope compared to the 1 μsec data. Further increasing the peak pressure to 20 GPa for a 1 μsec pulse duration produces a sample possessing the highest yield response of the shock parameter matrix tested, the slope of the data being similar to the 2 μsec 10 GPa shock. Figure 2 presents the room-temperature compressive true stress-true strain data for the 10 GPa shocks as a function of pulse duration. The quasi-static stress-strain curve of the annealed starting copper is included for comparison. Simililar to Figure 1, the yield strength of shock-loaded copper is observed to increase with increasing pulse duration. Additionally, the work-hardening rate is seen to systematically decrease with increasing pulse duration.

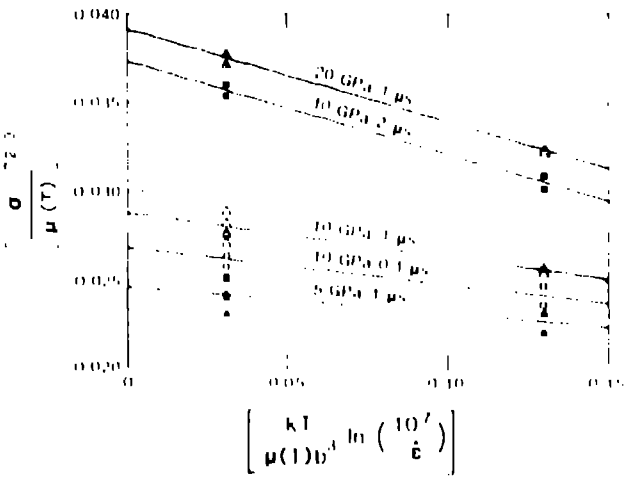

Figure 1: Normalized plot of reload yield stress vs. test temperature.

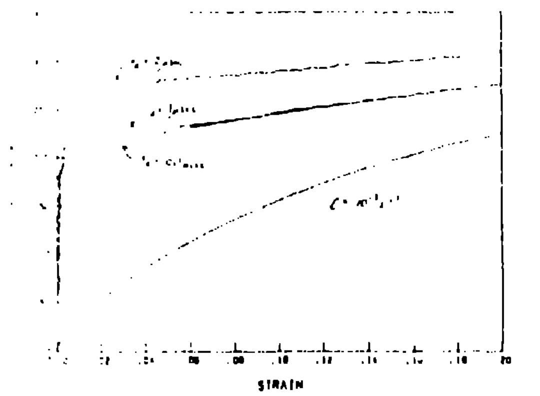

Figure 2: True stress-true strain plot showing effect of pulse duration.

Electron microscopic examination of the shock-loaded copper samples revealed that the dislocation substructure is dependent on the shock-wave paramenters. Figures 3 thru 8 present TEM micrographs (all [110] zone axis) characteristic of the deformation substructure of shock-loaded copper as a function of peak pressure and pulse duration. Consistent with the literature(1), increasing the peak pressure from 5 to 10 to 20 GPa, at a constant pulse duration, is observed to increase the overall dislocation density and decrease the dislocation cell size. The observed cell sizes for the 5, 10, and 20 GPa, 1 μsec shocks were approximately 0.6, 0.4, and 0.2 respectively. In addition to dislocation cells, shock-loading at 20 GPa produced deformation twins and concentrated bands of planar slip.(Figure 8) Dislocation loops were also observed to be very numerous in all of the shock samples examined; however no significant difference in loop density as a function of shock-wave parameter could be readily ascertained. Changing the pulse duration from 0.1 to 2 μsec is also seen to produce changes in the deformation substructure, although not as drastically as found with changes in peak pressure. Increasing the duration from 0.1 to 1 μsec produces more defined dislocation cell walls in the substructure, and a corresponding decrease in cell size from approximately 0.5 to 0.4 microns. Further increasing the duration to 2 μsec produced a poorly formed cellular substructure, approximately 0.3 micron in diameter, with the

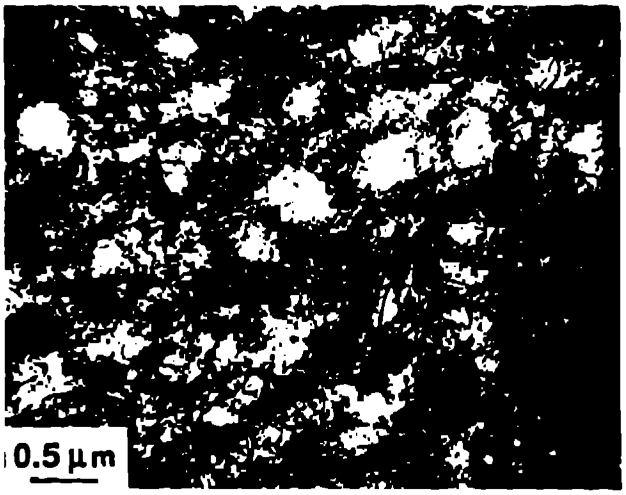

Figure 3:TEM micrograph of copper shock-loaded to 5 GPa 1 μsec.

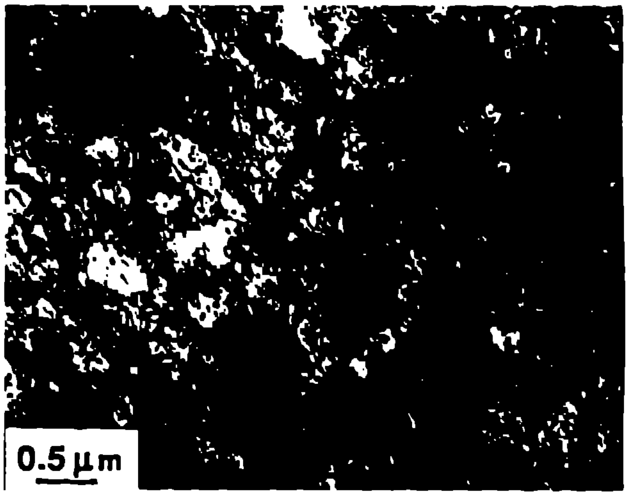

Figure 4: TEM micrograph of copper shock-loaded to 10 GPa 0.1 μsec.

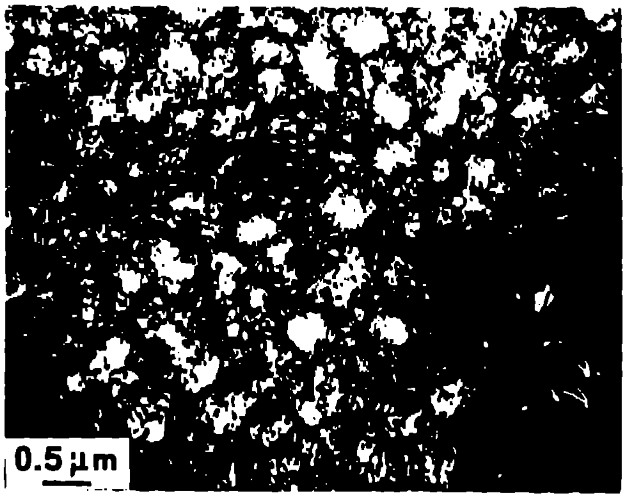

Figure 5:TEM micrograph of copper shock-loaded to 10 GPa 1 μsec.

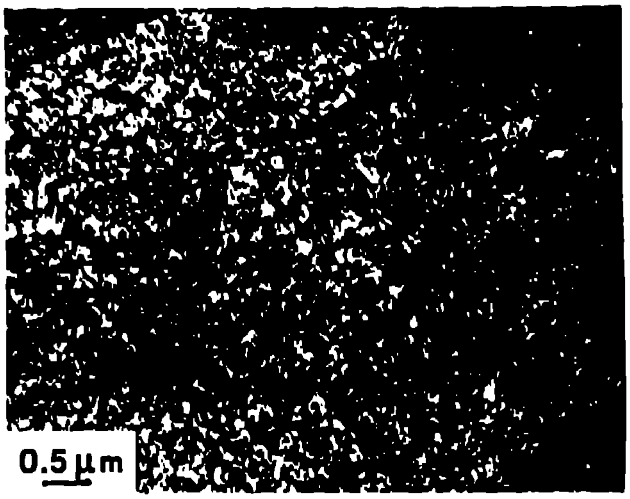

Figure 6:TEM micrograph of copper shock-loaded to 10 GPa 2μsec.

addition of planar intense slip bands and features resembling microbands in rolled copper(11) and nickel(12). Selected area diffraction analysis confirmed that the microbands occurred on {111} planes.

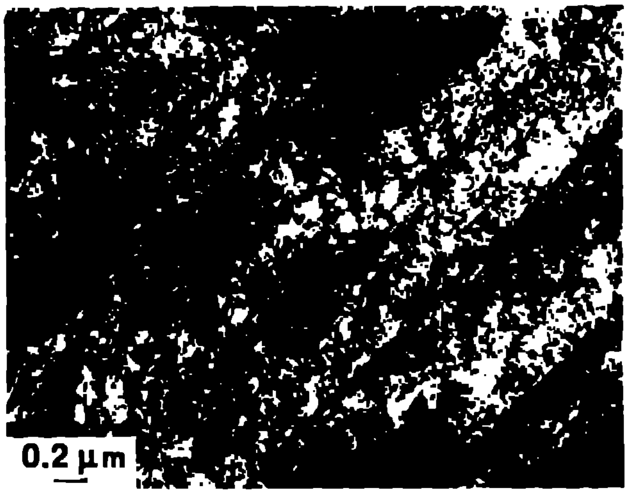

Figure 7:TEM micrograph of copper shock-loaded to 20 GPa 1 usec.

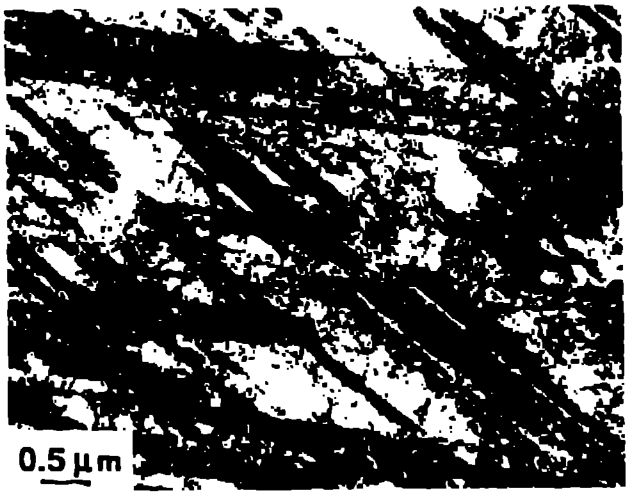

Figure 8:TEM micrograph of copper shock-loaded to 20 GPa 1 usec showing twins.

Discussion

The residual structure/property relationships of metals subjected to shock-wave deformation are well known to differ from those formed during quasi-static deformation, even when deformed to higher macroscopic strains. Peak shock pressure in the current study produced a cellular dislocation substructure 0.6 µm in diameter, from a 5 GPa shock, compared to a 0.6 to 0.9 µm cell structure seen in copper following cold-rolling(13). Increasing the peak pressure from 5 up to 20 GPa is observed to decrease the dislocation cell size, related to an increased dislocation density, and increase the yield strength consistent with previous studies(1). These observations are well documented and consistent with the fact that increasing shock pressure leads to enhanced dislocation storage as a result of increased dislocation generation to accommodate the increased transient shock strain with increasing pressure. In the present investigation, increasing the peak pressure from 10 to 20 GPa is additionally observed to alter the slope of the yield strength data suggesting the action of an additional strengthening mechansim. Based upon TEM observations, it is thought that either deformation twinning, planar slip, or the interaction of dislocations with vacancy loops may account for this change.

The effect of pulse duration on residual dislocation substructure and mechanical response remains a poorly understood stage of the shock process. The technique normally utilized, and used in this study, to vary pulse duration in symmetrical impacts is to vary the flyer plate thickness, with thicker flyer plates increasing the duration. This method however, also has a direct effect on the release rate by spreading the rarefaction out over time. If this decrease in rarefaction rate were indeed significant and pulse duration assumed to have no influence, then increasing the duration might be expected to reduce the dislocation density and yield response due to a lower strain rate on release. This is contrary however to experimental data.

The pulse duration is normally considered to be a time of nearly constant stress following the plastic deformation that occurred during the shock rise and before the tensile release. In the literature to date, the "bulk" of the deformation during shock loading has been attributed to the shock rise and indeed the strain rates are highest in this stage of the shock process which according to recent analysis(14) would lead to rapid dislocation generation rates. However, it is important to remember that equal amounts of plastic strain must be accommodated during both the rise and release. In this regard the shock process may be compared to a single fatigue cycle with a dwell time representing the pulse duration. Similar to high amplitude fatigue, hardening in shock loading of high stacking fault energy metals is associated with bundling of dislocations into tangles, and subsequent development of these tangles into walls of dislocations and finally cells.(15) In both cases, the magnitude of the strain amplitude determines the size, and to some extent, the nature of the cells. In fatigue, hardening is associated with Stage II unidirectional deformation of a single crystal, and the eventual plateau in the flow stress, termed "saturation". If one extends the parallel between fatigue and shock loading to dislocation formation mechanisms, a possible explanation of the effect of pulse duration on subsequent substructural and mechanical response may be postulated. During the shock rise to peak pressure, dislocations are generated, multiply, and tangle. To accommodate the applied plastic strain dislocations links bow out and shuttle across relatively free zones to be captured, and partially annihilated in opposing dislocation dense areas. As the strain is reversed during rarefaction, the links bow in reversed fashion. The pulse duration stage may then be considered to influence the amount of reversibility of slip by changing the time available for rearrangement or stress relaxation to lower the overall free energy. Such reorganization to reduce local anisotropies in the stress may be the result of postulated 1 to 2 kbar fluctuations in the peak pressure during the pulse duration.(16) This can effectively lock-in some of the dislocation debris reducing the amount of easy reverse flow thereby neccessitating more dislocation generation to accommodate rarefaction release. If correct, increasing the amount of rearrangement time, e.g. pulse duration, should result in an increased dislocation density resulting in a decreased cell size and increase in yield strength. The results of this study, and some other previous studies(4,5) support these concepts. The question then remains if shock experiments(1) in the 2 to 6 µsec duration range display a leveling off effect due to an equilibrium in the rearrangement time or some other mechanism. Due to the dependency of dislocation multiplication mechanisms on crystal structure and stacking fault energy it may be that pulse duration effects may not be consistent between various metals and alloys. Further experimental shock-recovery work in collaboration with real-time VISAR experiments are needed to address these points.

Conclusions

Based upon a study of the independent variation of peak pressure and pulse duration upon the shock loading response of OFE copper, the following conclusions can be drawn: 1) Increasing peak pressure or pulse duration was found to decrease the observed dislocation cell size and increase the yield strength. 2)The influence of pulse duration is attributed to the influence of reorganization time on the amount of dislocation generation during the rarefaction release.

Acknowledgments

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