DYNAMIC FAILURE OF NANOSTRUCTURED METALS

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ABSTRACT
The dynamic failure of nanostructured materials is considered. Both metallic and ceramic nanostructured systems have been investigated. The materials are made by a variety of techniques, including hot consolidation, equal channel angular pressing, sputtering and electro-deposition. A suite of experimental techniques is described for the determination of material properties and failure mechanisms under high rates of deformation. Under dynamic loading, both shear band-driven failure and microcrack-driven failure are observed. Microcrack-driven failures are observed in nano-composite ceramics (grain sizes ranging from 30 nm to 500 nm). It is possible that an effective plasticity is present in these ceramic systems. The shear instabilities are typically observed as a consequence of grain size reduction in bcc metals, where kink-dominated dislocation mobility dominates the constitutive response, leading to a substantial reduction in the rate-dependence of the flow strength at small grain sizes and therefore to a propensity for deformation instabilities.

1. INTRODUCTION

The dynamic failure of nanostructured materials is considered, with nanostructured materials being defined as bulk materials in which a significant grain size dimension is in the range of 100 nanometers. Both metallic and ceramic nanostructured systems have been investigated. It is commonly understood that nanostructured materials are very hard but relatively brittle, which translates also to a pronounced compression-tension asymmetry. This paper reviews recent results that help to develop an understanding of the processes of deformation active in such materials at high rates of deformation, and the impact of these processes on subsequent failure modes.

2. MATERIALS

The nanostructured materials investigated in this study were made by a variety of techniques, including hot consolidation, equal channel angular pressing, sputtering and electro-deposition. Grain sizes developed range from 30 nm to 300 nm. The metals investigated include iron, vanadium, tantalum and tungsten among the bcc metals; copper and nickel among fcc metals, and titanium as a hcp metal. The nanostructured ceramics that are examined are nanocomposites containing either zirconia and alumina or alumina and spinel.

Each of the techniques used for making nanostructured materials results in qualitatively different materials, and these differences have great significance with respect to failure processes. Thus, for example, consolidation typically results in substantial amounts of prior plastic work as well as some residual porosity. The prior plastic work sometimes leads to the exhaustion of strain hardening, and the residual porosity can accentuate the compression-tension asymmetry. Equal channel angular processing (ECAP) generates very large amounts of prior plastic deformation and thus a very high density of dislocations, but has very little porosity as a result of the large pressures developed during the process. ECAP materials are often strongly textured. Sputtering and electro-deposition typically generate materials with no prior plastic deformation, but the samples are extremely thin, may be textured and may have residual porosity. The small thickness of these samples makes certain failure modes (e.g. buckling or necking) far more likely, and greatly limits the experimental range of conditions that can be developed. Further, the majority of the

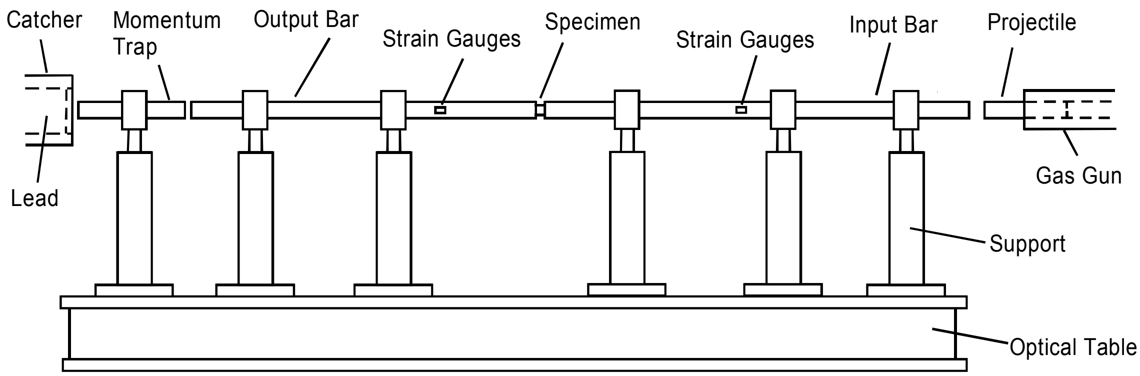

Figure 1. The miniaturized ("desktop") Kolsky bar, used for testing specimens with a typical dimension of 1 mm.

boundaries in some electrodeposited materials are low angle boundaries rather than high angle grain boundaries. Thus, even for one material (say pure tantalum), each type of processing may result in dramatically different mechanical properties and failure mode, and analyses of the failure mechanism should explicitly consider the consequence of the processes through which the nanostructured material was made.

3. EXPERIMENTAL TECHNIQUES

A suite of experimental techniques has been used for the determination of material properties and failure mechanisms. These techniques include servohydraulic testing for low rate behavior, compression and desktop Kolsky bars (Figure 1) and pressure-shear plate impact for the high strain rate behavior. All of the work presented here involves a superimposed compressive stress state. Samples sizes range from approximately millimeter-size cubes for the desktop Kolsky bar to thin sheets 25 mm in diameter and approximately 75 μm thick for high-strain-rate pressure-shear plate impact.

Descriptions of the compression Kolsky bar (or split-Hopkinson pressure bar) and desktop Kolsky bar techniques can be found in Jia & Ramesh (2004). The specimens in this case are either cylindrical or cuboidal, with length-to-effective-diameter ratios of about 0.6 and lengths of either 3 mm (the conventional bar) or approximately 1 mm (the desktop bar). Compressive strain rates as high as 10^4 per second are attained with these techniques. A DRS Hadland Ultra 8 camera has been coupled to these systems, so that high-speed photography of the failure process is possible.

Scanning electron microscopy (SEM), optical microscopy and transmission electron microscopy (TEM) are used for microstructural characterisation both before and after deformation.

3. RESULTS AND DISCUSSION

Stress versus strain curves are obtained from these experiments, and provide accurate constitutive information until the time at which a failure mode develops, resulting in a loss of uniformity in the stress and strain distributions. An example of stress-strain curves obtained on an ECAPed iron material are presented in Figure 2. Note the very high strengths (for pure Fe) associated with the small grain size.

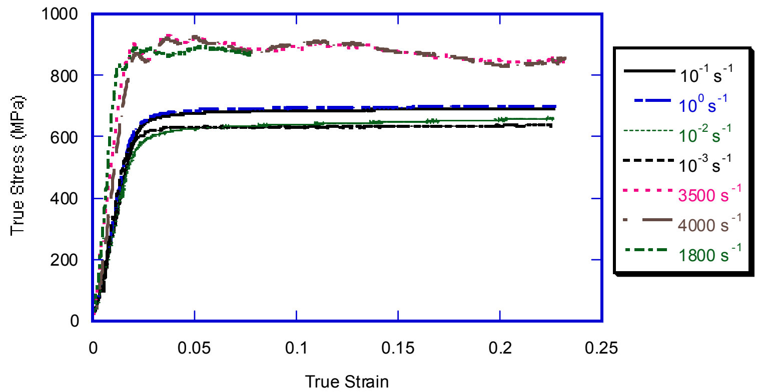

Figure 2. Quasistatic and dynamic test results for ECAPed iron

The rate sensitivity of this material is also smaller than that of the conventional grain size iron, and this leads to the possibility of deformation instabilities when coupled with the lack of strain hardening evident in Figure 2. Under dynamic loading, shear band-driven failure is observed in this material, as described by Jia et al. (2003) and Wei et al. (2002). The shear instabilities are typically observed as a consequence of grain size reduction in bcc metals, where kink-dominated dislocation mobility dominates the constitutive response, leading to a substantial reduction in the rate-dependence of the flow strength at small grain sizes and therefore to a propensity for deformation instabilities.

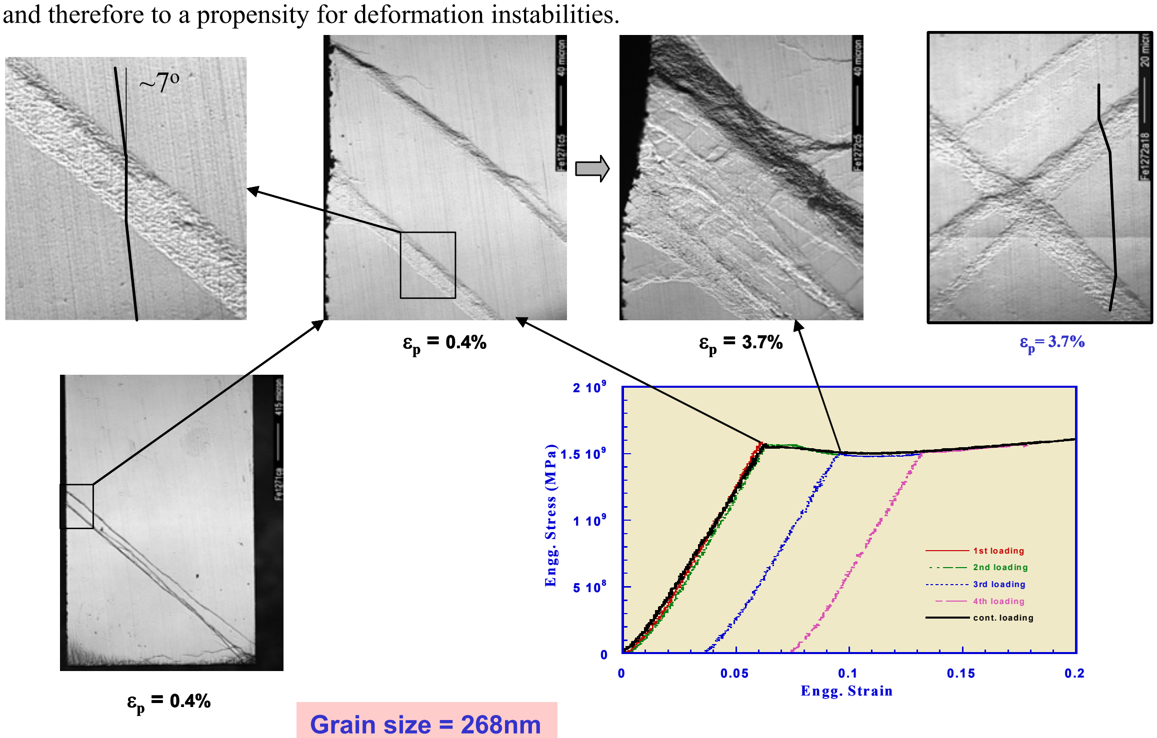

Figure 3. Shear band evolution in nanostructured iron during load-unload-reload cycles.

The development of the shear instabilities is evident in the sequence of micrographs obtained after load-unload-reload cycles during quasistatic testing and presented in Figure 3. These micrographs, which are analogous to those presented by Wei et al. (2002), are of the same region on the specimen as the overall compressive strain in the sample is increased. Note the development of the shear band after extremely small strains (indeed, at the onset of apparent macroscopic plasticity), and the subsequent broadening of the band, the nucleation of additional bands, and the overall compatibility of the deformations even when the shear bands intersect each other. TEM observations (Wei et al. 2002) indicate that a geometric softening mechanism is active in the shear bands.

Observations of deformation of other bcc metals indicates similar modes of failure are active even during dynamic deformations, whereas such shear bands have not been observed within this work during the deformation of nanostructured fcc metals. We believe the reason for this difference is the increasing rate sensitivity of fcc metals with decreasing grain size in this size range (Wei et al., 2004).

Nanostructured ceramics, on the other hand, show failure by fragmentation due to microcracking during dynamic compression. The observed strengths are not as high as expected, but this may be a result of difficulties with densification of the material during processing.

4. ACKNOWLEDGMENTS

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