Revealing deformation mechanisms in nanoscale metals

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Nanostructured metals show exceptional strength relative to their bulk counterparts. This fact has allowed sub-micrometer metal components and nanocrystalline films to be used reliably under extreme conditions in many technological applications. It has also led to numerous scientific studies aiming to understand the origin of the enhanced strength (e.g. [1-5]). Through the use of transmission electron microscopy, micro-mechanical testing, and computer simulations, a general picture for strength and deformation in small scale metals has emerged which is based on the interplay between sample size and initial defect density [4]. Simply put, if the sample initially contains no dislocations, as is often the case in nanoscale samples, yield is controlled by dislocation nucleation and is not expected to depend on sample size (Fig. 1(a)). In samples with micrometer sizes and moderate initial defect densities, interactions between defects and other possible obstacles lead to sample size dependent defect structures and strengths (Fig. 1(a)) [2]. In larger samples, dislocation structures are formed with characteristic spacings much smaller than the sample dimensions and sample size-independent bulk strength is expected. An important consideration in predicting strength is knowing whether initial or nucleated dislocations will run out of the sample entirely (as is expected in samples that are smaller than the interaction distances and without obstacles), or will interact to form a stable network.

TEM is one of the few experimental methods that allow in-situ studies of dislocations. Over the last several decades, and more intensely in the last several years, TEM studies have been applied to investigate the mechanisms of dislocation nucleation, interaction, and storage. The method is ideal for nanoscale samples which are electron transparent in their original form. However, dislocations are expected to move very quickly at the high stresses attained in the small samples, and current TEM detectors are not fast enough to image the dislocations unless they are slowed down by interactions with obstacles. Thus, even with in-situ studies, one often has to infer what has happened after the fact. Nonetheless, a synthesis of the literature studies allows some conclusions to be reached, including the prevalence of dislocation interactions even in very small sample volumes and evidence of defect forms and structures not common in bulk samples.

In an attempt to reach a deeper understanding of the deformation mechanisms in nanoscale samples and to determine how they mediate strength, we have undertaken a number of in-situ and ex-situ electron microscopy studies on nanoscale Au specimens of high crystal quality and with controllable dimensions. Specifically, we investigate storage of dislocations in deformed Au nanoparticles and nanoporous Au using post-mortem TEM, and study dislocation nucleation using in-situ tensile deformation of Au nanowires in both the TEM and the SEM (Figure 1 and 2). Characteristic dimensions of the samples range from 10 nm to 300 nm.

In this talk, the samples and the methods used for investigating deformation at the nanoscale will first be presented and assessed. Particular attention will be given to the advantages of stiff mechanical testing platforms for avoiding plastic instabilities. Then, the defects observed during and following deformation and the associated flow stresses of the three different nanoscale Au samples will be summarized. Different defect morphologies are observed that are based on either partial or full dislocation scenarios: (1) surface nucleation of partial dislocations leading to the storage of stacking faults and layer-by-layer growth of nanotwins, and (2) surface nucleation of full dislocations resulting in interactions and defect structures, as expected in bulk specimens. It will be shown that surface facets, stress state, and initial defects are more important in determining deformation in nanoscale samples than the actual size of the samples. A quantitative nucleation rate model will be

presented which can be used to predict the active defects, the nature of defect storage, and the flow stresses. The model gives good agreement with both the studies presented here and literature data for nanoscale fcc metal samples.

References

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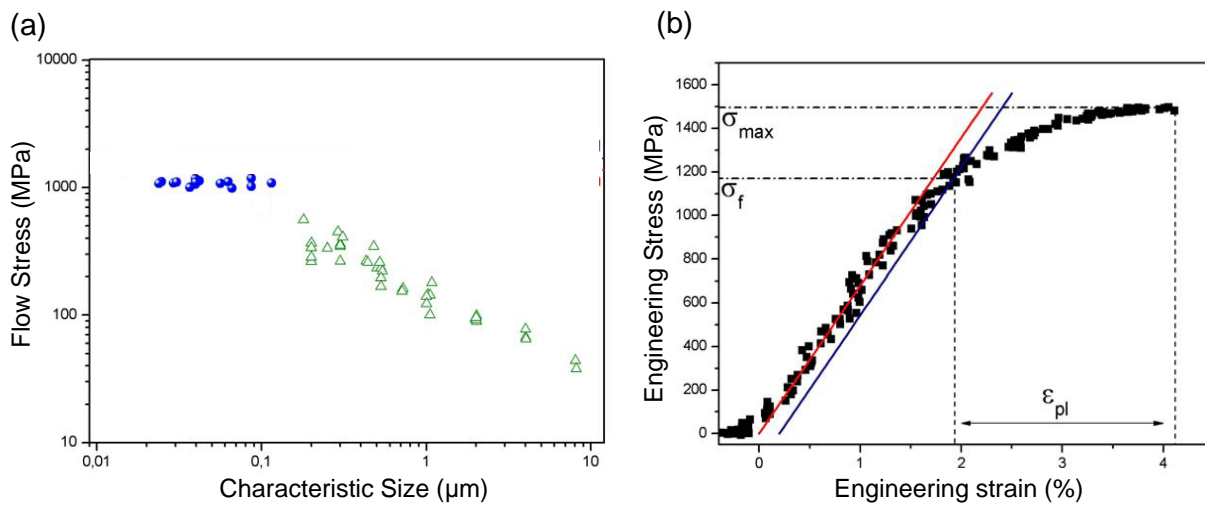
Figure 1. *(a) Flow stress of single crystal Au nanowires (filled circles) compared with flow stresses of FIB-cut single crystal Au columns determined by micro-compression testing (open triangles) [3]. The Au nanowires are initially defect free and their strength is controlled by the nucleation of dislocations. The Au columns initially contain many dislocations and their size dependent strength is attributed to the formation of size dependent dislocation structures. (b) Typical stress-strain curve from an 80 nm diameter single crystal Au nanowire obtained during in-situ testing in an SEM.*
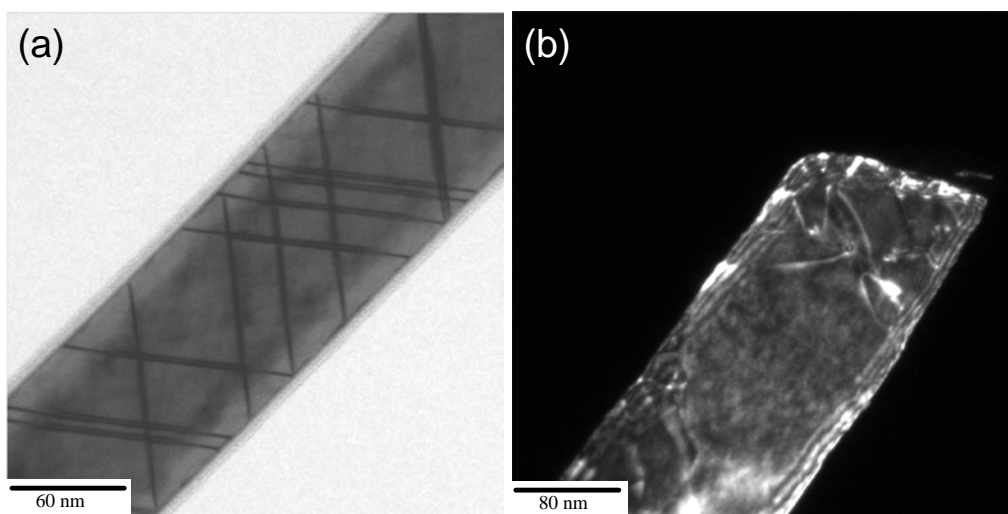
Figure 2. *Defect structures observed in faceted single crystal Au nanowires during in-situ deformation in the TEM. (a) Bright field image of stacking faults and nanotwins in a 100 nm wide Au wire. (b) Dark field image of full dislocations stored near the failure site of a 150 nm wide Au wire.*