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Circumferential shear strain in torsion-based severe plastic deformation

Ho Yong Um,[a] Hyeok Jae Jeong,[a] Heon Yong Kim,[b] Lee Ju Park,[c] Sunghak Lee[d] and Hyoung Seop Kim[a,d,*]

[a]*Department of Materials Science and Engineering, University of Science and Technology, Pohang 790-784, South Korea*
[b]*Department of Mechanical Biomedical Engineering, Kangwon National University, Chuncheon 200-701, South Korea*
[c]*Agency for Defense Development (ADD), Daejeon 305-152, South Korea*
[d]*Center for Advanced Aerospace Materials, Pohang University of Science and Technology (POSTECH), Pohang 790-784, South Korea*

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The dependence of the circumferential shear strains of two different shear modes in a cylindrical coordinate system on the shear planes during a torsion-based severe plastic deformation is investigated using strain–displacement relationships. Contrasting trends in the circumferential shear strains (increasing $\varepsilon_{z\theta}$ and decreasing $\varepsilon_{r\theta}$ with radial distance from the center in the axial plane torsion and radial plane torsion, respectively) are demonstrated, which are in good agreement with published results.

Keywords: Severe plastic deformation; Torsion; Finite-element analysis; Circumferential shear strain

The microstructural evolution of ultrafine-grained (UFG) and nanocrystalline (NC) materials have garnered significant attention during the past two decades because UFG/NC materials exhibit outstanding physical characteristics, particularly their mechanical properties [1–4]. Using severe plastic deformation (SPD) techniques has also enabled efficient and common top-down approaches for producing bulk UFG/NC metallic materials [5–26].

There are numerous SPD methods and these can be categorized into two types depending on the loading method: Type I compression-based methods, which include equal-channel angular pressing [5–9], multiple forging [10], accumulative roll bonding [11,12], repetitive corrugation and straightening [13], continuous confined strip shearing [14], radial extrusion [15], and caliber rolling [16]; and Type II torsion-based methods, which include high-pressure torsion (HPT) [17–19], twist extrusion (TE) [20], cone–cone method (CCM) [21], high-pressure tube twisting (HPTT) [22–25], and hollow-cone high-pressure torsion (HC-HPT) [26].

Although there are advantages and disadvantages in each SPD process category, the torsion-based processes are particularly attractive because the workpiece geometries in theory do not vary during the processes and much larger shear deformations can be applied continuously compared with the compression-based processes. It should be noted that a large plastic strain is the primary factor in successful SPD processes for grain refinement, as indicated by Valiev's second rule that "the degree of strain (true strain) during processing should exceed 6–8 for grain refinement" [5]. Indeed, the HPT process generates significantly finer grain sizes in face-centered cubic, body-centered cubic and hexagonal close-packed materials [17] because it generates much larger plastic strain than the other SPD processes developed thus far. The torsion-based SPD processes can produce various circular geometries including bars using TE, disks using HPT, rings using HPT, conical rings using CCM, tubes using HPTT, and hollow cones using HC-HPT. The circumferential shear strains in the

* Corresponding author at: Department of Materials Science and Engineering, University of Science and Technology, Pohang 790-784, South Korea. Tel.: +82 542792150; fax: +82 542792399; e-mail: hskim@postech.ac.kr

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torsion-based SPD processes can be categorized into two types depending on their shear planes: longitudinal normal plane (rθ-plane) shear (simple torsion, HPT and TE) and radial normal plane (zθ-plane) shear (CCM, HPTT and HC-HPT).

However, the major disadvantage of the torsion-based processes is the heterogeneous deformation that occurs in the workpiece, i.e. significant variations in the strain along the radial direction. It is known that simple torsion generates linearly increasing circumferential shear strains on the axial plane as the distance from the center increases. For example, HPT and TE processed materials represent higher stains and hardnesses, and finer grain sizes at the edge than in the center, as shown in Figure 1a. In contrast, the CCM and HPTT processes with radial plane shear deformation exhibit the opposite trends: higher strains and hardnesses, and finer grain sizes in the inner region than in the outer region, as shown in Figure 1b. The higher shear strain in the outer region in the HPT and TE processes is attributed to the greater circumferential displacement in the outer region than in the inner region.

However, a clear rationale for the reverse trends of strain, hardness and grain size distributions in the CCM, HC-HPC and HPTT processes has not yet been proposed. For example, Bouaziz et al. [21] demonstrated a decreasing strain with increasing distance from inner surface to the outer surface in the CCM process using the finite-element method (FEM); however, this trend was not explained. Tóth et al. [22] found a decreasing shear strain in Al with increasing distance from the inner surface and attributed it to the thickness of the tube and material behavior, as well as the applied hydrostatic stress. Pougis et al. [23] derived analytical equations for the shear stress and strain gradients in the HPTT process and demonstrated that the shear strain evolution strongly depended on material's strain-hardening behavior. However, it is questionable whether the shear strain evolutions in the inner and outer surfaces are dependent on the strain-hardening behavior under the boundary conditions of fixed rotation angles at the inner and outer surfaces. Wang et al.'s analysis [24] is basically the same as that of Pougis et al. Lapovok et al. [25] found a higher increase in hardness at the inner surface than that at the outer surface in conical rings during the CCM process, and this result was rationalized in terms of the difference in static and kinematic frictions and a potential partial slip between the die and conical workpiece. However, no reason has yet been determined for the decreased strain with increasing distance from the center in the twist because the total shear strain depends on the relative motion of the two counter-surfaces of the workpiece. Therefore, the moving part (irrespective of whether the inner or outer die is moving) and friction conditions are not critical for the strain (increasing or decreasing) trend with increasing distance from the inner surface, if the relative motions of the two workpiece surfaces are the same.

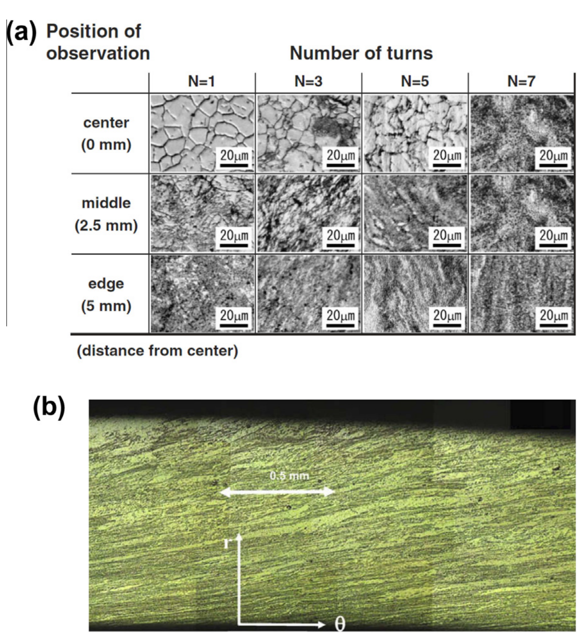

Figure 1. Metallographic picture of (a) HPT processed Al [13] and (b) HPTT processed Al tube [16].

In this paper, displacement–strain analyses were used to rationalize these opposing trends of strain vs. distance from the center in two torsion-based SPD processes: HPT and HPTT. The analytical solutions for the circumferential shear strain provide a better understanding of these torsion-based processes and the reverse strain phenomenon.

Figure 2 presents the schematics of two torsional (circumferential shear) deformation modes depending on shear planes: $\varepsilon_{z\theta}$ on the axial plane (rθ-plane) and $\varepsilon_{r\theta}$ on the radial plane (zθ-plane). The shear planes are shaded. The simple torsion in Figure 2a and tube twisting in Figure 2b without axial normal deformation were selected as the representative deformation processes of the circumferential shear on the axial plane and the circumferential shear on the radial plane, respectively.

Displacement–strain relationships [27] were used to obtain the analytical solutions of the shear strains for the torsion-based deformation modes. The initial dimensions of the tubular workpiece for the simple torsion and tube twisting processes were 10 mm in outer radius, 1 mm in thickness and 10 mm in height. The circumfer-

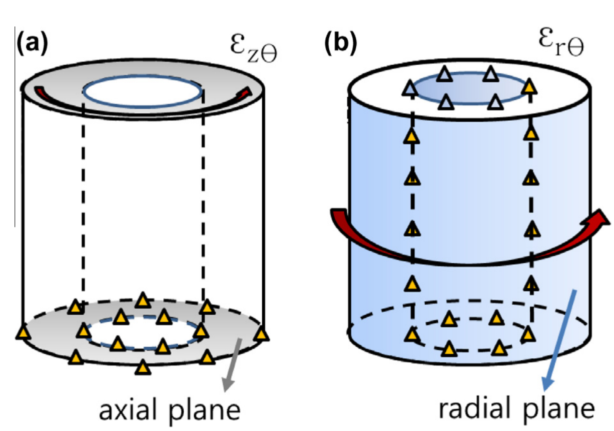

Figure 2. Two torsional (circumferential shear direction) deformation modes according to the shear plane: (a) $\varepsilon_{z\theta}$ on the axial plane and (b) $\varepsilon_{r\theta}$ on the radial plane. The triangles represent the fixed boundary condition.