MECHANISM OF DEFORMATION IN NANOCRYSTALLIZED MATERIALS

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Summary Recrystallization of the grain structure of metals into nano-sized grains by using mechanical means, has received wide attention in the last two decades. It is well known that materials with a fine-grain crystal structure have favorable properties compared to the same materials with course-grained crystal structure. Surface Mechanical Attrition Treatment (SMAT), a technique developed in the early part of this decade, has been successfully used to recrystallize the surface grains of metals into nanocrystals of the order of 10 to 100 nanometers from their original grain sizes on the order of 10 to 30 microns. Resulting enhancement in surface properties has quite interesting applications, varying from materials with improved fatigue resistance to medical devices. An experimental characterization study, with the objective of understanding the mechanism of length scale effect on the various characteristics of nanoplasticity such as pop-in load, residual strain and hardness, is reported in this paper.

INTRODUCTION

At low temperatures nanocrystallization is one of the few mechanical techniques that will increase strength and toughness without severely reducing ductility. The large number of grains and grain boundaries inhibit the movement of dislocations, and at low temperatures this strengthens the material. According to Hall Petch theorem, mechanical properties such as strength and hardness, will improve as grain sizes decrease until they are below the 10 nm size. Below 10 nm size the behavior is reverse, governed according to the inverse Hall Petch Theorem [1]. Nanocrystallization of a material is accomplished in various ways, such as electroplating [2], atomic layer deposition [3], severe plastic deformation (SPD) [4], inert gas condensation [13], and pulsed laser deposition [2] . In this experiment SPD is studied as the method for nanocrystallization. SPD leading to nanocrystallization can be enacted in several ways. Some popular techniques consist of equal angular channel pressing (ECAP) [5], high pressure torsion (HPT) [14], surface mechanical attrition treatment (SMAT) [7, 8], and hammer peening [9].

SMAT was chosen as in this study due to its relatively simplistic implementation and broad application for various materials. The surface of a material in most cases is where most of the fatigue and wear initiate, so improving the surface layer will improve the durability of the material as a whole. SMAT is accomplished by impregnating kinetic energy from an impulse into the surface of a material through strain hardening. The energy from the impact displaces and shifts dislocations in the materials crystal lattice. Frank Reed sources develop from the constant impact as dislocations continue to shift and combine. Shear bands and low energy dislocation structures form, storing strain energy from the impacts. These dislocation structures form into cells causing low angle tilt boundaries that make up the basis for new grain formation. The newly formed grains or dislocation cells range in size from 10 to 100 nm depending on the material and crystal structure.

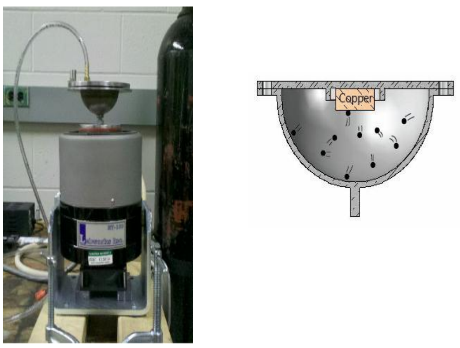

Figure 1 Surface mechanical attrition treatment (SMAT) Setup

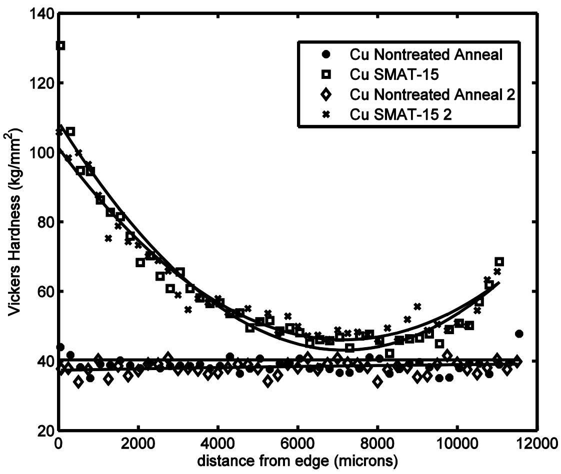

Figure 2 Variation of hardness through the thickness of SMAT sample

In the present study, bulk copper samples were characterized by both microindentation and nanoindentation testing. We studied the improvement in properties through the thickness by cutting the sample and probing the cross-sectional face.

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Microindentation testing clearly shows significant improvement in hardness at the surface. Deeper into the sample this enhancement in properties reduces and eventually reaches the untreated sample value (figure 1).

SAMPLE RESULTS AND DISCUSSION

By studying the characteristics under different loading conditions and rates, information leading to the better understanding of the mechanism of the nanoscale plasticity can be obtained. Sample results for the case of loading rate dependent behavior is shown in figure 3. The results show that on an average, when the loading rate becomes smaller, the displacement burst becomes shorter. The difference in the behavior is quite remarkable, especially when one consider the fact that we haven't even accounted for the thermal drift. Though an extensive investigation is necessary to quantify, it can be stated that this observation is probably an early indication of the dependence of dislocation movement on loading rate. Even more interesting is the observation from our preliminary results that the time duration of burst is, quite surprisingly, independent of the loading rate. Irrespective of the observed dependence of the amount of displacement burst on loading rate, we found that the time duration of the loading burst for both the 20 μN/s loading rate and 200 μN/s loading rate were around 2 to 4 milliseconds (Fig. 4).

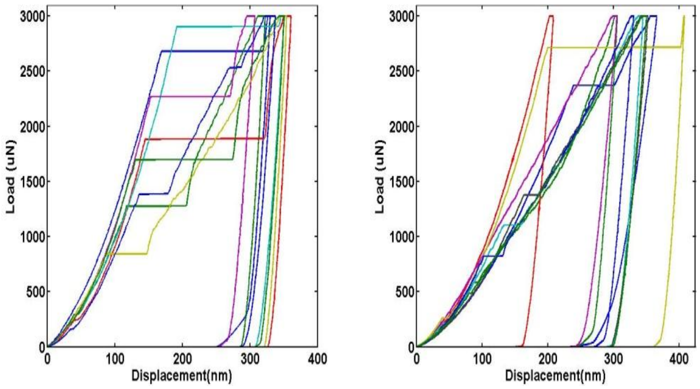

Figure 3 Displacement drop at bursts, on an average, reduced significantly when the loading rate was decreased by an order (smaller loading rate on the right)

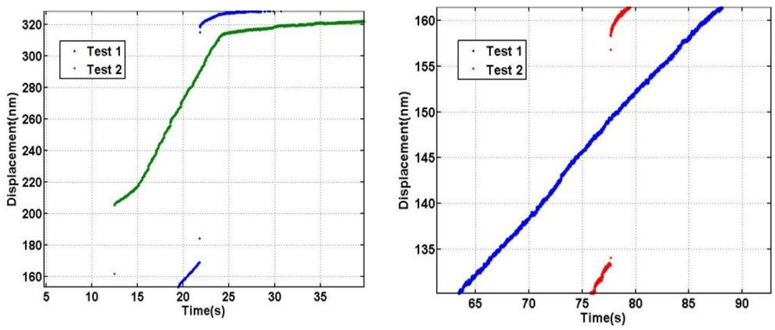

Figure 4 Time durtion of displacement burst, determined from sampling time, was found to be approxiamtely 2 to 10 milliseconds irrespective of 1 order difference in loading rate

CONCLUSION

An experimental characterization study on SMAT copper samples is reported in this article. SMAT samples have geometric features continuously varying from few nanometers to few micron meters through the thickness. Different loading conditions that include various loading/unloading/reloading sequences and different loading rates were considered. Several interesting characteristics of nanoplasticity were captured and an attempt to understand the mechanism of length scale characteristics on the nanoscale deformation is made.

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