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Hollow cone high-pressure torsion: Microstructure and tensile strength by unique severe plastic deformation

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Hollow cone high-pressure torsion (HC-HPT) is proposed as a new severe plastic deformation to produce ultrafine-grained (UFG)/nanocrystalline microstructure materials. UFG Cu with an average grain size of 550 nm and well-developed high-angle grain boundary after HC-HPT of only 1 turn of torsion exhibited a high tensile strength of 414 MPa and a fracture elongation of 25%. A higher plastic deformation in the inner region, the unique deformation mode of HC-HPT, was analyzed using the finite element method.

Keywords: Severe plastic deformation (SPD); High-pressure torsion; Ultrafine grained microstructure; Tension test; Finite element analysis

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Severe plastic deformation (SPD) processes have recently advanced as a primary process for producing bulk metallic materials with ultrafine-grained (UFG) or nanocrystalline (NC) microstructures [1–11]. The mechanical properties of SPD processed materials are significantly enhanced from the initial coarse-grained materials as a result of their grain refinements and increased dislocation densities. SPD processes have been developed in order to produce various shaped workpieces that can be classified into two types depending on the solidity: solid (bar, disk, plate, etc.) and hollow (tube, conical ring, etc.). Equal-channel angular pressing [1–3], high-pressure torsion (HPT) [1,4–6], accumulative roll bonding [7,8], equal-channel angular rolling [9] and twist extrusion [10] are solid workpiece processes; the cone–cone method (CCM) [11,12] and high-pressure tube twisting [12–15] are hollow workpiece processes. The hollow-type processes have been investigated in less depth than the solid-type processes, even though there are numerous tube and hollow cone shaped engineering parts, such as valves, nozzles, flying heads, penetrators and drill heads that require superior mechanical properties. The CCM process is a suitable manufacturing method for conical rings, which are hollow cone shaped parts [11,12]. In this paper, a hollow cone high-pressure torsion (HC-HPT) method is proposed for the fabrication of hollow cone shaped specimens with a closed cone head through the application of high pressure and torsion in order to obtain UFG/NC microstructures. Because the shapes of the initial and HC-HPT processed specimens are almost identical, sufficiently large strains (i.e. degree of rotating angle) can be imposed to modify the microstructures and mechanical properties of the hollow conical materials by controlling the pressure and rotation.

Figure 1a presents the procedure of the HC-HPT process. First, a hollow cone is set on the concave die; then, a convex punch is inserted into the specimen; and last, the preset pressure and rotation angle are applied to the hollow conical specimen. The HC-HPT process is similar to the HPT process because a large plastic deformation is imposed to the specimen using high pressure and torsion, while the primary difference is the sam-

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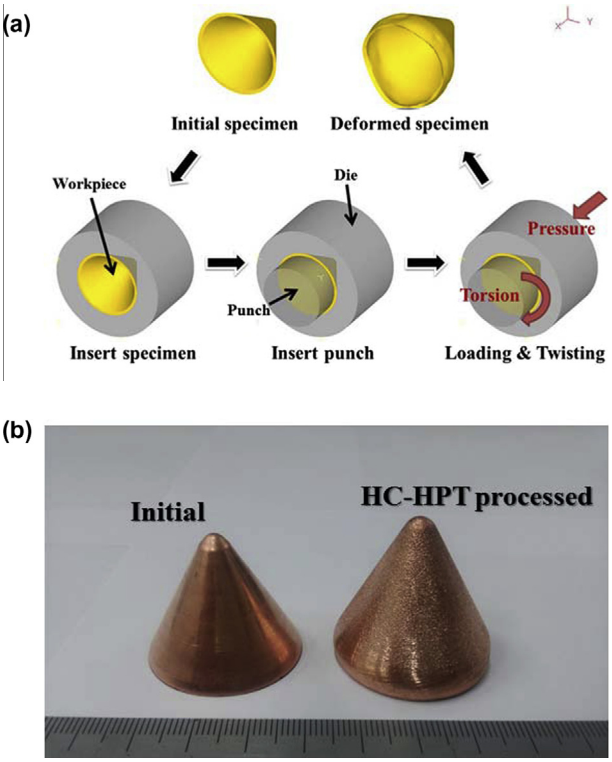

Figure 1. (a) Schematic of the HC-HPT process and (b) the initial and HC-HPT processed Cu specimens.

ple shape, which is a hollow cone in the HC-HPT process rather than a disk in the HPT process. It should be noted that the difference in workpiece and die geometries generates different deformation modes in HPT and HC-HPT. Copper hollow cones with commercial purity were used as preforms in the HC-HPT process. The Cu preforms were annealed at 600 °C for 2 h and then furnace cooled in order to homogenize the microstructure. The wall thickness, base diameter and cone height of the hollow cone specimen were 1.2, 33.4 and 31.1 mm, respectively. It should be noted that this cone specimen diameter (33.4 mm) was much larger than that of typical HPT samples (10 mm). The tools (die and punch) were adjusted in order to accommodate the specimen geometry. The surfaces of the die and punch were machined roughly in order to minimize sliding between the tools and specimen during the HC-HPT process.

The HC-HPT process was performed for up to 1 revolution and under 80 tons of force. The compressing force of 80 tons corresponds to the average compressive stress of 900 MPa in a cone with a diameter of 33.4 mm. This value of the applied compressive stress, 900 MPa in HC-HPT, is much less than general values of several GPa in HPT due to the larger projection area of the workpiece. Figure 1b presents the initial and 1 revolution HC-HPT processed specimens. As seen in the figure, the shapes of both specimens were almost identical. Hence, repetitive HC-HPT processing can be performed under adjusted pressure and revolutions in order to obtain the target mechanical properties and microstructures in the specimen. However, the base region of the specimen flew out between the punch and die during the HC-HPT process due to the high operation pressure and the open design of the punch and die bases; this resulted in the specimen being slightly taller and thinner after the HC-HPT process than the initial size.

Tensile tests were performed to evaluate the mechanical properties of the HC-HPT processed specimens. Figure 2 presents the tensile stress–strain results. The initial Cu had a low yield stress (YS) of ~142 MPa and ultimate tensile strength (UTS) of 219 MPa. After the HC-HPT process, the YS of the Cu increased significantly to 366 MPa under 80 tons of press and 1 revolution. The UTS also increased from 219 MPa to 402 MPa and 414 MPa after 0.5 and 1 revolutions, respectively. The initial Cu fractured soon after necking onset, while the HC-HPT processed Cu endured the fracture longer after the necking onset than initial Cu, which resulted in long post-necking strain. In contrast, the HC-HPT processed specimens had lower total elongation values compared with the initial Cu.

In order to understand the high tensile strength and ductility of the HC-HPT processed Cu, electron backscatter diffraction (EBSD) measurements were performed at the middle of the hollow cone for grain size measurement and microstructural characterization. A 3-D Total Analysis device (Helios Nanolab) equipped with a field-emission gun (Hikari EBSD detector) was used to conduct observations at an accelerating voltage of 15 kV and a tilt angle of 70°. Before the EBSD examination, the measurement plane was ground to SiC 4000, followed by electropolishing at RT and a voltage of 13 V for 15 s. The step size of the EBSD scan was as low as 20 nm depending on the grain size of the specimens and the EBSD data were analyzed by the program TSL OIM analysis. Figure 3 represents the results of the EBSD microstructure observation of the initial and HC-HPT processed Cu. The color images show the inverse pole figure (IPF) maps with the microstructure orientation. The curve images below the IPF maps show the grain boundaries, indicating the high-angle grain boundaries (HAGBs; black curves) and low-angle grain boundaries (LAGBs; red curves). The Cu grain size significantly decreased as the degree of rotations increased, which is the same as the HPT processed Cu [16–18]. The initial Cu had a coarse-grained microstructure with an average grain size of ~35.9 μm; this was refined to 0.97 μm and 0.65 μm after 0.5 and 1 revolutions, respectively. Most sub-grains with LAGBs after 0.5 revolution were transformed to HAGBs after 1 revolution. From the experiment results, it can be concluded that the pro-

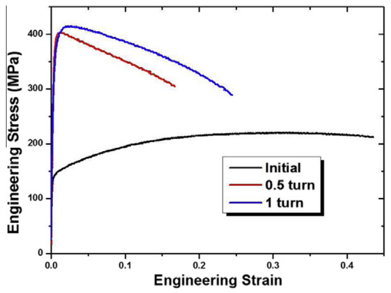

Figure 2. Engineering stress–strain curves of the initial and HC-HPT processed Cu specimens.