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TITLE: INFLUENCE OF PEAK PRESSURE ON THE SUBSTRUCTURE EVOLUTION AND MECHANICAL PROPERTIES OF SHOCK-LOADED 6061-T6 ALUMINUM

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NFLUENCE OF PEAK PRESSURE ON THE SUBSTRUCTURE EVOLUTION AND MECHANICAL 'ROPERTIES OF SHOCK-LOADED 6061-T6 ALUMINUM

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Systematic shock recovery experiments have been performed on 6061-T6 Al hocked to pressures of 2,8, and 13 GPa for 1 sec pulse durations. ompression samples EDM machined from the recovered samples show that the echanical behavior of 6061-T6 saturates rapidly under shock loading. lectron microscope examination reveals a random high dislocation density ubstructure, different from that observed in other shock-loaded aluminum lloys. Substructure evolution and mechanical response are discussed in light f the influence of strengthening mechanisms and shock recovery techniques.

INTRODUCTION

Shock recovery experiments, in which structure/property relationships are characterized quantitatively, provide important insights into the deformation behavior of materials during shock loading. While the micro-mechanisms of shock deformation of pure metals and some alloys have been widely studied, the substructure evolution during shock loading of precipitation strengthened alloys has received less attention.[1] Metallurgical studies of the influence of shock-wave deformation on precipitation strengthened aluminum alloys are particularly sparse.[2-5] Experiments on thoria dispersed nickel found that dispersed particles suppressed dislocation cell formation, planar dislocation array formation, and recovery.[1] Contrary to the TD nickel study, studies of 6061-T6 aluminum[2,3] reported heterogeneous shear band formation during shock deformation. The object of the present study was to investigate the substructure evolution and mechanical behavior of 6061-T6 aluminum as a function of peak shock pressure.

EXPERIMENTAL

Commercial purity 6061-T6 plate 25.4 mm thick was used for this study. The as-received plate was cross-rolled 75% and recrystallized at 550^{0}C for 3 hours and water quenched. This processing eliminated the elongated grain structure typical of hot-rolled aluminum plate and yielded an equiaxed grain structure of 40μm. Aging to T6 was done at 180^{0}C for 8 hours followed by an air cool. Samples of the as-received and equiaxed 6061-T6 material were cold-rolled 13, 25, and 50% to provide quasi-static comparisons with the shock studies. Shock recovery experiments were performed utilizing a 40-mm single-stage gas gun. The specimen assembly consisted of a 4.76 mm thick, 12 mm dia. sample tightly fitting into a similarly sized bored recess in the inner momentum ring/spall plate(25.4 mm dia.). This inner cylinder is inturn surrounded by two concentric momentum trapping rings. All sample components were made of 6061-T6 Al.

Aluminum samples were shocked to pressures of 2,8,and 13 GPa for a pulse duration of 1μsec by impacting a flyer plate projectile with the specimen assembly. Samples were "soft" recovered to minimize residual plastic strain and cooled by decelerating the sample in a water catch chamber. All of the recovered shock loaded samples studied possessed fixed residual strains of less than 1.5%. The shock-loaded samples were stored in liquid nitrogen ,excluding machining time, until tested. Compression samples were EDM machined from the recovered sample and reloaded at a strain rate of 0.0015 s^{-1}. Samples for optical and transmission electron microscopy(TEM) were also cut from the shocked sample. Observation of TEM foils was made using a JEOL 2000EX at 200 kV.

RESULTS

The substructure and re-load compression behavior of 6061-T6 Al was found to be relatively insensitive to the peak shock pressure variation, 2 to 13 GPa, studied. Figure 1 presents a plot of the reload yield stress-strain behavior of the starting material and shocked samples. Increasing the peak pressure is observed to only slightly increase the yield strength of the shock loaded 6061-T6 samples. The work-hardening behavior of the 2 and 8 GPa samples are observed to be essentially identical. The 13 GPa sample exhibits a nearly flat hardening response. TEM examination of the "soft-recovered" shock loaded 6061-T6 samples revealed that the overall dislocation substructure consisted of random dislocation debris. (Fig. 2) With increasing shock pressure microbands lying along {111} planes were also observed. (Fig. 3) The 13 GPa sample also displayed deformation twins. (Fig. 4) The cold-rolled 6061-T6 materials displayed random dislocation debris at low (13%) rolling reductions. Increased rolling was observed to increase the degree of microbanding, particularly in the elongated grain as-received material.

DISCUSSION

Investigations of the nature of deformation mechanisms during shock loading are beginning to document how the starting microstructure/properties of a material influence its response to shock-wave deformation. The residual structure/property relationships in 6061-T6 Al, compared to pure Al or other Al alloys shocked to similar stress levels[4,5], support the controlling role of intrinsic metallurgical strenghtening mechanisms on substructure evolution rather than processes specific to the shock itself. The mechanical response of 6061-T6 Al in the present study exhibits the same low work-hardening rate well documented in this alloy when quasi-statically deformed. The nearly flat reload hardening behavior of the 13 GPa shot is thought to represent either a dislocation generation/annihilation plateau in the yield response or reflect the influence of deformation twinning. The random dislocation substructure, seen in both the rolled and shocked 6061-T6 samples is believed to result from the dispersing effect of the precipitates in this alloy on slip. Shock loaded 99.99 Al displays a well defined subgrain substructure with a high density of dislocation loops.[4] The binary alloy, Al-4.8 wt% Mg, shocked to 13 GPa at -180^{0}C, displayed more deformation twinning and no microbands compared to the 6061-T6 in this study.

The exact mechanism of formation of the microbands observed in this study is not known; however research suggests they are most probably a recovery dislocation configuration and not formed during deformation.[6] The absence of microbands in the shocked Al-4.8 Mg may reflect the reduced dislocation mobility in this solid-solution alloy or a reduced amount of thermal recovery. Microbands in this context define elongated regions which are initially parallel to active slip planes.[6] Observations suggest that microbands develop with strain into non-crystallographic macroscopic shear bands which are able to penetrate both existing dislocation substructures and grain boundaries.[6] TEM observations in this study found no shear bands or evidence of adiabatic heterogeneous deformation as previously reported[2,3] in 6061-T6 Al. Microstructures in duralumin[5], identified as shear bands, were found to be the direct result of high strains and high local temperatures occurring during specimen deceleration and not from shock deformation. Crucial to accurate post-mortem metallurgical analysis of shock-loaded samples is careful consideration of isolating recovery effects, either mechanical or thermal, from the deformation uniquely the product of the shock event. Recent work on shock-loaded copper illustrates the overshadowing affect residual strain, caused by radial release and/or recovery effects, can play on substructure development.[7] The shear bands reported in 6061-T6[2,3] samples "hard" decelerated with aluminum honeycomb and steel plates therefore appear highly suspect; the anisotropic elongated grain structure used may also influence shear band formation. The mechanical behavior of the as-received material versus the equiaxed used in this study showed a much lower work-hardening rate in the as-received material which would favor localization. Overall, while phase transformations and local plastic instabilities, such as adiabatic shear bands, often occur more readily at high strain rates, low-residual strain shock processes appear in general to operate utilizing the same basic processes of metal plasticity, i.e. slip and twinning, as in quasi-static deformation.

CONCLUSIONS

Based upon a study of the variation of peak pressure on the structure/property behavior of 6061-T6 Al, the following conclusions can be drawn: 1) The re-load yield behavior and dislocation substructure saturates with increasing peak pressure. 2) Strengthening mechanisms influence the substructure development in Al alloys during shock loading. 3) Accurate post-mortem metallurgical analysis of shock-loaded samples requires "soft" recovery techniques.

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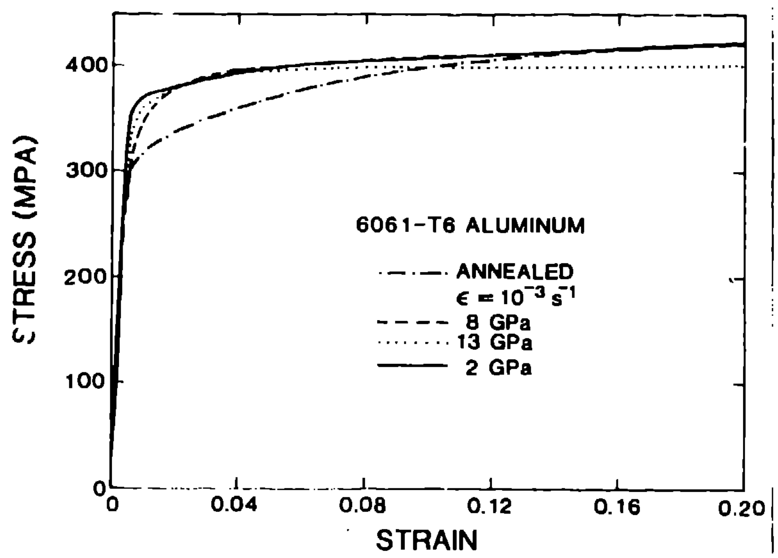

FIGURE 1

Plot of reload true stress versus true strain as a function of shock pressure.

FIGURE 2

TEM micrograph of 6061-T6 Al shocked to 2 GPa showing random dislocations.

FIGURE 3

TEM micrograph of 6061-T6 Al shocked to 13 GPa showing microbands.

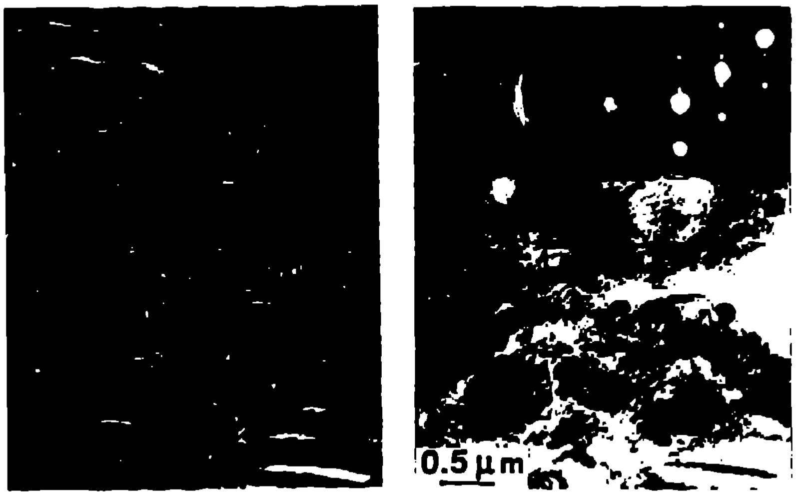

FIGURE 4

TEM bright field, dark field, and diffraction micrographs of deformation twins in 13 GPa shock loaded 6061-T6 Al.