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Mechanical properties of copper after compression stage of high-pressure torsion

Yuepeng Song [a,b], Eun Yoo Yoon [a], Dong Jun Lee [a], Jung Hwan Lee [c], Hyoung Seop Kim [a,*]

[a] Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Republic of Korea
[b] Mechanical and Electronic Engineering College, Shandong Agricultural University, Tai'an 271018, China
[c] Korea Institute of Materials Science (KIMS), Changwon 641-831, Republic of Korea

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ABSTRACT

The mechanical properties and microstructure of commercial purity copper subjected to various pressure values in a compression stage of high-pressure torsion (HPT) were investigated here by analyzing microhardness, deformed geometry, and electron back scattering diffraction images along the radial direction of the compressed disks. Compression before torsion significantly increases the hardness and low angle grain boundary in the center as well as in the intermediate and edge regions. It is found that the compressive strain is the reason for the increased strength and refined grain size in the center region during HPT. This result sheds light on the strategy for achieving microstructure and property homogeneity in HPT.

1. Introduction

Ultrafine grained (UFG) materials are attracting considerable interest because of their improved mechanical and physical properties, as compared to their coarse grained counterparts [1–3]. Recently, several processing techniques have been available for producing bulk UFG materials with submicrometer or nanometer grain sizes in a wide range of pure metals, metallic alloys and intermetallics. Of these various techniques for manufacturing bulk UFG metallic materials, the processes of severe plastic deformation (SPD) are especially attractive because of their great potential to impose significant deformations and to produce various bulk UFG microstructures [1,4–6]. Recent reports have shown that high-pressure torsion (HPT) leads to smaller microstructures than those achieved using the other SPD processes because of its development of higher strain and strain gradient [6].

The principle of HPT was first proposed over 70 years ago by Bridgman [7], while the process has received significant attention for grain refinement only within the last decade [8–14]. In processing by HPT, the initial samples are in the form of thin disks and are placed in the HPT gap between a stationary upper anvil and a vertically and rotationally moving lower anvil, are subjected to a very high pressure (generally several GPa), and are strained by torsion. HPT processing consists of two stages based on the motion of the lower dies and the workpiece, as shown in Fig. 1: first the compression stage and next the compression-torsion stage. During the compression–torsion stage, the compressive pressure is generally kept constant.

An interesting result commonly found in HPT processed UFG materials is that hardness in the center region as well as in the intermediate and edge regions increases. This is in contrast with the classical torsion theory that torsion strain at a point is proportional to the distance from the rotational center, and the strain at the center is always zero during torsion. Since plasticity is path dependent, unlike elastic deformation, the deformation that occurs at both stage I (compression) and stage II (compression + torsion) is important for the properties and microstructures of HPT processed materials. That is, the stage I deformation influences the stage II deformation. Hence, explaining the HPT behavior without considering the stage I deformation is not sufficient for full understanding. Although many reports have been published recently on the microstructural evolution, hardness distribution in HPT processed samples [8–15], and torsional behavior [16], all them ignores the stage I deformation and no studies on the properties of samples after the compression stage have been done, as far as can be determined. For example, Edalati et al. [10] investigated the microstructures and mechanical properties of pure Cu processed by HPT and proposed a unique single curve of hardness against

* Corresponding author. Tel.: +82 54 279 2150; fax: +82 54 279 2399.
E-mail address: hskim@postech.ac.kr (H.S. Kim).

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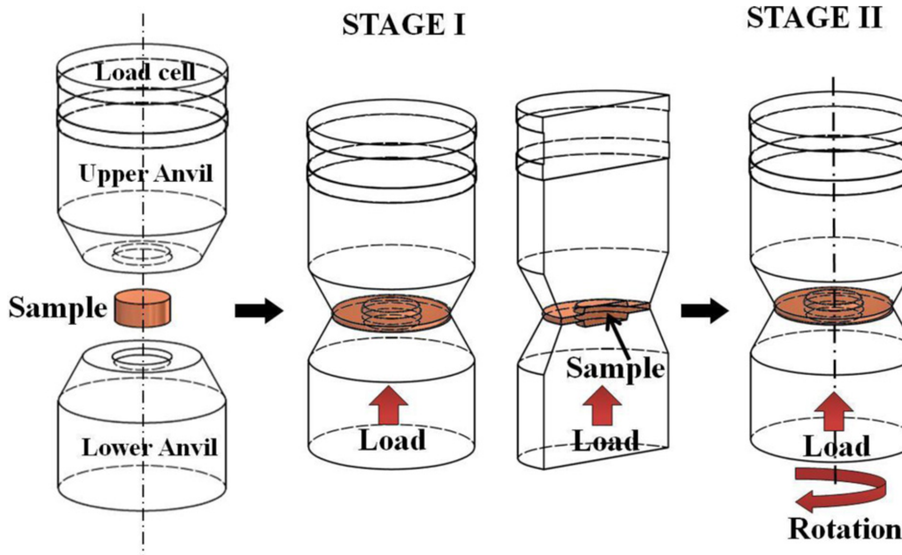

Fig. 1. Schematic of the HPT device showing set-up, compression stage (stage I), and compression-torsion stage (stage II).

the equivalent strain, however, they did not consider the stage I deformation and the compressive component of strains in their equivalent strain.

In this paper, we investigate the mechanical properties of copper after the compression stage in HPT by a systematic experimental approach. Microstructure, hardness and the distributions of microstructure and hardness were examined along the radial direction of compressed disks for various applied pressures in order to analyze the deformation and homogeneity in the workpieces during the compression stage, which controls the microstructure, mechanical properties and their homogeneities.

2. Experimental procedure

Commercial purity (CP) copper (99.98 wt%) was selected for the present research. This copper was supplied in a cold-drawn state. The as-received copper bars were machined to obtain cylindrical samples 9.5 mm in diameter and 2 mm in thickness for HPT processing. A homogenization annealing heat treatment, 600 °C for 2 h followed by furnace cooling, was performed on the as-received material, yielding grain sizes of 20–40 μm and a hardness of 56 HV. For the HPT experiments, five applied pressure values of 1 GPa, 2 GPa, 4 GPa, 6 GPa, and 8 GPa were imposed on the disc samples at room temperature. Compression loading time was set as 10 s after reaching the applied target loads.

Vickers microhardness was measured from the center to the edge of the HPT disks using a Future-Tech FM-700 tester. The applied load and dwell time were 100 g and 10 s, respectively. The microstructural features were examined by electron backscattered diffraction (EBSD) using a 3D Total Analysis device (Dual FIB: Helios Nanolab) equipped with a field-emission gun (Hikari EBSD detector) at an accelerating voltage of 20 kV. Crystal orientations were determined via automatic beam scanning with a step size of 100 nm on the measured area of 23.30 μm × 69.02 μm. A clean-up procedure was applied to all the EBSD images to adjust points that had a confidence index (CI) lower than 0.1. Misorientation angles <2° between two adjacent grains were excluded from analysis, considering the limitations of the angular resolution of the EBSD technique [17].

3. Results and discussion

Fig. 2 shows the compressed shapes of the samples in the HPT die under various pressures. It can be clearly seen that the sample geometries after 1 GP are quite different from the others. That is, the 1 GPa sample shape is still the same as the initial flat disk, while the samples subjected to pressures of 2 GPa or greater exhibit step and flash, with material forced outward from the workpiece [18]. The flash expands as the imposed pressure increases. Controlling flash is crucial for successful metal forming because it determines forming loads and the deformed shapes of the workpiece: small flash induces incomplete die filling and large flash generates redundant load. Without a constraint by the edge flash, the workpiece in the open die will become thin and flat under high pressures of several

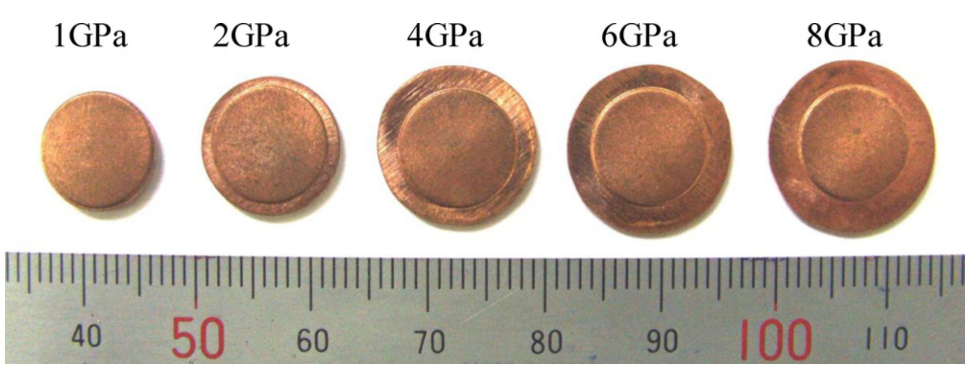

Fig. 2. Deformed shapes of the copper samples after the compression stages under various pressures.