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Principles of severe plastic deformation using tube high-pressure shearing

Jing Tao Wang,[a,*] Zheng Li,[a] Jin Wang[b] and Terence G. Langdon[c,d]

[a]*School of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, People's Republic of China*
[b]*Department of Mechanical Engineering, Qingdao Technical University, Qingdao 266033, People's Republic of China*
[c]*Departments of Aerospace & Mechanical Engineering and Materials Science, University of Southern California, Los Angeles, CA 90089-1453, USA*
[d]*Materials Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK*

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A new process of severe plastic deformation is described, termed tube high-pressure shearing (t-HPS), in which a tubular sample is subjected to shearing under a hydrostatic pressure. The fundamentals of this process are summarized, the strain relationships are derived and the process is validated using experiments conducted on an aluminum tube. An advantage of this process is that it provides a capability for producing ultrafine-grained materials with a gradient structure.

Keywords: Severe plastic deformation; Tube high-pressure shearing; Deformation structure; Gradient structure

High-pressure torsion (HPT) refers to the processing of materials whereby disk samples are placed between massive anvils and then subjected to an axial compressive force which produces a high hydrostatic pressure together with concurrent torsional straining [1]. In practice, this straining is driven by the frictional forces acting between the disk surfaces and the upper and lower anvils. Although the fundamental principles of HPT processing were first developed nearly 70 years ago [2,3], this type of processing has become important only in the last two decades because it is now recognized that it provides an opportunity to achieve very high strength and exceptional grain refinement. Detailed investigations over the last 20 years have provided significant information on the fundamentals of the HPT process. In addition, important progress has been made in extending the HPT technique to include small cylindrical samples [4–7] and ring samples [8–11] and by developing a continuous HPT processing technique for use with strip samples [12].

All of these developments provide promising opportunities for further investigation. Nevertheless there is a significant limitation inherent in the basic principles of HPT because the process introduces a radial strain gradient that makes it difficult to correlate material characteristics along the chords of disk samples. Furthermore, although the axial strain distribution is at least theoretically homogeneous in HPT, the disks are usually exceptionally thin and there is recent evidence for the development of inhomogeneities in the through-thickness directions of disks of some materials, such as magnesium alloys, after processing by HPT [13].

An alternative and very recent development is high-pressure sliding in which a shear strain is applied to a rectangular metallic sheet [14]. An examination of this process shows that it incorporates an important characteristic because it effectively changes the rotational motion of the anvils in HPT into a translational motion of the die pieces in high-pressure sliding and in this way it imposes a three-dimensional homogeneous strain on the processed sheet samples. In principle, it is readily apparent that processing using high-pressure sliding can be modified to introduce a tangential shear strain in the tube wall under a high pressure. Two examples realizing such a process were described earlier [15,16] and the process was designated high-pressure tube twisting (HPTT). The present report describes the general principle for introducing a tangential shear strain in a tube wall under high pressure in a process designated tube high-pressure

* Corresponding author. E-mail: jtwang@njust.edu.cn

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shearing or t-HPS. Details are presented for the average strains introduced by t-HPS, the strain distribution relationships and the total torque required in order to drive the t-HPS process.

The principle of t-HPS is depicted schematically in Figure 1 where the sample, in the form of a tube, is radially confined between a central mandrel and an outer cylinder. The principle of the process is that a sufficiently high hydrostatic pressure is introduced in the tube wall so that the frictional forces at the interfaces between the sample-mandrel and the sample-cylinder are high enough to prevent any localized slip. By fixing the mandrel and rotating the outer cylinder (or vice versa), a simple shear strain is then produced in the tube wall.

Inspection of Figure 1 shows that a critical factor determining the success of t-HPS is to obtain a sufficiently high hydrostatic pressure in the tube wall confined between the central mandrel and the outer cylinder. Different procedures may be adopted for introducing a hydrostatic pressure into the tube wall. A radial force may be applied at the cylinder surface by, for example, compressing the mandrel within the elastic regime. If an axial compression is applied to the mandrel, it will expand in the radial direction and compress the inner surface of the sample tube so that a hydrostatic stress will build up in the tube wall [15]. An alternative and attractive procedure is to apply an axial force at the two ends of the tube. This may be accomplished by fully confining the tube through the use of pressure rings at both ends of the sample and then compressing the rings directly to build up a high hydrostatic pressure in the tube wall as illustrated in Figure 1.

The process of t-HPS depicted in Figure 1 has a strain distribution which is significantly different from the distribution in the well-established process of tube torsion and twist. In fact, the twisting of tube samples was demonstrated nearly 70 years ago [3] and the torsion testing of thin-walled tubes subsequently became a standard mechanical testing method for characterizing the plastic flow of metals [17–19].

The schematic illustration in Figure 2 provides a direct comparison of the inherent strain features of (a) conventional HPT, (b) the tube torsion/twist process and (c) t-HPS. It is readily apparent that the shear deformation is identical in HPT and tube torsion/twist because in both processes a vertical line parallel to the axis of the HPT disk or the torsion tube is sheared directly into a curve as indicated by the dashed lines in Figure 2a and b, whereas a radial line on the surface of these samples remains straight. By contrast, in t-HPS the rotation of the outer cylinder means that a vertical line parallel to the tube axis remains parallel to the axis during deformation but a radial line is sheared into a curve as indicated by the dashed line in Figure 2c.

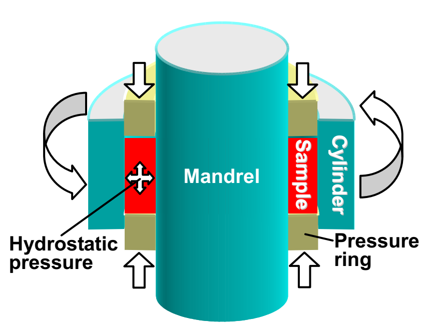

Figure 1. Schematic illustration of the principles of t-HPS with pressure rings to introduce a hydrostatic pressure in the tube wall of the sample.

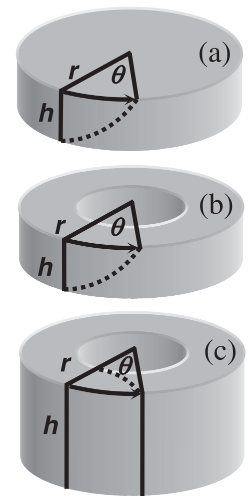

Figure 2. Comparison of the basic straining features of (a) HPT, (b) tube torsion/twist and (c) t-HPS.

The average strain introduced in the tube wall may be estimated using the approach depicted in Figure 3. Thus, a straight line within the tube is sheared to a slanting curve when the outer part of the tube rotates through an angle θ during t-HPS. Corresponding to an angular increment of $\Delta\theta$, the radius r is increased to $r + \Delta r$ and the local tangential shear strain is therefore:

$$\gamma = \mathrm{tg}\phi = (r\Delta\theta)/\Delta r = (r\mathrm{d}\theta)/\mathrm{d}r \tag{1}$$

In order to estimate the average strain, γ, in the tube wall, it is assumed that the strain in the wall is homogeneous, so that:

$$\theta = \int \mathrm{d}\theta = \int_{\mathrm{R}_i}^{\mathrm{R}} \gamma \mathrm{d}r/r = \gamma \int_{\mathrm{R}_i}^{\mathrm{R}} \mathrm{d}r/r = \gamma \ln(R/R_i) \tag{2}$$

and

$$\gamma = \theta/\ln(R/R_i) = -\theta/\ln(R_i/R) = -\theta/\ln\beta \tag{3}$$

where β is the ratio of the inner radius R_i over the outer radius R of the tube.

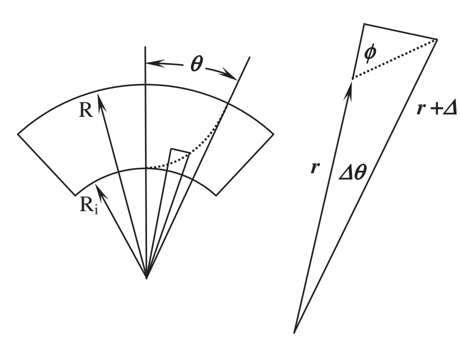

Figure 3. Schematic illustration of the deformation occurring in t-HPS.