Nanostuctured Aluminum for a Macrostructured World

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Bulk nanocrystalline aluminum constitutes an exciting and relatively new class of materials that takes advantage of the high-strength afforded by nanocrystalline microstructures in bulk form. The materials offer substantial opportunity to improve the performance of lightweight structural components for applications ranging from ballistic armor to pressure vessels for gaseous hydrogen containment to lightweight, high-strength aerospace structures without the significant loss in ductility generally associated with high-strength materials. We have teamed with UC Davis to produce nanocrystalline aluminum alloys via a cryomilling route and assembled a multidisciplinary team at Sandia to explore the physical and mechanical metallurgy of these materials.

Cryomilled materials take their name from the primary processing step where alloy powder is milled at cryogenic temperatures. Milling involves mechanically agitating the metal powder in the presence of heavy steel or ceramic balls, thereby inducing severe plastic deformation (SPD) in the powder. Cryomilling does not substantially reduce the size of ductile particulate, but the SPD results in a very fine grain size within the particulate, while the low temperature prevents the recovery and recrystallization processes active during deformation at higher temperature. Oxide inclusions are introduced into the material during cryomilling, however,, since high surface area of the starting powder is inevitably covered with an oxide layer. The SPD refines the size of the hard inclusions in the alloy (present in all engineering alloys), as well as the oxides, and uniformly distributes them in the microstructure. The milling step is followed by a consolidation step at elevated temperature the produces a bulk ingot at near full density. Subsequent, rolling or extrusion at elevated temperature produces the final wrought product in the desired form: plate, bar etc. The processing steps must be designed judiciously to avoid grain growth and loss of the nanocrystalline structure. These final working steps are conventional processes, thus in principle, standard engineering product sizes can be produced with nanocrystalline microstructures.

The strength of cryomilled aluminum alloys is clearly superior to similar conventional alloys with elongation similar to that expected of high-strength aluminum alloys. The yield strengths of cryomilled 5083 aluminum alloy and an Al-Mg alloy are both greater than 500 MPa (Figure 1) compared to values as high as 300 MPa for these alloys in conventionally strain-hardened condition. The higher strength of the cryomilled material is derived, to a large extent, from the small grain size on the order of tens of namometers (Figure 2). Moreover, annealing of the cryomilled materials at as much as 500˚C for 2 hours has only a modest effect on strength. Aluminum alloys tend to be sensitive to thermal exposure due to aluminum's low liquidus temperature, while nanocrystalline microstructures are inherently metastable, thus the excellent thermal stability observed here is unusual for nanocrystalline alloys and may have substantial benefit for maintenance of strength in welded structures as well as application at elevated temperature.

Recent trends in metallurgy have been toward improved alloy cleanliness and a reduction in hard brittle second phases, since such phases ultimately nucleate fracture in most engineering alloys. At first glance, the cryomilling process would then appear to be folly from the standpoint of maintaining ductility and resistance to fracture, since it increases the amount of second phase by virtue of its powder processing methodology. This might seem doubly foolish for nanocrystalline materials, which tend to have inherently low ductility due to their high-strength and small grain size. However, the high fraction of second phase in cryomilled aluminum appears to provide some of the beneficial features of these materials: (i) good ductility combined with significantly improved strength, and (ii) excellent thermal stability. Indeed, cryomilled alloys, have good ductility compared to other nanocrystalline alloys and show the fracture process to be predominantly ductile in nature with void nucleation at hard second phase particles (Figure 3).

Although generally undesirable in engineering alloys, hard second phases are essentially unavoidable in engineering practice due to solidification in complex engineering alloys and supplemented in cryomilled alloys by additional oxide. The SPD encountered during the cryomilling stage, however, is efficient at refining and distributing the second phases to a much greater extent than conventional processes. The result is a dispersion of very fine second phases that pin grain boundaries (as well as dislocation motion) and stabilize the microstructural to thermally activated phenomena such as recovery and recrystallization. Moreover, nucleation of ductile fracture at second phase particles is a common feature of most structural metals. The size of these hard phases is an important aspect of fracture since large, clustered particles tend to fracture at lower loads, thus reducing ductility and resistance to fracture. For this reason wrought product generally has superior resistance to fracture (higher ductility and facture toughness) than cast product as the wrought product goes through a number of deformation processes that refine the second phases in the cast microstructure. From this standpoint, the fracture resistance of cryomilled material might be expected to be superior to wrought product, however, this benefit is somewhat mitigated by the very fine grain size and high-strength.

In summary, bulk nanocrystalline aluminum produced by cryomilling appears to derive significant benefit from large amounts of otherwise detrimental second phase: high-strength, good ductility and excellent thermal stability. While we have developed a preliminary understanding of these new materials based on microstructural and fracture analysis, the deformation mechanics and constitutive behavior of these materials are from understood. The goals of our continuing study include developing models for simulating microstructural evolution from starting powder to final product (Doug Bammann), quantifying the strengthening mechanisms and thermal evolution of the microstructures (Gene Lucadamo and Nancy Yang) and understanding the deformation of these novel materials (Chris San Marchi).

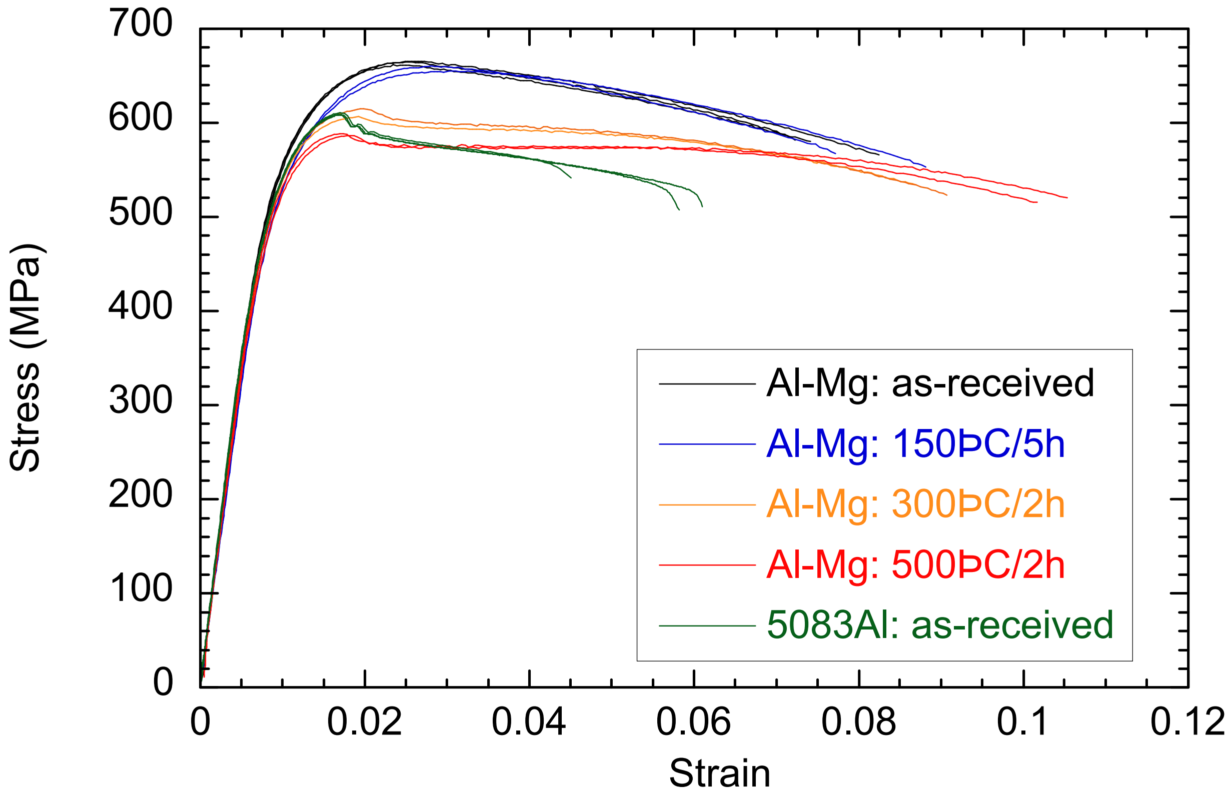

Figure 1. Tensile stress-strain curves of nanocrystalline alloys in the as-received condition and after annealing.

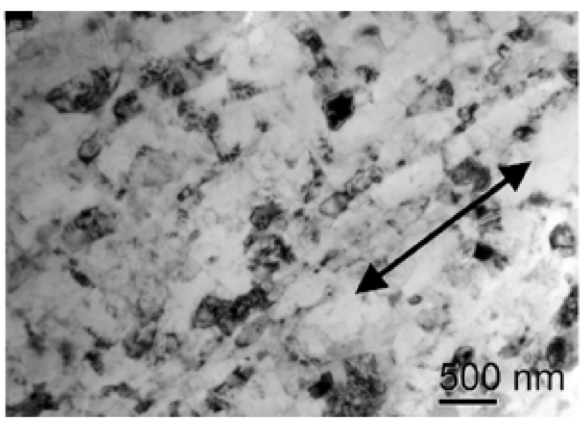

Figure 2. TEM micrograph of nanocrystalline 5083 alloy.

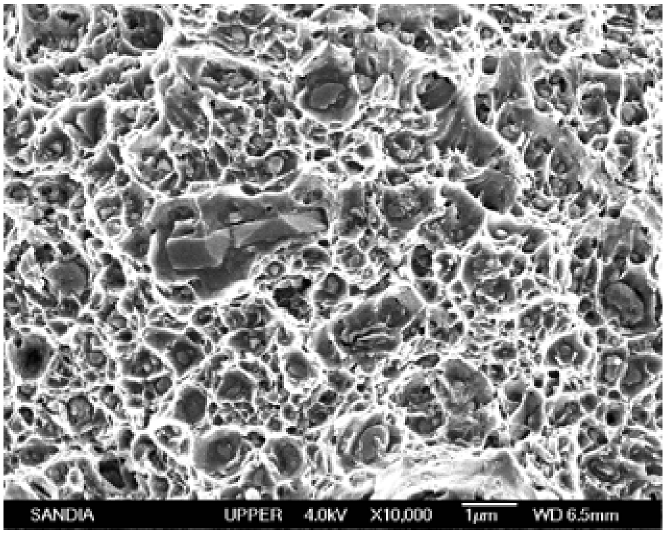

Figure 3. Fracture surface of nanocrystalline 5083 alloy.