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BAUSCHINGER EFFECT DURING SHOCK LOADING*

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Parallel shock recovery and wave profile experiments have been performed that exhibit a Bauschinger effect in Si-bronze shocked to 10 GPa. The unloading wave profile in Si-bronze exhibited a quasi-elastic release that had a greater departure from the ideal elastic-plastic response han the pure copper sample. The reload mechanical response of Si-bronze that was preshocked to 10 GPa exhibited less hardening than the annealed material to an equivalent strain while the reverse hardening effect was true for copper. The importance of a microstructurally-controlled Bauschinger component to defect storage during the shock process is discussed in light of the shock recovery, wave profile, and deformation substructure results.

1. INTRODUCTION

Due to the intrinsic nature of the shock process the structure/property response of a material is a result of the total shock excursion that is comprised of: 1) the compressive loading regime occurring at a very high (~10^5 - 10^8 s^{-1}) strain rate (shock rise), 2) a time of reasonable stable stress (pulse duration), and 3) a tensile release of the applied compressive stress returning the sample to ambient pressure at a lower strain rate. Collectively the shock / release sequence amounts to a single cycle stress/strain path with elastic and plastic deformation occurring during both loading and unloading.

In this regard the shock process may be compared to a single high-amplitude "fatigue-type" cycle with a dwell time representing the pulse duration.[1] The inherent stress/strain path reversal of the shock process is crucial to an understanding of the total defect storage during the shock process and the reduced shock strengthening in some materials. Some metals and alloys after reversing the direction of stressing quasi-statically, exhibit a reduced yield stress for plastic flow, termed a Bauschinger Effect.[2,3] In most two-phase materials and some single-phase alloys deforming via twinning, a back stress is developed in the matrix due to the presence of the unrelaxed plastic strain in the vicinity of the second-phase or twins.[3] Yielding in the reverse direction then occurs at an apparent reduced stress level compared with the forward flow stress level due to the inhomogeneous stress distribution. The identification of an apparent Bauschinger Effect contribution to shock loading is not a new idea.[4-6] This concept has been utilized to explain the deviation of the shock unloading stress-strain path from that predicted by simple elastic-plastic theory.[4-6] In materials exhibiting ideal elastic-plastic behavior, the unloading path will consist of a purely elastic wave to the lower yield surface and then a bulk plastic wave to ambient pressure. In reality, experimentally measured unloading wave profiles show evidence of the onset of plastic flow occurring immediately upon release from the shock state. This results in a gradual transition to the fully plastic state without a clearly defined elastic component. This phenomena is termed quasi-elastic release.

Utilization of the Bauschinger effect to explain this phenomena has however been restricted to manipulation of the unloading stress-strain path until the wave profile was satisfactorily reproduced. In the modeling work of Steinberg et al.[6] the transition from an ideal elastic-plastic release path to a curved quasi-elastic path is reproduced with the use of a variable effective shear modulus. While this modeling approach has duplicated the unloading profiles, it does not explain the micro-mechanisms of structure evolution, defect storage processes, and/or provide physical understanding of the shock release process to facilitate realistic modelling of material behavior.

Recent shock recovery experiments by Gray[1] showed evidence of a Bauschinger effect in a shock-loaded two-phase Al-4wt.% Cu alloy as a function of microstructure. The purpose of this paper is to present results of a study using shock recovery and wave profile measurements in parallel to investigate the Bauschinger effect in silicon bronze.

2. EXPERIMENTAL

A single-phase 3 wt.%Si-Cu alloy (Silicon bronze) of composition (in wt.% 3.3 Si, 0.53 Mn, 0.52 Zn, 0.12 Sn, 0.08 Fe, and bal. Cu) was studied. This low-solute alloy was chosen to allow direct comparison with the reload mechanical response and unloading profiles of pure copper. Copper-based brass and bronze alloys exhibit pronounced quasi-static Bauschinger effects, due to deformation twinning, while pure copper does not.[3] Samples of copper and silicon bronze were shock loaded to 10 GPa for a pulse duration of 1 μsec and "soft" recovered. Samples to evaluate the reload mechanical properties and for transmission electron microscopy (TEM) were sectioned from the shock-recovered disc. Further details of the experimental set-up, shock recovery, and characterization techniques utilized are presented in-depth elsewhere.[7]

The shock wave experiments involved impacting copper (or Si-bronze) targets that had C-cut (0001) sapphire windows at a velocity to generate a 10 GPa stress wave in the target. C-cut sapphire windows were also used as impactors to generate nearly (within a few ns) simple centered release into the sample at the impactor-target interface. This impactor target configuration allowed the fine structure of the quasi-elastic release to be displayed with minimum distortion. A Hemsing[8] VISAR was used for wave profile measurements. The electronic system consisted of specially built photomultiplier circuits that had 1 ns risetimes. The records were recorded on a Tektronix DSA 602A digital signal analyzer that interleaved the amplifiers to obtain a 1 ns timing resolution. The C-cut sapphire windows closely matched the impedance of the targets. This target geometry minimized to the extent possible, hydrodynamic perturbations at the target-window interface.

3. RESULTS AND DISCUSSION

Figure 1 compares the stress-strain response of an annealed copper sample that has been quasi-statically loaded after being shock-prestrained to 10 GPa. The shock-loaded stress-strain curve is plotted offset at the approximate total transient strain [calculated as 4/3 $\ln(V/V_0)$ where V and V_0 are the compressed volume during the shock and the initial volume, respectively] for the shock experiment. The offset curve shows that the reload behavior of the shock-loaded sample (to an equivalent strain level) exhibits a flow stress considerably higher than the unshocked copper. This phenomena has been attributed to the very high strain rates associated with shocking and the subsonic restriction on dislocation velocity requiring the generation and storage of a larger dislocation density during the shock process than for quasi-static processes.[1]

Figure 2 shows the stress-strain response of annealed Si-bronze compared to the stress-strain response of the alloy following shock-loading (offset by the transient strain). Contrary to the enhanced hardening the shock produces in copper loaded to 10 GPa, Figure 1, the Si-bronze exhibits a reload yield less than the unshocked material strained to an equivalent strain level. This response is similar to that seen in the θ' precipitate containing microstructure in Al-4Cu previously studied by Gray.[1] The deformation substructure of the shock-loaded copper and silicon bronze were observed to differ considerably. In the copper, uniformly distributed dislocation cells predominated whereas a high density of closely spaced (~50 nm) deformation twins comprised the substructure in the silicon bronze.

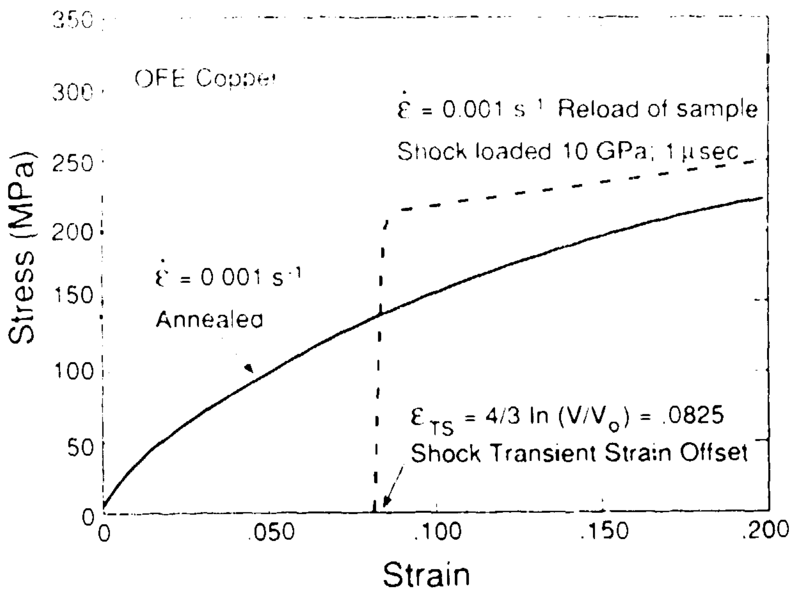

FIGURE 1

Reload stress-strain of shock-loaded copper compared to the annealed condition (based on an equivalent strain).

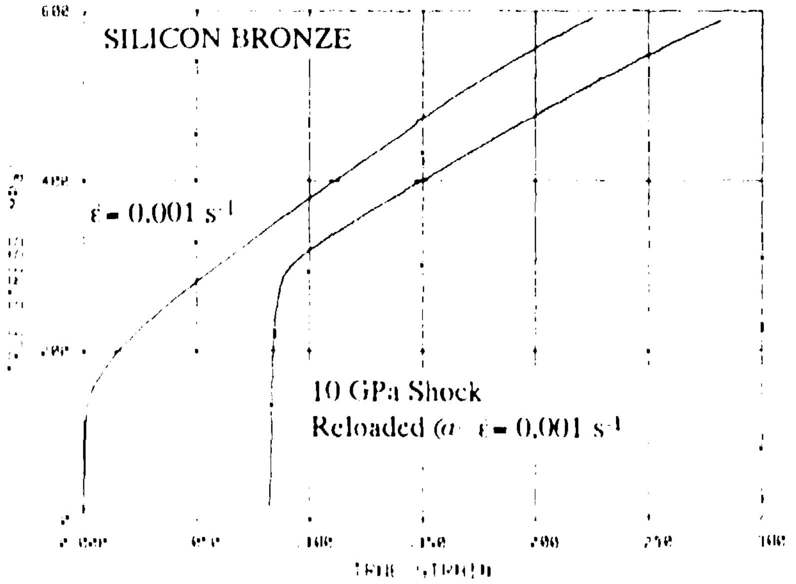

FIGURE 2

Stress-strain of shock-loaded Si-bronze contrasted to the annealed alloy showing evidence of a Bauschinger Effect.

The unloading wave profiles of both the copper and Si-bronze alloy were both measured using a VISAR. Figures 3a and 3b show the wave profiles of Si-bronze and copper shock loaded to 10 GPa for identical pulse durations. Several features are evident from these profiles. In the case of the Si-bronze the wave profile displays a distinct elastic precursor consistent with the initial higher strength of this alloy. Following the pulse duration at constant pressure a gradually decreasing(concave down) unloading release wave behavior is seen suggesting a strong departure from ideal elastic-plastic response. In contrast, the copper shock-wave profile displays a weak, poorly-defined elastic precursor reflecting the low initial strength of copper. In addition the unloading wave shape (indicated by arrow) is seen to consist of an initially sharper drop in velocity followed by a shallower wave shape. While this profile clearly is not ideally elastic-plastic, the unloading wave does suggest a release behavior that is more ideally elastic-plastic than the Si-bronze quasi-elastic release wave.

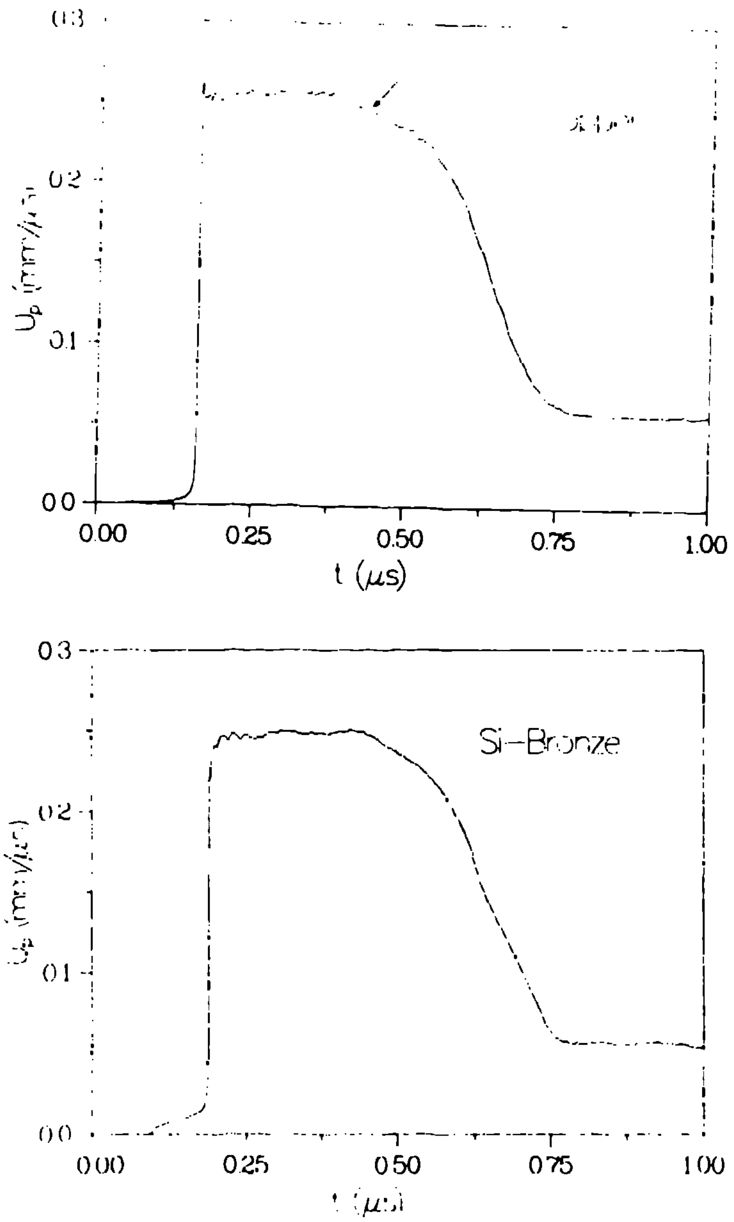

FIGURE 3
VISAR Wave profiles of: a) Copper and b) Si-bronze at 10 GPa exhibiting differing unloading wave shapes supporting a Bauschinger contribution to unloading for the bronze.

For a given amplitude of the quasi-elastic release wave, the more the release wave approaches the ideal elastic-plastic response the greater the strength at pressure of the material. The lack of an ideally elastic-plastic release wave in copper appears to suggest a limited reversal component, however this is much less than in the Si-bronze. Collectively, the differences in wave profiles between these two materials are consistent with a microstructurally-controlled Bauschinger component as supported by the shock recovery results. A detailed analysis of these profiles will be given in a future publication.

Deformation in the shock-loaded silicon bronze occurs by planar slip and deformation twinning. Intersection of the dislocation debris with the twins are believed to have sufficient strength to act as strong barriers to dislocation glide. The bronze response is therefore similar to 2-phase materials. The twins act as barriers to support large numbers of dislocations in planar glide pileups. When the direction of stress is reversed, the barriers to dislocation activity are essentially removed and the material yields at a stress much lower than the forward flow stress. This reduced yield stress is reflected in the quasi-elastic release for the bronze. For copper, based on its lack of a Bauschinger effect, it appears that the stress required to produce dislocation activity associated with the cell structure is independent of polarity.[3]

Further study on a wide range of materials is required to quantify these findings and ascertain the influence of this phenomena on defect storage during the shock as reflected in the wave profiles.

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