LASER-INDUCED SHOCK COMPRESSION OF COPPER AND COPPER ALUMINUM ALLOYS

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Abstract. Single crystal copper and copper 2-wt% aluminum alloy with [$\bar{1}$34] and [001] orientations are compressed by means of a high energy short pulse laser. Pressures ranging from 20 GPa to 60 GPa are achieved. The shocked samples are recovered and the residual defect substructure is analyzed by transmission electron microscopy. Results show systematic differences depending on orientation and stacking fault energy. Samples with orientations [001] are symmetrical with simultaneous activation of eight slip systems. This leads to a higher work hardening rate. The [$\bar{1}$34] orientation is asymmetrical with one dominating slip system, and thus a reduced work hardening rate due to a prolonged easy glide region for dislocations. These differences in work hardening response affect the stresses required to achieve the twinning threshold pressure. The effects of stacking fault energy on the defect substructure and threshold twinning are also characterized. Experimental results are rationalized in terms of a constitutive description of the slip-twinning transition using a modified MTS equation. Differences in the mechanical response of the orientations and the chemical compositions are responsible for differences in the shear stress in the specimens at the imposed pressures and associated strains.

INTRODUCTION

The effects of shock waves on metals have been studied for over fifty years [1]. Most experiments have used explosives and flyer plates as the means of creating the compression pulse. The short duration of the shock pulse (0.1 – 2 μm) renders direct measurements of deformation mechanisms nearly impossible, and therefore have to be inferred from post-shock examination of the residual defect substructure. It is only recently [2,3] that pulsed x-ray diffraction has been used to obtain quantitative information of the lattice distortions at the shock front. Recent experiments by Meyers et al. [4] using copper single crystal specimens showed that dislocation configurations and the twinning threshold pressure using laser-induced shock waves are nearly identical to those obtained at durations 10 – 100 times longer as in explosively driven flyer plate studies. The early experiments by Johari and Thomas [5] showed decreasing cell sizes with increasing shock pressures in copper aluminum. More recently, results by Murr [6] confirm that cell sizes decrease and dislocation densities increase with increasing shock pressures. These results are a clear confirmation that defects are generated at the shock front.

EXPERIMENTAL TECHNIQUES

The shock experiments were carried out at the OMEGA Laser Facility at University of Rochester's Laboratory for Laser Energetics (LLE). Single crystals of copper and copper 2-wt% aluminum were obtained for two orientations as shown in Figure 1: [001] (symmetrical) and [$\bar{1}$34] (asymmetrical) and prepared into 3 mm diameter cylinders for the laser shock experiments.

The input laser energies used in the presented experiments are 70 J and 205 J. The laser spot size

CP706, *Shock Compression of Condensed Matter - 2003,* edited by M. D. Furnish, Y. M. Gupta, and J. W. Forbes

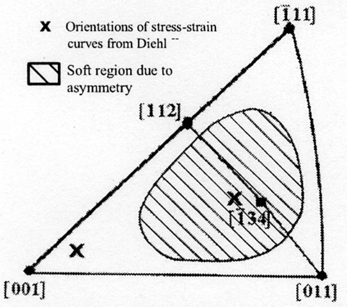


FIGURE 1 Stereographic projection showing [001] and [$\bar{1}$34] orientations as used in the laser-shock experiments.

was on the order of 2.5 mm to 3.0 mm depending on the size of the sample. The pulse duration was 2.5 ns. The energies can be translated into pressures using Lindl's equation [7]:

$$P = 4000\left(\frac{I_{15}}{\lambda}\right)^{2/3} \qquad (1)$$

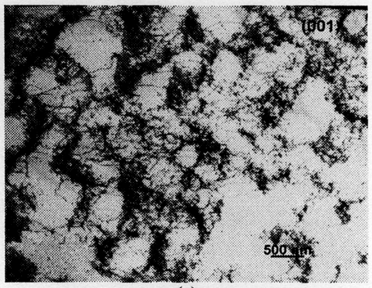
where P is pressure (GPa), I_{15} is laser intensity (10^{15} W/cm^2), and λ is wavelength in micrometers. Thus, 70 J is equivalent to 20 GPa and 205 J is equivalent to 40 GPa. The results obtained by TEM of the shock recovery conditions are reported herein.

EXPERIMENTAL RESULTS AND

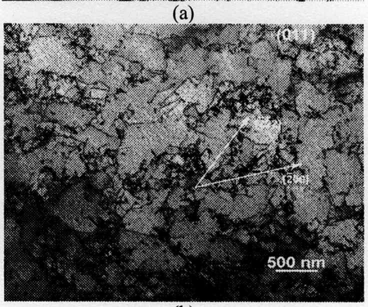
Laser Energy of 70J (Pressure of 20 GPa)

The low energy shock in pure copper creates a cellular organization of a low density of 1/2<110> dislocations. The cells are homogeneous, Figure 2(a), with an average diameter of 0.25 μm for the [001] orientation. The results obtained in general confirm previous observations, albeit at a pulse duration that is lower by a factor of 10-100, than those achieved by Murr [6]. The predicted cell size from the plot in [4] at a pressure of 20 GPa, is 0.22 μm.

The [$\bar{1}$34] orientation shocked at 20 GPa contains a similar well-defined cellular network with a slightly larger (0.3-0.4 μm) average cell size, Figure 2(b). The dislocation density is on the order of 10^{13} m^{-2}. The cells are comprised



(a)



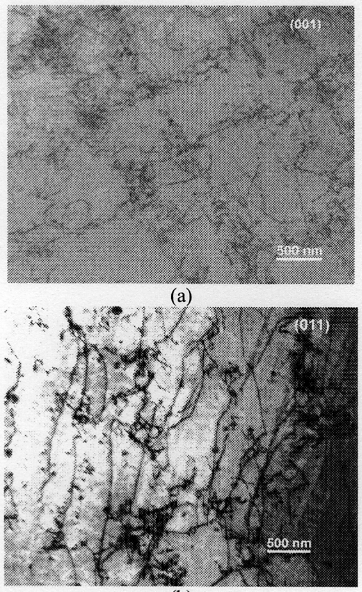
(b)

FIGURE 2. Dislocation cells in pure copper shocked with laser energies of 70 J; (a) [001] orientation is, B = [001]; g = [020]; (b) [$\bar{1}$34], B = [011], g = [$\overline{2}\overline{2}$2].

primarily of three dislocation systems: (111)[$\bar{1}$01], (111) [1$\bar{1}$0], and ($\bar{1}$11)[101].

The dislocation substructure observed in Cu-2wt% Al oriented to [001] shows a transitional structure between dislocation cells and stacking faults when shocked at 20 GPa. The dislocations are arranged into square cells as precursors to stacking faults and twins. The average cell sizes are found to be slightly larger (0.4 μm as in Figure 3(a)). It is also important to note the nature of the dislocations. In the alloyed materials, the dislocations have a greater energy barrier to overcome for cross-slip to occur. Instead, dislocations tend to pile-up and form planar arrays.

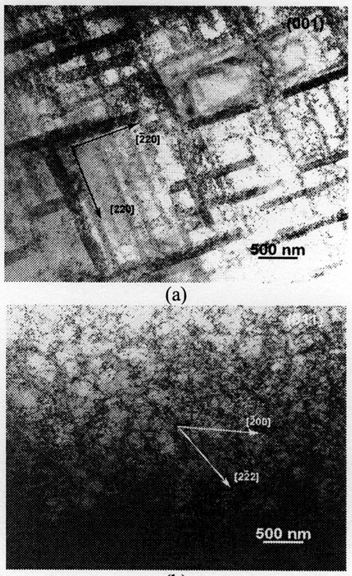
In the Cu-2wt% Al single crystal oriented to [$\bar{1}$34], the dislocation substructure is less organized. The dislocations have a greater line length compared to the pure Cu samples (Fig. 3(b)). Large densities of dislocation loops are observed. The dislocations are found to be from three predominant slip systems found as expected by Schmid factor calculations. Dislocations densities are lower than expected, but this could be a result of sample thickness.



(a)

(b)

FIGURE 3. Cu-2wt%Al shocked with laser energy of 70 J (20 GPa); (a) [001] orientation, B = [001]; (b) $[\bar{1}34]$, B = [011].



(a)

(b)

FIGURE 4. Pure Cu shocked with laser energy of 200 J (40 GPa); (a) [001] orientation, B = [001]; (b) $[\bar{1}34]$, B = [011].

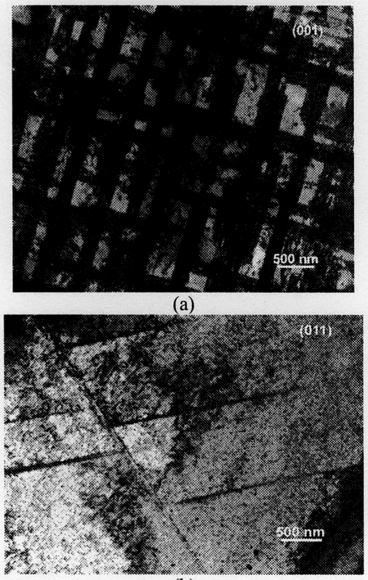
Laser Energy of 205J (Pressure of 40 GPa)

Impacting pure copper oriented to [001] with 205 J energy input creates dense dislocation tangles, stacking faults and micro-twins. There are no readily discernible dislocation cells. These traces (Figure 4(a)) are characteristic of stacking-fault bundles and twins which are analogous to previous observations by Murr [6], especially, Figs. 20, 21, and 23 of [6]. These features are significantly different than the ones at the lower energy. Traces of planar features are seen when the beam direction is <101>.

For the $[\bar{1}34]$ orientation, the deformation sub-structure is cellular, albeit finer at a 0.15 μm average cell size and a significantly higher dislocation density, 10^{14} m^{-2}, Figure 4(b). This is in direct contrast to the mechanism change observed in [001]. Again, the three slip systems previously described dominate the deformation sub-structure. A large number of loops were also visible. These were found to contribute to the cell walls and were often commonly found in the cells at lower concentrations.

As expected, in the Cu-2w% Al [001] copper shocked at 200 J, the material twins readily as shown in Figure 5(a). At least two variants are observed and they are both well defined. When imaged at B = [001], they appear at exactly 90° to each other aligned along $[2\,2\,0]$ and $[\bar{2}\,2\,0]$ directions. They are also present roughly in the same proportion. The density of twins is quite high. The twins vary in size and length with an average width of 20-30 nm and length on the order 1 μm. A large number of dislocations are also readily observed between the twins, which are not observed in pure copper when shocked at pressures above the twinning threshold [4].

The results obtained for Cu-2%wt Al oriented to $[\bar{1}34]$ showed two twinning variants activated where the domain of one twin may be the nucleation site for the second activated twinning system (Figure 5(b)). The twins are in lower proportions than one would expect. The twins vary in size and proportion with the primary variant, $(111)[\bar{2}11]$, having the largest size and the secondary variant, $(1\bar{1}1)[\bar{1}\bar{1}2]$, being greater in number.



(a)

(b)

FIGURE 5. Cu-2wt%Al shocked with laser energy of 200 J (40 GPa); (a) [001] orientation, B = [001]; (b) [$\bar{1}$34], B = [011].

ANALYSIS

Prediction of Threshold Amplitude for Twinning

FCC metals have a stacking-fault energy dependent threshold pressures for the initiation of twinning [8]. If one assumes that slip and twinning are competing mechanisms, where plastic deformation by slip has a strain rate and temperature dependence well described by the theory of thermally-activated obstacles, then it is reasonable to assume that slip is highly favored at most conditions. This methodology to predict the threshold shock amplitude was delineated by Murr et al. [9] and Meyers et al. [10] The application of this criterion to the shock front necessitates the knowledge of the strain rate. The strain rate at the shock front has been established by Swegle and Grady [11] to be:

$$P = k_{SG}\,\dot{\varepsilon}^{1/4} \qquad (2)$$

Two separate aspects have also to be considered in the analysis: (a) shock heating, and (b) plastic strain at the shock front. By applying the Rankine-Hugoniot and Grüneisen relationships, equations relating these terms can be developed (See [12]). The response of the copper monocrystal is represented by the modified mechanical threshold stress (MTS) expression below:

$$\sigma=\sigma_0 f(\varepsilon)\left[1-\left(\frac{kT}{Gb^3 g_0}\ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right)\right)^{2/3}\right]^2 + kd^{-1/2} \qquad (3)$$

For twinning, one assumes a strain rate and temperature independent σ_T. Setting $\sigma_T = \sigma_s$, one can obtain the critical twinning stress as a function of ε, $\dot{\varepsilon}$, and T. The work hardening term, $f(\varepsilon)$, incorporates orientation dependence. Figure 6 shows the predicted threshold for different initial temperatures and orientations in pure copper. It is clear that the [001] orientation has a lower twinning threshold pressure, in agreement with earlier results by De Angelis and Cohen [13].

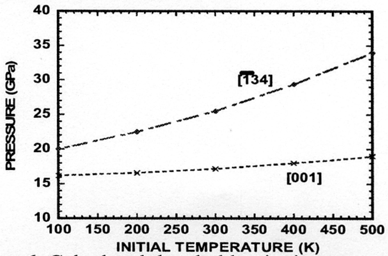


Figure 6. Calculated threshold twinning pressure for [001] and [$\bar{1}$34] orientation as a function of initial temperature.

Research supported by the DOE (Grant DE-FG03-98DP00212) and by Lawrence Livermore Nat. Lab.

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