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Severe plastic deformation of metals by high-pressure tube twisting

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A new severe plastic deformation (SPD) process is proposed that is suitable for deforming cylindrical tubes to extremely large strains without changing their dimensions. High hydrostatic pressure is achieved by axial compression of a cylindrical mandrel placed into the tube. The tube is twisted by an external torque with the help of the friction force generated by the hydrostatic pressure. This new SPD technique seems to be very promising for future industrial applications.

Keywords: Severe plastic deformation; Tube twisting; Simple shear; High-pressure torsion; Copper

There has been much interest in recent years in improving material properties by severe plastic deformation (SPD). Since 1974, several new SPD processes have been proposed. The most commonly used are equal channel angular pressing (ECAP [1,2]), high-pressure torsion (HPT [3]) and accumulated roll bonding (ARB [4]). ECAP and ARB are processes that require several passes to achieve large strains (i.e. $\bar{\varepsilon}_{VM} \gg 1$). HPT distinguishes itself by deformations that are practically unlimited in a single operation. Its disadvantage is that the samples are small disks with a linear strain gradient.

In this work, a new SPD process is proposed that is suitable for deforming thin-walled tubes to very high strains in a single operation. The process is named high-pressure tube twisting (HPTT). The experimental setup is shown schematically in Figure 1. The test piece (a tube) is positioned inside a rigid disk. A mandrel is placed into the tube, which is compressed with a compression machine in its elastic regime. Due to the axial compression of the mandrel, it expands slightly in the radial direction. Its expansion, however, is constrained by the tube and the disk, and so a large hydrostatic stress builds up in the tube. This hydrostatic stress provides a large friction force on both sides of the tube. Finally, the deformation of the tube is achieved by rotating the disk with an external torque while keeping the mandrel fixed. Provision is made to prevent the tube from thinning in the following way: the tube is slightly longer than the thickness of the disk and is compressed plastically with the help of two disks and suitable screws before the axial force is applied; see Figure 1. Due to this compression, there is a material flow from the tube as shown in Figure 2 all around the upper and lower ends of the tube. The purpose of this operation is twofold (i) the tube is perfectly constrained and (ii) the "ears" produced in this way restrict the testing material to a constant volume and ensure a large gradient in the hydrostatic stress within the ears.

During twisting, the deformation mode is locally simple shear where the shear plane normal is the radial direction of the tube and the shear direction is parallel to the circumferential direction. For a thin-walled tube, the amount of shear can be estimated from the geometry as follows:

$$\gamma = \frac{r_0 \beta}{t}, \tag{1}$$

where r_0 is the average radius of the tube, β is the angle of twist and t is the thickness of the tube. As an example, for a geometry of $r_0 = 10$ mm and $t = 1$ mm, a 360° rotation would result in $\gamma \approx 63$. This is an extremely large strain which can lead to a very efficient grain refinement process of the tested material. The strain, in principle, is unlimited, as the twisting can be increased without limits assuming that there is no slip between the sample and

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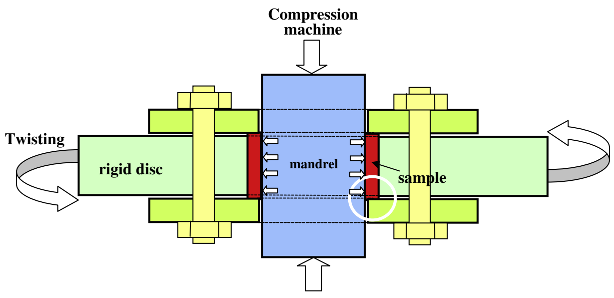

Figure 1. Schematic vertical section of the experimental tube twisting setup under high hydrostatic pressure. The sample is in red. The encircled area is shown in Figure 2. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

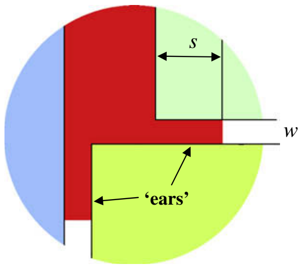

Figure 2. The encircled part of Figure 1 showing the material outflow from the sample. These 'ears' ensure a large pressure gradient that contribute to the build up of the hydrostatic pressure in the sample.

the mandrel. In this respect, the process is similar to HPT; however, the sample can be much larger. The sample dimensions are only limited by the capacity of the compression machine and the required twisting torque. The geometry is also more interesting than HPT as tubes are very frequently used in practical applications. SPD leads to sub-micron or even near-nanosized grain structures, thus increasing the strength of the metal. Dubravina et al. [5] have measured a Vickers hardness of 1500 MPa after HPT of pure Cu with an average grain size of 70 nm. Stronger metals allow the thickness of the tube (at equivalent loading conditions) to be decreased, leading to a significant reduction in the amount of material used and the weight of the structure.

The hydrostatic stress provided by the compression of the mandrel plays a central role in the HPTT process. Its magnitude can be estimated from the "ears" that form at the top and bottom surfaces of the tube (see Fig. 2). By assuming that the friction stress is equal to the flow stress τ_f of the material in shear (Tresca's friction law) and using the method of slices in plasticity, the following formula can be obtained for the hydrostatic stress, p, within the sample:

$$p = 2\tau_f \frac{s}{w}. \tag{2}$$

Here, s is the length of the "ear" and w is its thickness. In our experiments, we have measured the following values for pure Cu tube twisting: $s \approx 0.5$ mm and $w \approx 0.1$ mm. Thus, for a material that hardens up to about $\tau_f = 200$ MPa, the estimated hydrostatic pressure goes up to about $p \approx 2$ GPa. This pressure is large enough to generate the frictional force necessary to twist the tube. Nevertheless, to enhance friction, the inner and outer surfaces of the tube, as well as the surfaces with which it was in contact during testing, were sand blasted before the test was performed.

In the first experiments, commercially pure Al (1050 series) and Cu tubes were tested. For both cases, the inner diameter of the tubes was 20 mm, the wall thickness was 1 mm and the height of the samples was 11 mm. The applied compression force on the mandrel was 200 kN. The twisting torque T was applied by hand with the help of two bars attached to the main disk and its value was not measured. Nevertheless, its value can be calculated from the geometry and the shear flow stress of the material. As an example, for $\tau_f = 200$ MPa, T is 1256 Nm. This is a typical value for highly deformed pure Cu. For Al, the torque is much less, so that the test can be done more easily by hand. Figure 3 shows a metallographic picture of the deformed Al sample. As can be seen from the deformed grain structure, the plastic deformation was fully extended into the whole thickness of the Al tube. The twist angle was 30° in this experiment, after which the test was stopped because this was the maximum torque that we could apply by hand. The corresponding shear strain from Eq. (1) (assuming uniform shear) is $\gamma = 6.02$. However, as can be seen from Figure 3, the shear strain deviates from uniformity. In order to quantify the strain gradient present in the tube, the shear strain was measured as a function of the distance from the inner surface of the tube. The initial grain structure was globular with an average grain size of about 50 μm. After shearing, the grains became ellipsoidal and the shear strain can be obtained from the orientation α of their main axis with respect to the θ direction as follows [6]:

$$\gamma = \frac{2}{\tan(2\alpha)}. \tag{3}$$

The α angle can be readily measured from the micrographs because the shear strain is large; thus α agrees well with the orientation of the stringers formed by the grain boundaries, see Figure 3. The shear strain thus obtained is plotted in Figure 4 as a function of the position within the tube wall. As can be seen, the shear strain varies from $\gamma = 14$ at the inner surface down to $\gamma = 2$ at the outer surface. The average value is about $\overline{\gamma} = 6$ which agrees well with the estimate obtained above for uniform shear. There is still another condition that has to be fulfilled, i.e. that relation between the total rotation

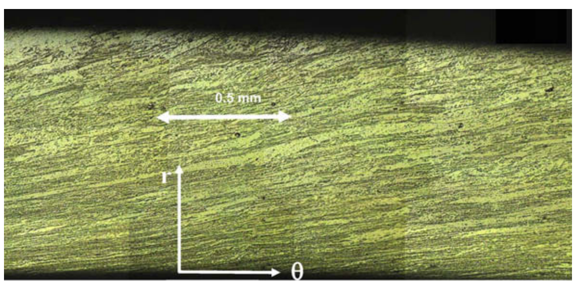

Figure 3. Metallographic picture of the HPTT deformed Al tube.

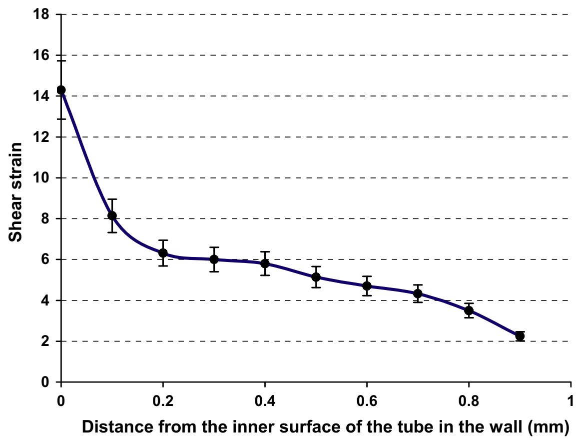

Figure 4. Variation of the shear strain within the wall of an HPTT deformed Al tube.

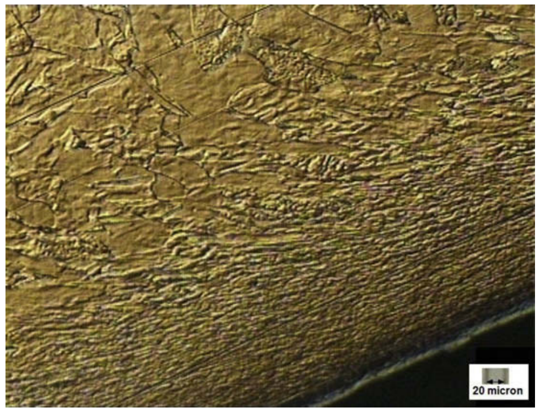

Figure 5. Metallographic picture of a commercially pure copper tube deformed in HPTT. The image was taken in the $r - \theta$ section of the tube; the inner surface of the tube wall is visible.

β of the outer disk and the distribution of the shear strain within the tube. From simple kinematics, one can readily obtain the following relation:

$$\beta = \int_{r_1}^{r_2} \frac{\gamma(r)}{r} dr. \tag{4}$$

Here, r_1 and r_2 are the inner and outer radius of the tube, respectively. In fact, the integration of the shear strain shown in Figure 3 agrees well with the applied 30° rotation angle. This agreement also means that there was no slip between the tube and the testing device.

The shear strain does not have to be constant within the tube wall. Although the boundary conditions for the displacements that are applied at the inner and outer surfaces correspond well to simple shear (for a thin-walled tube), it does not mean that the shear has to be constant within the plastically deformed zone. The shear might even be concentrated in one single layer, i.e. in a shear band. Such instabilities may develop depending on the geometrical conditions of the test but also depending on the material behavior. A case in such shear bands were observed in ECAP—which is also a simple shear process—was successfully modeled in Ref. [7].

The obtained strain gradient in the Al sample leads to a gradient in material properties within the tube wall. Nevertheless, as the shear strain is practically unlimited (with appropriate tooling), the material properties could be homogenized so that they would correspond to a state where saturation occurs at extremely large strains. This statement, of course, needs further experimental validation.

An attempt was made also to twist commercially pure Cu tube. However, our experimental setup was not completely suitable for Cu as slipping occurred between the mandrel and the tube. Nevertheless, the inner surface layer was heavily deformed to thickness of about 170 μm (see Fig. 5).

The strain gradient observed in the above experiments can be related to the thickness of the tube. Indeed, it is plausible that for a thin-walled tube the stress state is nearly constant within the wall. Consequently, for a constant stress state, uniform shear is expected. However, when the thickness is relatively large with respect to the diameter of the tube, the stress state is not uniform but depends on the radial position within the tube wall, leading to a gradient in the strain. The gradient should depend also on material behavior (strain hardening and strain rate sensitivity) as well as on the applied hydrostatic stress. As shown above, there are large differences in the strain gradient between the Al and Cu samples which might be due to the combined effects of the differences in the material parameters.

In conclusion, a new SPD process is proposed in this paper that is suitable for deforming thin-walled tubes to extremely large strains. Deformation of the Al and Cu samples resulted in full plastification in the Al sample, and plastification in a surface layer in the Cu tube. An analysis of the shear strain within the Al tube was also carried out, showing a shear gradient within the tube wall. Further experiments are needed for a better understanding of the process and to develop experimental setups suitable for deforming harder materials.

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