Materials Science & Engineering A 679 (2017) 155–161

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Hydrostatic pressure effect on mechanical behavior and texture evolution of Al and Brass

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ARTICLE INFO

Keywords:
Hydrostatic pressure
FCC
Shear strength
EBSD
Dislocation
Texture

ABSTRACT

The effect of hydrostatic pressure on shear strength and microstructural evolution of polycrystalline FCC metals was investigated. Hydrostatic pressure of up to 5 GPa was imposed on commercial purity aluminum and 70/30 brass samples using a modified opposed-anvil apparatus (tri-anvil) that allows for measurement of shear strength in thin foil specimens. Similar to the previous investigations made in BCC metals (Ta and Mo), the shear strength of FCC metals increases significantly as the pressure rises. At 5 GPa, the shear strength of aluminum increased to 8 times its value at atmospheric pressure and 70/30 brass increased by a factor of 2.7. EBSD analysis reveals an evident accumulation of dislocations in all sheared samples, with an approximately 50% decrease in grain diameter. Texture analysis suggests that, in addition to helping form selectively oriented dislocation walls, hydrostatic pressure also serves as a threshold to select certain favorable orientations in sheared metals. We propose that these hydrostatic pressure effects are intrinsically due to the excess volume associated with the cylindrical strain field of dislocation lines.

1. Introduction

The fundamental Tresca and von Mises models [1,2] of classical plasticity theory assume that material strength is independent of pressure and that plastic flow initiates solely from deviatoric stresses. The pressure dependent Steinberg-Guinan model [3] includes the effect of pressure, but only in affecting the value of the shear modulus. The studies of Bridgman [4], Weir [5] and Spitzig [6] on a wide selection of metals show substantial strength increase with increasing pressure. Since that time, much work has been put into designing and constructing a wide variety of apparatuses that can generate high levels of pressure on various forms of matter [7]. The most commonly used device is the diamond anvil cell (DAC) [8–10], which can impose high pressure on specimens. However, the standard DAC poses inconveniences such as the very small sample size (30 µm ~ 500 µm in diameter) and the development of high deviatoric stresses and stress gradients. Alternatively, an opposed-anvil technique based on procedures established by P.W. Bridgman [4,11–17] have been employed to assess the influence of pressure on material strength [18–20]. This methodology somewhat resembles the high-pressure torsion (HPT) system which produces highly refined microstructures: a thin disk shaped sample is placed between two hardened steel anvils, then pressure is applied with subsequent torsion about a single axis coinciding with the sample axis [21,22]. The experiment consists of recording the force required to rotate the anvils as a function of the applied pressure [11–13]. Obviously, the shear deformation imposed on specimens is linearly dependent on the radius position on the axial disk surface ($d = \theta\Delta r$). To remove this shear deformation gradient introduced by the twisting and disk axes overlapping, a tri-anvil instrument was designed based on the idea of placing specimens away from the twisting axis. This modified instrument is able to isolate hydrostatic pressure effects as it has relatively uniform shear deformation and no pressure gradient over the samples. This feature enables the test to provide a reliable and well controlled procedure to study the effects introduced by pressure without having to deconvolute the effects introduced from the gradient in shear strain. A detailed description of the tri-anvil method can be found in our previous publication [23]. Using the tri-anvil apparatus, a considerable increase in shear strength was measured in BCC Ta and Mo specimens subjected to pressures in the 1–5 GPa range [23]. Well-developed dislocation cells were observed both experimentally by TEM study and computationally with dislocation dynamics simulation when the superimposed pressure was

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http://dx.doi.org/10.1016/j.msea.2016.10.030
Received 18 January 2016; Received in revised form 3 August 2016; Accepted 10 October 2016
Available online 11 October 2016
0921-5093/

high (4 GPa), and the formation of this dislocation network is believed to be the reason for the strengthening effect [17].

The dislocation activity depends upon the available slip systems and is inherently related to the crystalline structure of the given material [24–26]. Consequently, the immediate question that follows is to determine if similar behavior as that observed in BCC Ta would be exhibited in non-BCC metals. To answer this question, experiments were conducted to investigate the effect of pressure on the shear response of FCC metals with different stacking fault energies. Specifically, the results reported herein comprise the shear strength measurements on commercial purity aluminum and 70/30 brass foils. Since it is well established that dislocation glide will lead to the rise of preferred orientation of the crystal, or texture [27], we expect that the unique dislocation motion under pressure will give rise to texture evolution. Post mortem study of the microstructure of these FCC metals was conducted using electron backscatter diffraction (EBSD) analysis [28].

2. Experimental procedure

Thin disk-shaped specimens with a diameter of 3.175 mm were acquired from metal foils using a typical TEM punch. The thickness of the commercial purity (CP) aluminum foil is 26.9 ($\pm$ 1.7) μm, and 77.2 ($\pm$ 9.1) μm for 70/30 brass. As prepared specimens were then processed with the tri-anvil instrument and deformed to shear strains of approximately 10 under hydrostatic pressures of 3, 4 and 5 GPa. The ability of the apparatus to generate shear while superimposing hydrostatic pressure on thin foil samples was verified in our previous publications [17,23]. The tri-anvil design uses a similar approach to the Bridgeman single anvil press, which enables hydrostatic pressure and shear loading at the same time. The major modification for the tri-anvil set-up is that three identical anvil sets are aligned on the periphery of a large circle. The ratio of the radius of the large circle to the radius of the specimen is large enough (30:1) that one can assume a uniform linear displacement between the top and bottom anvils in each set. This displacement is recorded by built-in extensometers mounted directly in each compressing anvil set. The as acquired displacement is then divided by the original foil thickness to generate shear strain results. There are two loading steps in the tests, first a compression is applied to the specimens through the anvil sets to impose pressure and keep the specimens from sliding. Then, as the compressive load is held constant, the bottom anvils rotate a small angle ($\theta \approx 0.5°$) around the axis of the large circle making an in-plane translational motion relative to the mating top anvil, creating a shear under pressure condition for the thin foil specimens (Fig. 1). All specimens, after being sheared under various superimposed pressures along with the original foil samples were then mechanically polished on their axial surface for EBSD observation [29], with a finishing step in the vibratory polisher using 0.02 μm colloidal silica suspension.

EBSD data of as polished samples were collected with a Schottkey source field emission scanning electron microscope. The scanning step size was kept relatively small with respect to the grain size in each sample: 0.1 μm for aluminum and 0.08 μm for 70/30 brass. Each sample was scanned over a surface area that contained more than 10,000 grains to generate statistically reliable texture information. EBSD analysis was then carried out using commercial software (TSL OIM Analysis 5). Scan points with low confidence index number (CI < 0.1) [30] were eliminated. The grain tolerance angle to define grain boundaries was set to 5°. Average CI after filtering was around 0.8 for all samples, no cleanup or alteration of data was performed for texture analysis.

3. Results and discussion

3.1. Pressure influence on shear strength

Applied axial pressure, torque, and extensometer displacement were recorded by data collection software connected to the tri-anvil apparatus. Torque was then converted to shear stress and plotted against extensometer displacement which was converted to shear strain, generating shear stress/shear strain curves (Fig. 2). Both aluminum and 70/30 brass stress-strain curves have notable shear stress increase as a function of rising pressure, and the curves end in an almost linear part with some finite positive slope instead of approaching horizontal (constant stress), this behavior is consistent with the observations made by Bridgman [13] that superimposed hydrostatic pressure generally increases the ductility and strength of metals. It suggests that the strengthening mechanism previously observed in BCC structured metals also applies to FCC metals.

Stress value at strain=1 for each curve was extrapolated as a measure for flow stress (referred to as "shear strength" here and after following Bridgman) and plotted against pressure (Fig. 2). Shear strength value in Fig. 2 was also normalized with respect to the typical shear strength for each metal at atmospheric pressure and plotted as an inset to show the relative strengthening effect. Both metals show a clear tendency of shear strength increase with rising pressure: Shear strength of aluminum increased to more than 8 times (700% increase) its value at 1 atm and 70/30 brass increased to about 2.7 times (170% increase). These scales are in good agreement with Bridgman's calculation in which he concludes 10 times shear strength increase in aluminum, 4.45 times increase for copper and 2 times increase for zinc under 4.9 GPa hydrostatic pressure [11,13] (Fig. 3).

It is natural to consider the strength increase as a result of the refinement of grain size since the deformation procedure is intrinsically the same with high-pressure torsion (HPT) [21] processing of metals, and a major strengthening effect of HPT is from grain size refinement. Both metals experienced notable grain refinement, the grain diameters decreased about 40–50% as pressure increased to 5 GPa (Fig. 4, left,

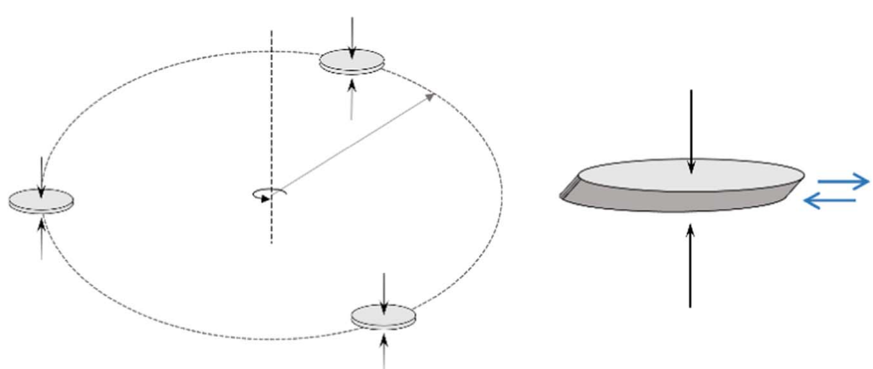

Fig. 1. Illustration of the tri-anvil set up. On the left the three disks represent the location of specimens, the radius of the large circle is 44 mm. On the right shows the deformation state of each specimen under shear loading.