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Materials Science and Engineering A 409 (2005) 270–281

MATERIALS SCIENCE & ENGINEERING A

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Effect of shock compression method on the defect substructure in monocrystalline copper☆

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Received in revised form 20 May 2005; accepted 30 June 2005

Abstract

Monocrystalline copper samples with orientations of [0 0 1] and [2 2 1] were shocked at pressures ranging from 20 to 60 GPa using two techniques: direct drive lasers and explosively driven flyer plates. The pulse duration for these techniques differed substantially: 40 ns for the laser experiments at 0.5 mm into the sample and 1.1∼1.4 μs for the flyer-plate experiments at 5 mm into the sample. The residual microstructures were dependent on orientation, pressure, and shocking method. The much shorter pulse duration in the laser driven shock yielded microstructures in recovery samples closer to those generated at the shock front. For the flyer-plate experiments, the longer pulse duration allows shock-generated defects to reorganize into lower energy configurations. Calculations show that the post-shock cooling for the laser driven shock is $10^3 \sim 10^4$ faster than that for plate-impact shock, increasing the amount of annealing and recrystallization in recovery samples for the latter. At the higher pressure level, extensive recrystallization was observed in the plate-impact samples, while it was absent in laser driven shock. An effect that is proposed to contribute significantly to the formation of recrystallized regions is the existence of micro-shear-bands, which increase the local temperature beyond the prediction from adiabatic compression.

Keywords: Laser; Shock compression; Plate impact; Shear localization in copper; Shock waves; Explosives

1. Introduction

It is indeed a distinct honor to give a presentation in this symposium and to author a paper commemorating this festive occasion. The principal themes of Prof. J.C.M. Li's work have been micromechanisms of mechanical behavior in crystalline and amorphous materials (metals, metallic glasses, porous materials, and polymers). The nature of his work has been both theoretical and experimental. Professor Li is undoubtedly one of the global authorities in this field, and his contributions have spanned 50 years. Among the numerous original inroads into heretofore uncharted territory, the following come to mind:

- mechanism for plastic deformation of metallic glasses (e.g. [1–4]);
- shear localization in metallic glasses (e.g. [2–4]);
- mechanism for the grain-size dependence of yield stress (e.g. [5]);
- use of impression testing using micron-sized cylindrical indenters to determine adhesion, creep resistance, viscosity, and the kinetics of stress relaxation (e.g. [6]);
- dislocation dynamics through stress relaxation (e.g. [6,7]);
- combustion synthesis of intermetallic compounds (e.g. [8]);
- thermally-activated description of plastic flow (e.g. [9]).

Shock compressed materials show a great variety of microstructures in which the mechanisms envisioned by Prof. Li play a pivotal role. Although the effects of the uniaxial-strain high-strain-rate loading have been studied for the past 50 years, not all aspects have been elucidated. Smith [10] first described the shock compression of materials in mechanistic terms. In the early techniques, samples were subjected to shock compression

☆ Submitted for the TMS Symposium: Micromechanics of Advanced Materials II, in Honor of James C.M. Li's 80th Birthday, February 13–17, 2005, San Francisco, CA.

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0921-5093/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2005.06.076

by explosives, either by direct loading or by impact. The samples were recovered and the microstructure was analyzed to evaluate the effects of the shock pre-straining on the material. Later, different kinds of experiments have been designed to investigate the dynamic behavior of different materials [11–15].

Recovery experiments provide a convenient way to study defect generation and energy storage mechanisms in materials subjected to shock waves especially given the difficulty involved in studying the physical properties of the materials during the shock (rapid loading rate and short time interval). Since that time, much work has been done on quite a number of materials to develop a hydrodynamic understanding of the material behavior, and several reviews have summarized the systematic changes in the structure–property relationships generated by shock wave passage through the material [16,17]. Most of this work correlates the microstructure and mechanical property changes to the compression characteristics like peak pressure, pulse duration, rarefaction rate, and even temperature. Also, much work has been done to model these responses and to compare the behaviors to those observed at low strain rates [16–18]. Remington et al. [19] review the most significant recent work.

For the experimental techniques of shock compression, it is essential that the principal parameters be well characterized in the experiments. Flyer-plate impact and laser shock are two typical loading methods employed in shock–recovery experiments. In the flyer-plate impact experiment, the plate impacts a target at a known velocity. If the impact is perfectly planar and if the velocity vector of the impacting plate is perfectly normal to the impact plane, then a state of pure one-dimensional strain will be produced in both flyer plate and target. The minimization of lateral strain in shock compression has been shown by Gray et al. [20] and Mogilevsky and Teplyakova [21] to be important.

Lasers deliver high energy densities in extremely short pulse durations enabling research in regimes of pressure and strain rates never before explored. Lasers have been shown to generate pressures from 10 to over 500 GPa. The TPa regime is also currently accessible (e.g. [22]) through the use of the *hohlraum* concept. R. Cauble et al. developed methods to obtain the equation-of-state data in the 10–40 Mbar (1–4 TPa) regime [23]. Lasers also provide an easy way to vary pulse duration (“dwell time”) with picosecond resolution, which can then be correlated to the pressure data to yield a strain rate. Lasers typically produce less residual strain as compared to other techniques and post-shock heating is minimized because of the short-duration pulses and the small specimen size/geometry. Laser-driven shocks are created by the rapid heating of the surface from the intense laser illumination of the material [24]. Lasers are uncovering a new frontier in materials dynamics under extreme states of shock compression.

Both the flyer-plate impact [25] and laser [26] techniques have recently been employed to explore the post-shocked residual microstructures of monocrystalline copper. Significant differences in the residual microstructure have been observed at high pressures.

It is the objective of this paper to demonstrate that the differences of the residual microstructures (which are orientation dependent) are to a large extent due to how the heat generated inside the samples during shock is extracted. Post-shock recovery (annealing) and recrystallization processes dominate the residual microstructures, if the time interval and temperature are sufficient. The unique advantage of laser shock compression over plate impact, namely the rapid post-shock cooling, is discussed.

2. Experimental methods

Explosively driven flyer plates and direct drive lasers produce different shock pulses. Fig. 1 shows the characteristic shapes of these two shock waves. The shock wave produced by plate impact has initially a square shape (Fig. 1(a)) [24]. It has a flat top that has a length equal to twice the time required for the wave to travel through the projectile. The portion of the wave in which the pressure returns to zero is called the “release”. During impact, elastic waves with velocity C_0 and shock waves with velocity U_s are emitted into the target and projectile. For the experiments reported herein, the duration of the pulse at a depth of 5 mm from the impact interface was in the 1.1–1.4 μs range. For the cases studied here (thick samples, ∼1 mm) and moderately short laser pulses (2–3 ns), the launched shock quickly

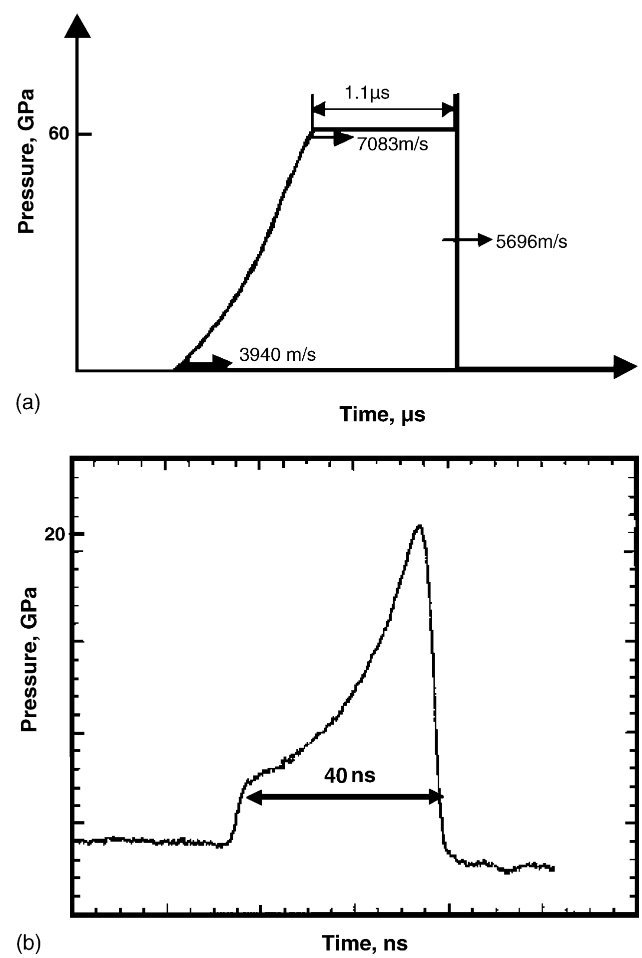

Fig. 1. Shock wave configurations: (a) shock wave (trapezoidal) produced by plate impact: time duration is 1.1 μs and peak pressure is 60 GPa; (b) pulse shape of typical laser shock experiment: time duration is 40 ns and peak pressure to 20 GPa.