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SHOCK COMPRESSION OF CONDENSED MATTER 1991
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MICROSTRUCTURAL EVOLUTION IN HIGH STRAIN, HIGH STRAIN-RATE DEFORMATION

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Under high strain rates, plastic deformation can be assumed to be adiabatic, and a significant temperature increase can occur at large strains. In this study, shock-hardened polycrystalline copper was subjected to high strains ($\gamma \sim 5$) at high strain rates ($\dot{\gamma} \sim 10^4$ s^{-1}) using a stepped specimen in a Hopkinson bar. Microstructural analysis by transmission electron microscopy revealed that the highly deformed shear-band region consisted of a gradual decrease in grain size with increasing strain. The center of the shear band is characterized by very small grains (~ 0.1μm) with a relatively low dislocation density. An analysis is developed, based on dynamic recrystallization (enabled by the adiabatic temperatures rise associated with plastic deformation), that predicts a transient grain size during plastic deformation in which grain size varies inversely with strain and strain rate. This analysis has been used to predict that nanocrystalline grain sizes are achievable. This dramatic microstructural refinement (from > 50μm to < 0.1μm) enables a thermomechanical response that may lead to extensive, stable plastic deformation tension.

1. INTRODUCTION

The very high strains undergone by copper jets in shaped charges have been attributed to a lateral inertia by Grady[1], Fressengeas and Molinari[2], and Romero[3]. The X-ray diffraction experiments by Jamet[4,5] have conclusively shown that the jet is solid in aluminum, and at least partially solid (the surface was crystalline) for copper. Recently, Chokshi and Meyers[6], and Meyers *et al.*[7] proposed that dynamic recrystallization plays a key role in the stability of the jet. The recovery and observation of jet and slug fragments, as has been demonstrated by heat transfer calculations by Meyers *et al.*[7], cannot yield reliable results because the cooling times are orders of magnitude larger than the deformation times. In the research reported herein a special experimental procedure is described for capturing the microstructure developed at high strains and strain rates. The experimental method subjects a thin (~ 200μm) region of copper to very high strains ($\gamma \sim 5$) at high strain rates ($\dot{\gamma} \sim 10^4 s^{-1}$). Upon completion of deformation, the region is cooled to one-half the original temperature change in less than one millisecond.

2. EXPERIMENTAL METHODS AND MATERIALS

Copper was shock hardened by planar impact using an explosively accelerated flyer plate in the set-up shown schematically in Figure 1. The detonator initiates a plane wave generator, which in turn, initiates simultaneously the top surface of a cylindrical charge of PBX 9404 explosive. The explosive charge accelerates a flyer plate (4.7 mm thick stainless steel) which impacts the system containing a copper disk; lateral and bottom momentum traps were provided to ensure that one single compressive pulse traversed the specimen. Velocity pins were used to determine the impact velocity, which was equal to 2.2km/s. This velocity corresponded to a pressure, in the copper disk, of approximately 55 GPa [8].

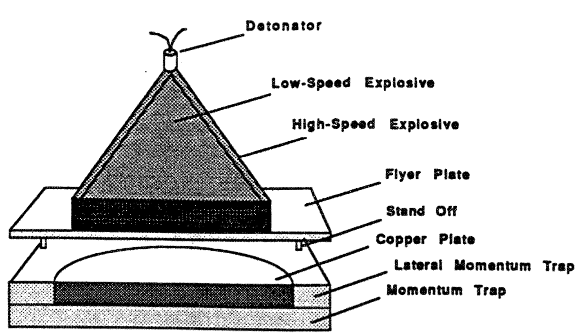


FIGURE 1
Experimental set-up for shock hardening copper.

The "hat-shaped" specimen, developed by Hartman *et al.*.[9], and machined from the shocked-hardened copper, is schematically shown in Figure 2 within the split Hopkinson bar set-up. The design generates high strains in the shear concentration region marked in Figure 2. A spacer ring was used to establish the maximum plastic deformation.

Specimens for transmission electron microscopy were prepared by sectioning the area that underwent high shear strains, cutting 3mm disks, dimpling them on the shear concentration region and jet-polishing them in a solution of 20% nitric acid and 80% methanol at -20°C. A Philips CM-30 transmission electron microscope operated at 300kV accelerating potential was used to characterize the microstructural deformation evolution surrounding and within the shear bands.

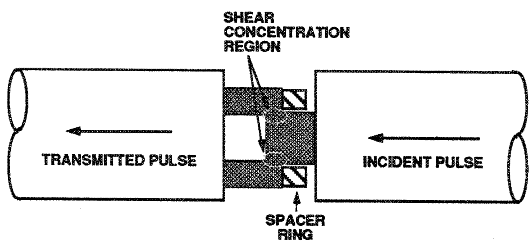


FIGURE 2
Hat-shaped specimen within split Hopkinson pressure bar set-up used to generate high shear strains at high-strain rate (10^4 s^{-1}).

3. RESULTS AND DISCUSSION

The shock hardened copper exhibited a much higher yield stress than its original value at low strain rate, and there is no work hardening after a strain of 0.03. The flow stress for annealed copper is approximately 200MPa at the same strain rate, and exhibits normal work hardening. The objective of shock hardening the copper prior to the mechanical tests was to more closely simulate the condition of a metal undergoing high strain, high strain-rate plastic deformation in a shaped charge jet or explosively forged projectile. The detonation of the explosive in intimate contact with the metal generates, in the latter, a shock wave of high amplitude which significantly modifies its thermomechanical response.

Figure 3 shows the high shear strain region in the hat-shaped specimen after a shear strain of 5. No microstructural features can be distinguished within this region. The grain structure of the copper can be seen outside of the shear band, containing deformation twins characteristic of shock-loaded copper[10].

Observations by transmission electron microscopy enabled clear identification of the dark shear areas in Figure 3. The sequence of transmission electron micrographs given in Figure 4 shows the evolution of the microstructure as a function of the imposed strains and temperature excursion. Outside of the high strain region the microsctructure is typical of shock-hardened copper. Profuse dislocations are seen in Fig. 4(a), although no deformation twins were imaged. As the shear band area is approached further, a gradual refinement of the microstructure is observed. Figure 4(b) shows the region just within the shear band; these elongated features eventually break down, leading to a microcrystalline structure as the prominent feature in the center of the shear concentration area (Fig. 4(c)). The continuous rings of diffraction spots in Fig.4(c) verify that these micrograins are oriented in all directions. The dislocation density within these micrograins is quite low, and the diameter of these grains is approximately 0.1μm. Thus, intense plastic deformation under quasi-adiabatic conditions leads to a reduction in grain size from ~50μm to ~ 0.1μm.

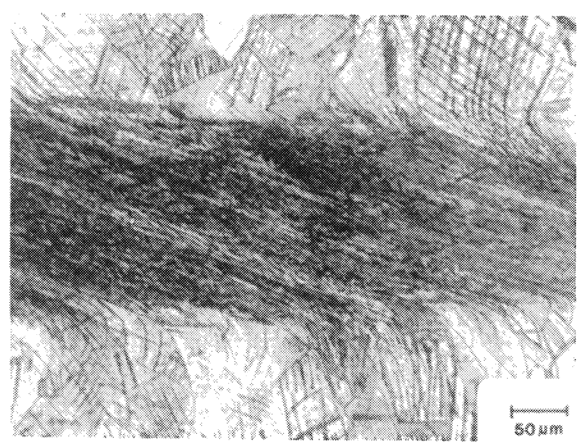
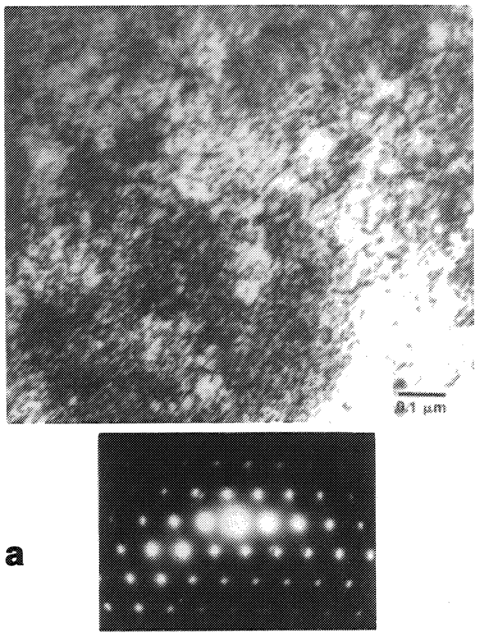
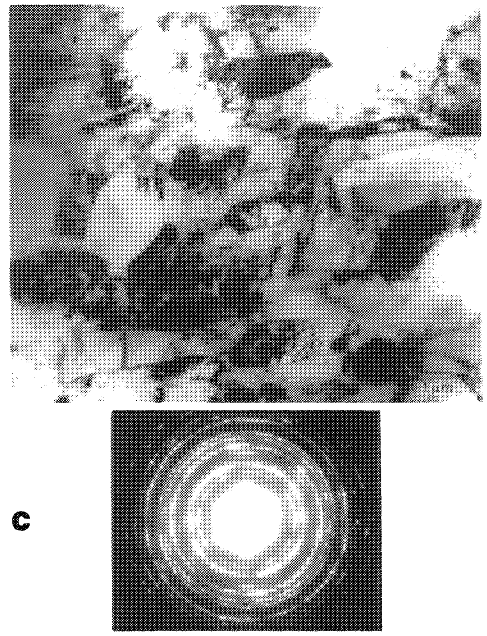


FIGURE 3
Optical micrographs of region subjected to high strain (γ=5) and high-strain rate (10^4 s^{-1}).



a



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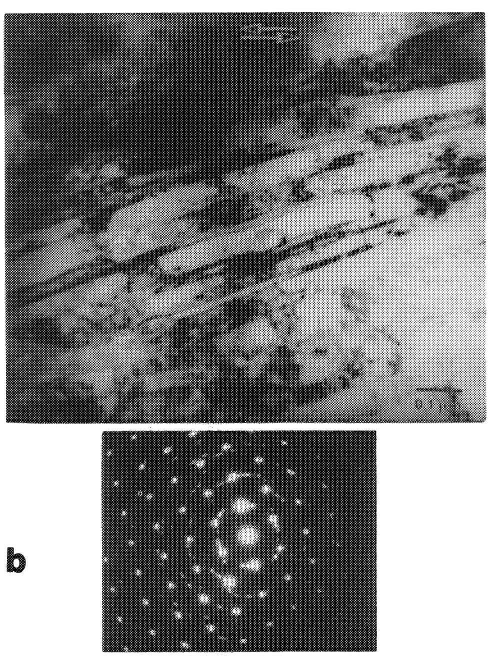

b

FIGURE 4
Transmission electron micrographs and diffraction patterns from copper specimen subjected to high strain:
(a) region outside shear localization area;
(b) region at onset of shear localization area;
(c) region at center of shear localization area.

Dynamic recrystallization is a well-known mechanism of microstructural modification. As the material is plastically deformed, at a sufficiently high temperature (> 0.5 T_m), new defect-free grains nucleate and grow within the deforming grains. As a direct consequence, the microstructure becomes refined. The rates of nucleation and growth establish the steady-state grain size. Sandstrom and Lagneborg[11] and Derby and Ashby[12] proposed theories for dynamic recrystallization that predict the recrystallized grain size as a function of strain rate. Both theories predict the relationship: $d_{ss} \propto \dot{\varepsilon}^{-1/2}$, where d_{ss} is the steady-state recrystallized grain size and $\dot{\varepsilon}$ is the strain rate. This refinement in grain size can profoundly affect the mechanical response of the deforming materials. Temporary superplasticity was proposed by Baudelet[13] for a Cu-P alloy. This superplasticity, induced by a drastic grain size reduction produced by dynamic recrystallization, was proposed by Chokshi and Meyers[6] to explain the large plastic deformations undergone by shaped charges in copper. Classical superplasticity occurs by grain boundary sliding and the strain rates encountered within the deforming band of Fig. 3 are on the order of 10^4 s^{-1}. This is also the strain rate within a stretching jet of a shaped charge. Chokshi and Meyers[6] calculated a required grain size of $\leq$ 0.01μm at this strain rate. The grain sizes observed in Fig. 4(d) are larger, by one order of magnitude, than these. An alternative mechanism for extended stable plastic deformation under continuous dynamic recrystallization is being developed by the authors[14]. It is based on a balance between dislocation generation (due to plastic deformation) and dislocation annihilation (due to advance of recrystallizing boundaries) and yields, in its simplest form, a relationship between the steady-state stress and strain rate of the form:

$$\sigma \propto \dot{\varepsilon}^m$$

where the strain-rate sensitivity, m, is found to be equal to 0.5. A value of m > 0.3 is a necessary requirement for superplasticity. Thus, the microstructure generated by dynamic recrystallization can exhibit extended ductility in tension, and the stretching of shaped charge jets could be attributed, at least partially, to the mechanism described above.

The dynamic recrystallization is made possible by the adiabatic rise in temperature as the plastic deformation proceeds. By applying the Johnson-Cook constitutive equation to copper with various initial flow stresses[6,7] the temperature excursions as a function of applied strain can be determined. The temperature required for dynamic recrystallization, 0.5 T_m (T_m = 1356 K) is reached at a plastic strain of ~ 2.4. Thus, the rationale provided here for extended stable tensile plasticity in copper under high strain rate conditions is sound.

4. CONCLUSIONS

Microstructural analysis of high strain, high-strain rate deformed copper specimens has led to the development of a phenomenological model based on dynamic recrystallization which may account for the very small grain sizes observed. Preliminary quantitative analysis using this model predicts that nano-scale grain structures can evolve under the conditions discussed.

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