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Influence of grain shape and orientation on the mechanical properties of high pressure torsion deformed nickel

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ABSTRACT

Severely plastically deformed (SPD) materials, for example those produced by high pressure torsion (HPT), are reported to possess outstanding mechanical properties. A typical HPT microstructure consists of elongated grains, usually of grain size well below 1 μm, which are aligned parallel to the shear plane and showing typical shear texture components. To answer the question of how these single features of a SPD microstructure affect the mechanical properties individually, such as the yield strength, the ultimate tensile strength, the uniform elongation and the reduction in area, uniaxial tensile tests have been conducted. The samples were tested in two different orientations. Within the same testing orientation the average grain aspect ratio was also varied. The variation in grain aspect ratio within a sample was achieved through a slight back rotation of the already deformed material and selective radius-dependent specimen extraction. The main results are as follows: the ductility (in terms of the reduction in area) is influenced by the grain aspect ratio. In contrast, the ultimate tensile strength is independent of the grain aspect ratio but shows an explicit dependency on the specimen orientation.

1. Introduction

Severely plastically deformed (SPD) materials are promising candidates to exhibit high strength combined with high ductility as shown for instance in [1–4]. A lot of research has been undertaken to identify and understand the physical processes behind this extraordinary phenomenon. Studies focused on both strength and ductility are often performed using equal channel angular pressing (ECAP) processed materials, because standard tension experiments can be performed. The effect of the number of passes and the types of ECAP routes have frequently been studied [5–8]. The same also applies to sheet materials processed by Accumulative roll bonding (ARB), where in two directions conventional tensile tests can be performed [9–11].

Focusig on ECAP, the numbers of applied passes have typically been between 2 and 8, which corresponds to an accumulated shear strain of about 4–16 regarding an intersection angle of 90°. In this strain regime, the grain size and the ratio of high angle to low angle grain boundaries is significantly affected by the number of passes and applied processing route. As a consequence, the strength and ductility related measures are also influenced by these main processing parameters. The shear strain applied by HPT is usually larger compared to ECAP. In most single phase materials or alloys a saturation in grain refinement and a constant ratio between high and low angle boundaries is observed for shear strains larger than 40. This usually results in a higher saturation hardness. Due to the small size of HPT samples, very often only the hardness evolution is examined. Tensile strength and ductility of the saturation microstructure is not frequently investigated and the tensile behaviour can in general only be investigated in the tangential direction due to the thinness of HPT disks [12–14]. The possible anisotropy of strength and ductility regarding different testing directions has not been studied so far—except in some micro experiments [15]. The present study analyses the orientation dependency of strength and ductility of the saturation microstructure. The questions addressed in this paper are

- Does an orientation dependency in the tensile properties exist?
- Is the strength and ductility affected by the grain shape?
- Is the crystal texture developed during HPT important for the tensile properties?

Initially as the microstructure plays a key role in answering the above questions a short summary of the most important parameters controlling the HPT microstructure is presented. The experimental results will then be presented and discussed.

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1.1. Remarks regarding the structural evolution during HPT

The structural evolution during HPT has been extensively investigated in the last 10 years [2,16–24]. The most important characteristics are summarized in order to introduce the investigated saturation microstructure in a more general sense.

At strains larger than 1, a well defined cell structures develop in a metallic material which deforms by dislocation glide. With increasing strain the cell and cell block size decreases and the misorientations between these structural elements increase. This fragmentation reaches a saturation between a shear strain of 20–60 and the boundaries become more similar to ordinary grain boundaries. Further straining does not change the grain size, grain aspect ratio, the texture or the misorientation distribution [17,20,23]. The saturation microstructure is mainly dominated by the following factors.

1.2. Deformation temperature

A dynamic recovery process based on grain boundary migration is, in conjunction with the fragmentation process, responsible for the saturation microstructure. This dynamic recovery process strongly depends on the deformation temperature. An increase in the deformation temperature leads to an increase in the average grain size. In contrast, a decrease in temperature leads to finer microstructure. Further details regarding the temperature dependency are given in [17,25,26]

1.3. Alloying and chemical composition

One major parameter which influences the minimum size of the saturation microstructure is alloying. Alloying of aluminium with magnesium causes a significant reduction of the saturation grain size [27]. The HPT deformation of an alloy consisting of two or more phases should result in smaller grains compared to a single phase material after application of the same strain. One explanation is that the dynamic recovery process is slowed as the presence of phase boundaries reduces the grain boundary mobility. For single phase alloys (solid solution) a size difference between the atoms may have an effect on the saturation microstructure but this is less effective than the presence of two phases.

1.4. Impurities

The total quantity of impurities (in terms of unintentional alloying elements) is less important than the type and amount of the different impurity elements. For example, the presence of 0.06 wt% carbon leads to a hardness increase of 70% as a consequence of the strong grain refinement. Furthermore, this carbon strengthening effect is more pronounced than a change in deformation temperature of 600 °C. A carbon free nickel deformed at liquid nitrogen temperature (−196 °C) achieves a similar saturation hardness than a nickel containing 0.06 wt% carbon (600 ppm) deformed at 400 °C [26].

1.5. Strain path

After applying a large strain by HPT, a shear texture evolves in the saturation microstructure and the single grains are not equiaxed. The longest grain axis is oriented parallel to the HPT shear plane whereas the shortest grain length is achieved parallel to the HPT rotation axis. This is not completely valid as the shear deformation does not lead to a grain orientation perfectly parallel to the HPT shear plane. In reality the grains are slightly tilted with respect to the HPT shear plane by a few degrees [17,20,23]. A change in the strain path, as for example by changing the HPT rotation direction, does not affect the saturation microstructure. The only difference is that the grains are tilted in the opposite direction as shown for cyclic HPT experiments in [20].

The following described experiments have been designed to treat the previously specified questions. From cyclic HPT deformation experiments it is known that it is possible to change the grain orientation without changing the average grain size. This offers the possibility to produce a HPT sample with different grain aspect ratios while keeping a similar grain size. A nickel disc with a diameter of 30 mm is deformed to the saturation regime. Subsequently, the disc is deformed into the opposite direction for a quarter of a full rotation by a simple change of the rotation direction of the HPT equipment. This slight rotation in the opposite direction causes no change in the grain size itself but it changes the aspect ratio of the grains over the disc. As shown schematically in Fig. 1a, the aspect ratio in the disc centre and the outer region is similar but the grain orientation is opposite.

The centre still shows alignment of the grains in the primary direction whereas the outer region has grain alignment in the secondary deformation direction. The aspect ratio along the radius from the centre to the outside of the disk initially increases to a maximum at about half of the radius and then decreases towards the disk edge. In this way, equiaxed grains can be expected in a region around half of the radius. Conducting tensile tests on samples prepared in this manner gives the unique possibility to answer the aforementioned questions.

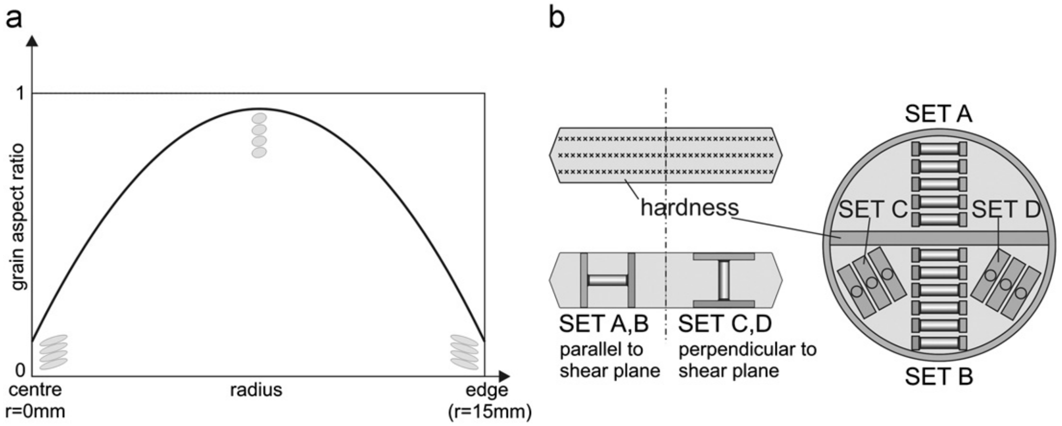

Fig. 1. (a) A schematic sketch of the expected grain aspect ratio distribution of a “back rotated” HPT disc and (b) tensile test sample orientation of the parallel and perpendicular tensile test samples and the cut disc which was used for the hardness measurement.