IN-SITU X-RAY DIFFRACTION FROM HOHLDRAUM-DRIVEN SHOCK WAVES IN SOLIDS

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March 17, 2003

DOE Progress Report: DE-FG03-98DP00212

INTRODUCTION

Single crystal copper and copper aluminum alloys, oriented to [001] and [134], have been the subject of a number of laser-induced shock compression experiments over the past two years. The effects of orientation and pressure decay on recovered samples have been characterized by transmission electron microscopy and explained by the application of physically-based constitutive equations. Dislocation densities, dislocation structures, stacking faults, and twinning have all been characterized. Our current work is focused on examining compositional differences as it relates to the stacking fault energy. Additional research has been performed on the nucleation, growth and coalescence of voids in samples shocked at the highest pressures.

The recovery experiments are one part of a broad range of experiments characterizing the effects of extreme pressures and strain rates in materials. In this progress report, the results to date are briefly reviewed and an outline of ongoing work is presented. Appendix A is a listing of all the samples shocked to date listing the shock conditions, sample size, and the current status of its analysis. Appendix B lists the relevant presentations, posters and papers prepared based on this research.

CURRENT WORK

A series of laser driven shock experiments have been performed in collaboration with LLNL at the OMEGA Laser Facility in Rochester, NY. Single crystal copper has been systematically characterized by dynamic x-ray diffraction, VISAR wave measurements, and recovery experiments. The focus of the work at the University of California, San Diego was the characterization and analysis of the recovered specimens. Pure copper samples with orientations of [001] and [134] were shocked at peak pressures ranging from 12 GPa to 60 GPa with pulse durations on the order of 2-3 ns. The samples ranged in thickness from 1mm for samples oriented to [001] to 5mm oriented to [134]. More recently, monocrystalline samples of Cu-2% Al were also shocked at a similar range of pressures and with a thickness of 2.5 mm. The results of each of these four conditions will now be discussed.

Monocrystalline Copper [001]

Pure copper oriented to [001] was shocked at initial peak pressures of 12 GPa, 20 GPa, 40 GPa, and 60 GPa. Systematic differences in the deformation substructure was observed and analyzed. Furthermore, the results were compared with physically-based constitutive equations in order to gain more insight in the deformation mechanisms.

Samples shocked at 12 GPa and 20 GPa are shown in Figure 1. Both of these samples exhibit behavior similar to experiments performed by explosively driven flyer plate experiments in FCC materials such as nickel and copper. The deformation substructure is exclusively made up of dislocations which have relaxed into clearly defined dislocation cells. A small number of dislocations are observed within the cells themselves and most often these are small loops. Careful analysis suggests that these are vacancy loops, however further work on a transmission electron microscope must be carried out to conclusively determine this. The dislocation cells decrease in diameter as the impact pressure is increased. The average size of cell for the samples shocked 12 GPa is 500 nm and for 20 GPa 200 nm. The dislocation densities are on the order of 10^{12} - 10^{13} m⁻².

Figure 1 Transmission electron micrographs of the deformation substructure in laser shock compressed monocrystalline copper oriented to [001]: (a) Shocked at 12 GPa (40 J); (b) Shocked at 20 GPa (70 J).

The samples shocked at 40 GPa show a drastic change in the deformation substructure. Near the impact surface, four variants of stacking faults are observed as predicted by the Schmidt factors. The stacking faults (precursors to twins) vary in length from 0.5 μm to 2 μm and have an average thickness of 50 nm. The back surface of the sample shows a complex cellular network with a dislocation density on the order of 10^{14} m^{-2} . The average cell size is about 0.25 μm in diameter. Again, each of the slip systems activated is predicted by the Schmidt calculation. Figure 2 shows an TEM image of the stacking faults.

Figure 2 TEM image of the deformation substructure in [001] copper shocked at 40 GPa.

For [001] copper shocked at 60 GPa, several features are observed. Near the front surface, a large number of microtwins are observed aligned to the $\langle 112 \rangle$ orientations. These twins have an average length of 200 nm and width of 20 nm. The highest concentration of twins observed near the sample center. Away from the center, wavy laths are observed suggesting a thermal recovery induced by shear since a preferential orientation of the laths is observed along the $\langle 220 \rangle$ directions. It is interesting to note that within several of these laths are additional microtwins, which gives us hints into the time constraints of the operating deformation mechanisms. TEM micrographs are shown in Figure 3.

Figure 3 TEM images of [001] Cu showing (a) twinning at 60 GPa; and (b) micro-laths aligned to [220] direction

Monocrystalline Copper [134]

Due to the asymmetry of single crystal [134] copper, the dynamic response is considerably different as compared to the symmetric [001] orientation. Samples of [134] shocked at pressures of 20 GPa revealed a network of dislocation cells made up of a large number of dislocation cells. One dominating slip system is observed as expected based

on the 1-D Schmidt calculations. Two secondary slip systems contribute to the work hardening behavior and are relatively prominent in the deformation substructure. The average cells size is 0.15 microns, which is less than those observed in [001] at similar pressures. This difference in cell size translates into a higher dislocation density. Micrographs showing the front surface and middle of sample are shown in Figure 4. As the peak pressure decreases through the specimen, the dislocation density decreases and the average cell size increases as expected.

Figure 4 TEM images of the [134] Copper shocked at 20 GPa: (a) 0.25 mm from impact surface; (b) 2.25 mm from impact surface.

Unlike the [001] copper samples, no stacking faults or twins were observed in the [134] samples shocked at 40 GPa. Again, these samples consisted of a large number of dislocation cells to the point of saturation. It becomes difficult to resolve the actual cells near the front surface (Figure 5), but dislocation densities above 10^{14} m^{-2} are attained. Also, as the pressure decays, cells become more clearly defined and dislocation densities decrease.

Figure 5 TEM images of the [134] Copper shocked at 40 GPa: (a) 0.25 mm from impact surface; (b) 2.25 mm from impact surface

The high pressure experiments on [134] showed twinning at the front surface and then high densities of dislocation cells as the distance from the impact surface increased. The observed twins were a single variant of the [011](211) type. The twins varied in length from 0.5 μm to 3 μm and were an average thickness of 50 nm. It was typical to observe regions of twins and then regions of high dislocations on the front sample. Dislocation densities were estimated to be on the order of 10^{15} m^{-2} , which is nearly the maximum possible in a deformed sample. Figure 6 shows TEM micrographs of the front and back surface of the shocked sample. Figure 7 shows a plot of the cell sizes for the three shock pressures as a function of distance from the impact surface.

Figure 5 TEM images of the [134] Copper shocked at 40 GPa: (a) 0.25 mm from impact surface showing twinning; (b) 1.75 mm from impact surface showing dislocation cells.

Figure 7 Variation of cell size in [134] single crystal Cu with distance from energy deposition surface of three levels of energy input.

Constitutive Description of Slip-Twinning Transition in Copper

The results of the single crystal copper experiments were compared to results obtained through a physically based constitutive description of the slip-twinning threshold. By assuming slip and twinning are competing mechanism, a modified MTS equation is applied to the given system. Both work hardening and the temperature rise due to shock compression are incorporated. Also, by utilizing an orientation dependent work hardening term, it is possible to obtain the critical pressure for the twinning transition in copper as a function of orientation. The results of this method agree relatively well with the current experiments as well as previous experimental work performed at pulse durations 10-100 times greater in length. It was found that the critical twinning pressure in pure single crystal copper with a [001] orientation is 16-19 GPa and for [134], it was found to be 25-28 GPa about 50% higher. The pressure differentiation in the current experiments and theoretical work can be explained by the exponential pressure decay in the samples. From these calculations, the critical resolved shear stress for each twinning system can also be determined.

Monocrystalline Copper 2% Aluminum [001]

The effect of 2 weight percent aluminum on the dynamic behavior of copper is substantial. The change in the stacking fault energy is nearly cut in half which corresponds to a much lower pressure threshold to obtain twinning and a marked difference in dislocation structure. At lower pressures (12-20 GPa) stacking faults are observed near the front surface transitioning into dislocations as the distance from the impact surface increases. The dislocation substructure has is more systematic and the number of large loops is decreased. The cell sizes are somewhat larger as well.

For samples shocked at higher pressures (40 GPa), both dislocations and stacking faults are observed throughout the sample. Twinning is also observed near the front surface. The stacking fault density decreases in density from the front surface to the back surface similar to the decrease in dislocation density. The dislocations are typically preferentially oriented in square-like cells. Again, the dislocation densities are slightly lower than those found in pure copper.

Figure 8 TEM image of [001] Cu 2% Al shocked at 12 GPa

Figure 9 TEM image of [001] Cu 2% Al shocked at 20 GPa

Monocrystalline Copper 2% Aluminum [134]

The [134] copper aluminum has been the most interesting to analyze thus far. Further work is necessary to confirm the current results. Several features have been observed in these samples including twinning, stacking faults, dislocations, second phase precipitates, and an unusual surface contrast. As expected, twinning occurred in the samples shocked at higher pressures, and dislocations and stacking faults were observed at both the low and high pressure experiments. The second phase precipitates were only found near the front surface of the high pressure experiments. The surface contrast has been observed in both the low pressure and high pressure experiments, but not in the as-received condition. The contrast is aligned to the [011] direction and has a spacing of 20-30 nm. This work is ongoing as experiments were repeated at OMEGA as of late February 2003.

Figure 10 TEM image of [134] Cu 2% Al shocked at 40 GPa

Void Nucleation and Growth

In addition to the defect characterization, void nucleation, growth and coalescence has been examined in a number of shocked specimens and a theoretical framework has been developed in collaboration with Professor Vlado Lubarda at the University of California, San Diego. Scanning electron micrographs of the spall surface and nearby voids are shown in Figure XX. Possible explanations for the nucleation of voids in single crystals have been studied, but theories such as vacancy diffusion do not have the necessary time scales to achieve the necessary size. Research is ongoing in this field and a study of orientation effects during void growth is underway.

Figure 11 SEM micrographs of voids at three length scales; dark areas represent voids.

FUTURE WORK

Monocrystalline Copper 6% Aluminum [001] & [134]

In February 2003, several samples of copper 6 wt% aluminum with [001] and [134] orientations were shocked at the OMEGA laser facility. These samples are 2-3mm in size providing us with an average of 5 specimens per shock condition. The conditions used in these experiments were 20 GPa and 40 GPa. Previous work has suggested the presence of a martensitic transformation as well as an increase in the second phase precipitate observed in the 2% aluminum experiments. The defect substructure will be studied and then the effect of composition on the stacking fault energy will be studied using a theory and then implemented into the constitutive description of the slip-twinning transition.

CONCLUSIONS

Copper and copper aluminum alloys have been subjected to high pressure and a short pulse duration shock. The samples have been recovered and the defect substructure characterized in terms of initial pressure, orientation, distance from impact surface and stacking fault energy. Because of these varying conditions, the observed post-mortem defect microstructure is systematically different. These differences have been explained by applying a physically based constitutive description for FCC materials. Ongoing research will continue to examine the defect substructure of copper 2 - 6 wt% aluminum as well as the slip-twinning transition in these materials. Void nucleation and growth will also be studied further.

APPENDIX A: SUMMARY OF RESULTS

SAMPLE DESCRIPTION	ENERGY	POST-SHOCKED MICROSTRUCTURE
S-X Cu [001] A	40 J	Dislocation Cells – Avg: 0.5 mm
S-X Cu [001] A	70 J	Dislocation Cells – Avg: 0.3 mm
S-X Cu [001] A	205 J	Stacking Faults – 4 variants w/ spacing of 0.23 mm
S-X Cu [001] B	205 J	Dislocation Cells – Avg: 0.15 mm
S-X Cu [001] A	320 J	Twins (2 sets) and Laths
S-X Cu [134] A	70 J	Dislocation Cells – Avg: 0.37 mm
S-X Cu [134] B	70 J	Dislocation Cells – Avg: 0.72 mm
S-X Cu [134] D	70 J	Dislocation Cells – Avg: 1.87 mm
S-X Cu [134] E	70 J	Dislocation Cells – Avg: 2.67 mm
S-X Cu [134] A	200 J	Dislocation Cells – Avg: 0.14 mm
S-X Cu [134] B	200 J	Dislocation Cells – Avg: 0.22 mm
S-X Cu [134] C	200 J	Dislocation Cells – Avg: 0.41 mm
S-X Cu [134] D	200 J	Dislocation Cells – Avg: 0.76 mm
S-X Cu [134] E	200 J	Dislocation Cells – Avg: 1.43 mm
S-X Cu [134] A	300 J	Twinning – Single Variant and Dislocation Cells
S-X Cu [134] B	300 J	Dislocation Cells – Avg: 0.08 mm
S-X Cu [134] C	300 J	Dislocation Cells – Avg: 0.20 mm
S-X Cu [134] D	300 J	Dislocation cells – Avg. 0.44 mm
S-X Cu [011] A	100 J	Dislocation Cells

SAMPLE DESCRIPTION	ENERGY	POST-SHOCKED MICROSTRUCTURE
S-X Cu-2%Al [001] A	70 J	Stacking faults
S-X Cu-2%Al [001] B	70 J	Dislocation cells
S-X Cu-2%Al [001] C	70 J	Dislocation cells
S-X Cu-2%Al [001] D	70 J	Dislocation cells
S-X Cu-2%Al [134] A	70 J	Stacking faults
S-X Cu-2%Al [134] B	70 J	Dislocation cells
S-X Cu-2%Al [134] C	70 J	Dislocation cells
S-X Cu-2%Al [134] D	70 J	Dislocation cells
S-X Cu-2%Al [001] A	200 J	Stacking faults and twinning
S-X Cu-2%Al [001] B	200 J	Stacking faults
S-X Cu-2%Al [001] C	200 J	Stacking faults
S-X Cu-2%Al [001] D	200 J	Stacking faults
S-X Cu-2%Al [134] A	200 J	Dislocations, striations and stacking faults
S-X Cu-2%Al [134] B	200 J	Dislocations, striations and stacking faults
S-X Cu-2%Al [134] C	200 J	Dislocations and stacking faults
S-X Cu-2%Al [134] D	200 J	Dislocations and stacking faults
S-X Cu-2%Al [001]	130 J	Not Analyzed – Upcoming
S-X Cu-2%Al [134]	130 J	Not Analyzed – Upcoming

APPENDIX B: List of Recently Presented Work

Papers

“Laser Induced Shock Compression of Copper: Analysis and Characterization” Acta Mat., (2003) **5** 1211.

High Pressure, High Strain Rate Lattice Response of Shocked Materials Journal of Plasma Physics, in press 2003

“Laser Induced Shock Compression of Copper: Orientation and Pressure Decay Effects”, to be published, to be submitted 2003.

“Void Growth by Dislocation Emission”, to be submitted 2003.

Presentations:

Laser Induced Shock Compression in Copper, APS Shock Compression, Atlanta, GA July 2001

“High Pressure, High Strain Rate Lattice Response of Shocked Materials” APS Division of Plasma Physics, Orlando, FL November. 2002

“Laser Induced Shock Compression of Copper: Orientation and Pressure Decay Effects” TMS Annual Meeting, San Diego, CA March 2003.

“Materials Science at Extreme Pressures and Strain Rates” TMS Annual Meeting, San Diego, CA March 2003.

Posters

“Materials Science at Extreme Pressures and Strain Rates” APS Division of Plasma Physics, Orlando, FL November. 2002

“Laser Induced Shock Compression in Copper: Orientation Effects” TMS Annual Meeting, Seattle, WA Feb. 2002