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Strain-induced coarsening in nano-grained films

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Abstract

The potential use of nanostructured materials in structural applications is severely restricted by their low ductility, which due to a limited capacity for work-hardening. Since nanograin size eliminates the dislocation–dislocation interactions that ordinarily control work-hardening, new hardening mechanisms must be identified and exploited if this problem is to be overcome. One possible approach to controlling work hardening is to exploit strain-induced reconfiguration or coarsening of the grains themselves. In the present work, we discuss recent observations of mechanically induced grain coarsening during the nanoindentation of micro-grained and nanograined aluminum. These phenomena are studied directly through in situ nanoindentation in an electron microscope.

Keywords: TEM; Nanoindentation; Nano-grained microstructure; Deformation mechanisms

1. Introduction

The achievement of nanograin sizes in structural metals and alloys has led to exceptionally high strengths, at least as measured by superficial hardness. This behavior is in accord with the well-known Hall–Petch relationship [1,2]

$$\sigma_y = \sigma_0 + K_y d^{-1/2} \tag{1}$$

where d is the mean grain size and σ_0 and K_y are constants. Grain refinement produces very impressive increases in strength even in nominally soft materials. For example, Tsuji et al. [3] have documented an increase in the yield strength of 1100 Al from 40 to 250 MPa (more than 600%) on decreasing grain size from 10 to 0.27 μm.

However, high-strength materials have limited practical use unless that strength is combined with some useful ductility and toughness. And, unfortunately, almost all efforts to achieve ultrahigh strength by grain refinement have resulted in catastrophic losses in useful ductility when the grain size falls below about 1 μm. The reason lies in the early onset of plastic instability in ultrafine-grained alloys, which leads to necking and fracture under tensile load. Research on a variety of materials, including soft aluminum [3] and high-strength steel [4,5] have shown that it is difficult to maintain useful ductility at grain sizes below about 1 μm.

The basic mechanism is illustrated in Fig. 1 [5]. A specimen strained in tension becomes unstable with respect to necking and subsequent failure when the Considère criterion is satisfied:

$$\theta = \mathrm{d}\sigma/\mathrm{d}\varepsilon = Q_\sigma \tag{2}$$

where σ is the true stress, ε is the true strain, θ is the true work-hardening coefficient and Q is a geometric factor, of order 1, that depends on the shape of the sample ($Q=1$ for a cylindrical sample). The stress at which Eq. (2) is satisfied determines the ultimate tensile strength (σ_u) since it sets the highest load the sample can bear. The strain at σ_u is the uniform elongation, ε_u, the true strain at necking. The consequences of grain refinement are illustrated qualitatively in Fig. 1(a), where we have assumed that grain refinement increases strength without affecting work hardening and taken $Q=1$. The dramatic decrease in elongation with grain refinement is apparent. As illustrated in Fig. 1(b), the yield and tensile strengths increase together, but the increase in tensile strength is more rapid. At some value of the grain size, the ultimate strength actually falls below yield and ductility essentially disappears. While the model illustrated in Fig. 1 is highly simplified, both more elaborate analyses [5] and the available experimental data [3] yield very similar results.

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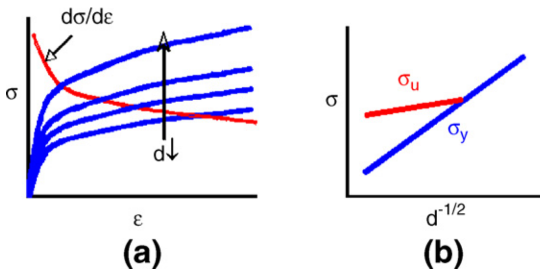

Fig. 1. (a) Schematic drawing illustrating how the Considère criterion leads to a decrease in uniform elongation with increasing strength at constant work hardening. (b) Schematic drawing illustrating the change in yield and ultimate strength with grain size.

It follows from this discussion that the search for methods to improve the ductility of nanostructured materials should concentrate on methods for controlling work hardening. In the case of nanostructured materials, the available mechanisms for doing this are limited. The ultrafine grain size severely limits the dislocation density and the dislocation–dislocation interactions that largely govern work hardening in conventional materials. If this problem is to be solved, new hardening mechanisms must be identified and exploited.

While it is difficult to observe dislocation activity in nanograined materials, the available work suggests that dislocations do not provide a straightforward path to a high work-hardening rate [6,7]. Computer simulation studies, in particular, show grain boundary sliding accompanied by dislocation nucleation and transmission across grains, leaving little or no intraganular debris. While grain boundary sliding can produce a high transient rate of work hardening, as the most favorable sliding sites exhaust themselves, and can lead to extensive "superplastic" ductility in the creep regime (diffusion-dominated deformation at high temperature or very slow strain rate), it does not appear to be a promising mechanism for stable plastic deformation at ordinary temperatures and strain rates.

Transformation-induced plasticity (the "TRIP" effect) provides an alternative deformation mechanism that can add to the ductility of ultrafine-grained steels with carefully adjusted composition [4], but is inapplicable to materials that lack a strain-induced martensitic transformation that intrudes under just the right conditions.

Still a third possibility, stress-induced grain growth, is attracting increasing attention since its recent discovery in research on nanograined Al [8] and Cu [9]. Both in situ [8] and post-deformation [9] studies of ultrafine- and nanograined materials that have been deformed by nanoindentation show that significant grain coarsening occurs locally during the indentation process. Both Jin et al. [8] and Zhang et al. [9]

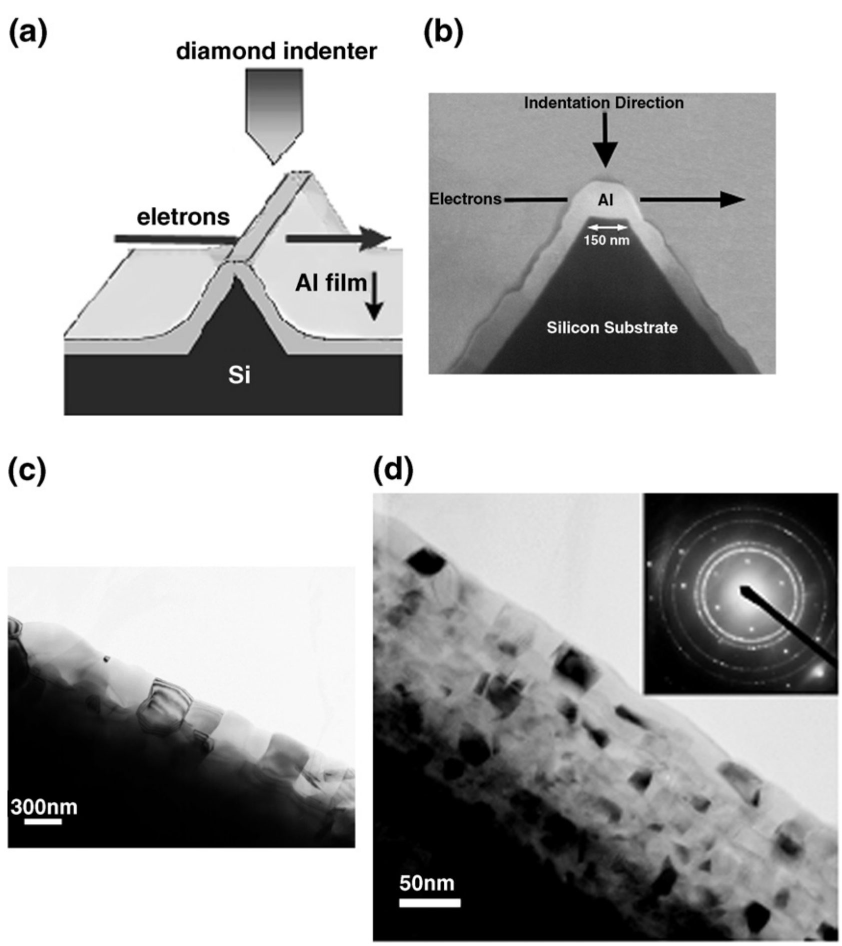

Fig. 2. Sample preparation: (a) Al film deposited on Si wedge. (b) Detail of deposited film. (c) TEM image showing transparency of ultrafine-grained film. (d) TEM image showing nanograined film.