NANOSTRUCTURED METALS

Retaining ductility

Structural applications of nanostructured metals often require both high strength and good ductility. But although these metals usually have high strength, their ductility is often too low. New experimental work suggests that it is possible to retain the ductility of metals after nanostructuring by activating certain deformation mechanisms.

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Nanostructured metals have structural features that are less than 100 nm in at least one dimension[1]. These features are usually produced by processing ('nanostructuring') metals in one of two ways: a two-step approach, such as inert gas condensation, or a one-step approach, such as severe plastic deformation (SPD).

Nanostructured metals produced by the two-step approach often have defects, such as porosity and cracks, that lead to very low ductility (defined as less than 5% elongation to failure)[2]. In comparison, the one-step approach can produce 100% dense and defect-free nanostructured metals that exhibit mechanical properties controlled by their intrinsic deformation mechanisms. However, even these metals usually have disappointingly low ductility. Is it possible to produce nanostructured metals with both high strength and good ductility? Experimental work presented at the 2004 Spring Meeting of the Materials Research Society (MRS) in San Francisco suggests this possibility.

The ductility is controlled by two material parameters: work hardening and strain-rate sensitivity. High values of these parameters help delay the onset of localized deformation ('necking') under tensile stress, thus improving ductility. Work hardening is caused by the accumulation of crystalline defects, such as dislocations, and makes further deformation harder. However, in nanostructured metals, dislocation accumulation becomes impossible because of the small grain sizes[3]. Dislocations are emitted from one grain-boundary segment and disappear at another, leaving no dislocations to accumulate inside the grain interior. Indeed, most nanostructured metals have been found to exhibit zero work hardening[4]. The strain-rate sensitivity of nanostructured metals has not been well studied; this issue needs further investigation.

The lack of work hardening has led to the conclusion that nanostructured metals have intrinsically low ductility[5], and will exhibit good ductility only at low temperatures and/or high strain rates[6]. This is confirmed by the experimental data plotted in Fig. 1, which shows that most nanostructured metals fall into the 'high-strength/low-ductility' region, shaded blue. However, there are several examples, all of them from nanostructured copper samples, that demonstrate both high strength and very good ductility.

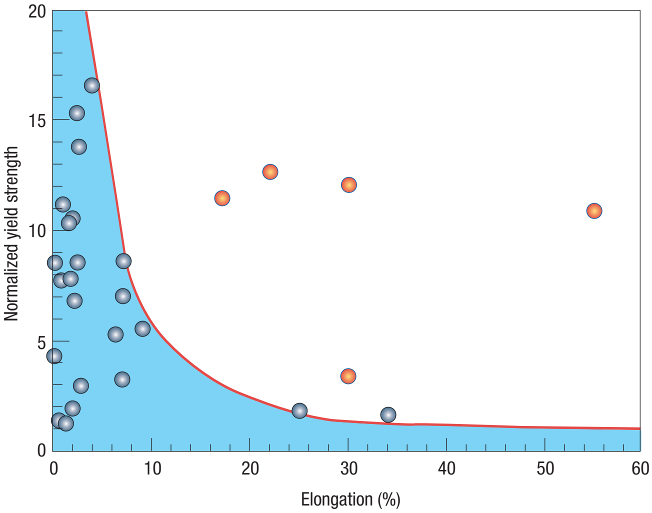

Figure 1 Normalized yield strength versus percentage elongation (ductility) for nanostructured metals. Measured yield strength has been normalized by dividing it by the yield strength of a material's coarse-grained counterpart. Most nanostructured metals have a strength–ductility trade-off; that is, high strength accompanied by low ductility (the blue region). However, several nanostructured copper samples (red points outside the blue region) exhibit both high strength and good ductility, indicating the possibility of retaining good ductility in nanostructured metals. Data from ref. 2.

Several speakers at the MRS meeting reported results that may help explain the good ductility observed in these metals. Nanostructured copper processed by an SPD technique, equal channel angular pressing (ECAP), showed longer uniform deformation (delayed necking) with increasing numbers of ECAP passes (F. H. D. Torre *et al.*, Monash University, Clayton, Australia). This indicates that larger processing strain improves the ductility. The formation of sharp, narrow grain boundaries was suggested as the reason for this observation. Nanostructured nickel samples with grain sizes below 100 nm showed significantly more pronounced strain-rate sensitivity than those with larger, submicrometre-sized grains (S. Suresh, T. Hanlon and M. Dao, Massachusetts Institute of Technology, Massachusetts). It is also found that the microhardness of nanostructured copper decreases with increasing indentation time (K. Zhang and

J. R. Weertman, Northwestern University, Illinois). In other words, the stress relaxes with time, which could be partially responsible for the high strain-rate sensitivity of nanostructured metals. High strain-rate sensitivity helps improve the ductility.

The strength and ductility of materials are determined by their deformation mechanisms, which in turn are determined by their microstructures. However, it is not yet clear what particular microstructures or deformation mechanisms are responsible for the good ductility of some nanostructured metals. Both molecular dynamic simulations[7,8] and experimental observations[9,10] have revealed that nanostructured metals deform via mechanisms not accessible to their coarse-grained counterparts. Partial dislocation emission from grain boundaries becomes a major deformation mechanism when the grain size decreases to below 100 nm (refs 7–10).

Nanostructured metals produced by SPD techniques often have non-equilibrium grain boundaries, characterized by excessive dislocations. Some dislocations may dissociate into pairs of Shockley partials, which could move away from the grain boundary under a stress (D. L. Medlin *et al.*, Sandia National Laboratories, California). Such grain boundaries thus act as partial dislocation sources. However, partial dislocations can also be emitted from grain boundaries by atomic reshuffling[7]. The deformation behaviour of nanostructured aluminium, nickel, cobalt and copper at a variety of temperatures and strain rates also indicates that partial dislocations play a primary role in the deformation (E. Ma, Johns Hopkins University, Maryland).

The activation of partial dislocations also produces deformation twins, even in nanostructured aluminium[8–10], which in its coarse-grained state never deforms by twinning except at crack tips. The nucleation of twins usually requires high external shear stress, but once twins are nucleated, it is very easy for them to grow (H. Van Swygenhoven, Paul Scherrer Institute, Villigen, Switzerland). These are deformation mechanisms unique to nanostructured metals. However, a clear connection between a particular deformation mechanism and the ductility has not yet been established. Future studies are needed to systematically introduce certain nanostructures and relate them to the mechanical behaviour of nanostructured metals.

In situ transmission electron microscopy (TEM) and atomic force microscopy are particularly powerful tools in this regard. *In situ* TEM permits direct observation of dislocation activity, grain boundary sliding and twinning processes in a localized area. Conventional TEM has yielded unexpected results, such as the observation of wide stacking faults in nanostructured aluminium (Y. T. Zhu *et al.*, Los Alamos National Laboratory, New Mexico). *In situ* TEM is more powerful in that it can observe the action of a deformation mechanism in real time, and is expected to yield more insightful information on the deformation of nanostructured metals. *In situ* atomic force microscopy enables observation of a relatively large area (a few square micrometres) on a sample surface, and, if performed systematically on the same area after varying strains, can give a near-quantitative estimate of how much each mechanism contributes to the deformation. These two complementary techniques have just begun to be applied to the study of nanocrystalline metals, and promise to provide comprehensive experimental evidence of the underlying deformation mechanisms responsible for the spectacular mechanical properties of these materials.

References

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