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Influence of mode of plastic straining on the microstructure of Ni and Ti deformed through rolling and torsion

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ABSTRACT

The influence of the mode of deformation (rolling and torsion) on the microstructures in Ni and Ti was studied. The microstructure of samples deformed to the same von Mises equivalent strains were characterized by electron backscatter diffraction (EBSD) and X-ray line profile analysis (XLPA). The maximum equivalent strains for Ni and Ti were 2.65 and 0.5, respectively. It was found that despite the same equivalent strains, significant differences were found in the microstructures deformed by rolling or torsion. For instance, the Ni sample rolled to the equivalent strain of 2.65 has larger grain size with less distorted grain interiors than in the specimen torsion tested to the same strain. This difference resulted in a lower stored energy in the rolled sample. The difference in stored energy and lattice strain between rolled and torsion deformed samples is attributed to differences in slip activity in each mode of deformation. In the case of Ti, the initial texture resulted in different contributions of $< c >$ / $< c + a >$ dislocation slip and twinning to plastic deformation during rolling and torsion. Due to the higher twinning activity in the Ti specimen rolled to the strain of 0.5, the fraction of $< c >$ / $< c + a >$ dislocations is smaller than in the torsion tested sample. Despite the different microstructures, the stored energies in the two Ti materials do not differ significantly, as the lower fraction of $< c >$ / $< c + a >$ dislocations in the rolled sample is compensated by their less clustered arrangement.

1. Introduction

The microstructure and properties of metallic materials can be tailored through thermomechanical processing (TMP), involving sequences of cold/hot deformation (e.g., through rolling, forging and drawing) and annealing cycles [1]. During TMP, static recrystallization (SRX) and dynamic recrystallization (DRX) are important phenomena that affect the microstructure development. The SRX and DRX depend not only on the overall stored energy but also on the spatial distribution of defects. The heterogeneity in the deformed microstructure is an important factor that influences the recrystallization kinetics as well as the resulting microstructure and texture [1,2]. During TMP, materials undergo deformation under different states of stress depending on the deformation mode, e.g., forging, rolling, extrusion etc. In view of this, for analysing the recrystallization behaviour of materials it is important to understand the influence of the deformation mode on the strained microstructure. Surprisingly, there are very few studies in the literature that analysed the influence of the deformation mode on the microstructure and its effect on SRX/DRX behaviour [3–7]. In our recent study on Ni [8], we observed that for a given equivalent von Mises strain (ε_{VM} = 1.6 and 2.65), deformation by torsion had resulted in a larger fraction of high angle grain boundaries (HAGBs) and a higher density of potential recrystallization nuclei when compared to samples subjected to rolling. The above differences were attributed to the dependence of the slip system activity on the stress state. The SRX kinetics of torsion deformed Ni samples was significantly faster and the grain sizes were smaller when compared to rolled samples [9].

α-Ti is a low symmetry hexagonal close-packed (HCP) structure with significant anisotropy that undergoes deformation through dislocation slip and twinning [10–12]. Ti samples deformed through hot rolling under different strain paths has been shown to exhibit different textures [10] and stored energy values [13]. The slip activity and propensity of twinning during tension and compression are shown to be strongly dependent on orientation [14,15]. The bulk mechanical properties of Ti are orientation dependent and it depends on the basal/near-basal orientation [16]. The microstructure and texture of deformed and annealed Ti depends on the rolling mode, i.e., unidirectional rolling and multistep cross rolling [17]. Ti samples with different initial texture after compression to same strain exhibited different recrystallization rates during annealing [18]. It can therefore be expected

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that the stress state will have a significant effect on the microstructural evolution in Ti. To the best of our knowledge, there is no systematic study in the literature on the effect of the straining mode on the deformed microstructure in HCP metals from the perspective of recrystallization.

In this study, the influence of the mode of deformation (rolling and torsion) on the deformation microstructure from the perspective of recrystallization is analysed in Ni and Ti samples using electron backscattering diffraction (EBSD) in scanning electron microscope (SEM) and X-ray line profile analysis (XLPA). Ni and commercial purity (CP) Ti (referred to as Ti hereafter) are selected as model materials as they represent a medium stacking fault energy face-centered cubic (FCC) material (which undergoes deformation through slip only at ambient temperature), and an HCP material (which undergoes deformation through both slip and twinning at ambient temperature), respectively. In our previous study on Ni, the samples were deformed to large strains (ε_{VM} = 1.6 and 2.65) and the microstructural heterogeneities were analysed using EBSD [8]. In the present study, we report microstructural analysis on Ni samples deformed through rolling and torsion to equivalent strains of ε_{VM} = 0.5, 2.65 and Ti samples deformed through rolling and torsion to equivalent strains of ε_{VM} = 0.33, 0.5, respectively. In addition, the energy stored in the microstructure is calculated. The microstructures and stored energies obtained for the samples deformed by rolling and torsion are compared.

2. Material and Methods

Ni and Ti samples for torsion and rolling deformation were machined out of extruded rods with the diameters of 15 mm (shown in Fig. 1). Torsion test details and specimen dimensions are given in [19]. Ni samples were deformed through free end torsion for 2 and 9.6 turns.

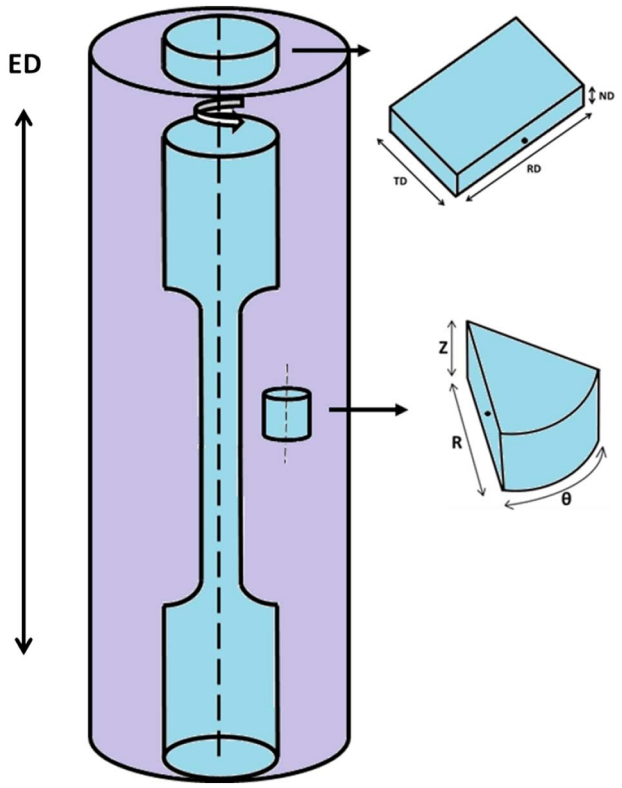

Fig. 1. Schematic of rolling and torsion test sample obtained from annealed extruded Ni and Ti rod. ED: extrusion direction of rod, RD: rolling direction, ND: normal direction and TD: transverse direction of rolling sample, Z: axial direction, R: radial direction and θ: tangential direction of torsion test sample. The dots indicate the sections on which EBSD was performed.

Ti samples were deformed through free end torsion for 2 turns at which sample failed. In the case of the torsion tested samples, the strain varies along the specimen radius and hence sections corresponding to ε_{VM} values introduced through rolling were studied. The von Mises equivalent strain along the radius of the torsion tested samples can be calculated as:

$$\varepsilon_{VM} = \frac{\theta r}{\sqrt{3}\, l} \tag{1}$$

where θ, l and r are the angle of rotation, the height of the cylindrical specimen (l = 38 mm in this case) and the distance from the sample center, respectively.

Ni samples were rolled to the thickness reductions of 35% and 90% which correspond to ε_{VM} of 0.5 and 2.65, respectively, as calculated from the following formula:

$$\varepsilon_{VM} = \frac{2}{\sqrt{3}}\, ln \frac{1}{1-t} \tag{2}$$

where t is the thickness reduction. The Ti samples were rolled to the thickness reduction levels of 25% and 35% which correspond to ε_{VM} of 0.33 and 0.5, respectively. The rolling was performed with 5% reduction per pass for both and Ni and Ti samples.

The microstructural characterization of the deformed samples was carried out by XLPA and EBSD. For XLPA, X-ray diffraction patterns were measured by a high-resolution rotating anode diffractometer (Rigaku) with CuKα_1 radiation (wavelength: λ = 0.15406 nm). The Debye–Scherrer diffraction rings were detected by two dimensional imaging plates and the line profiles were determined as the intensity distributions perpendicular to the rings. The evaluation of the patterns was carried out by the Convolutional Multiple Whole Profile (CMWP) fitting method [20]. In this procedure, the experimental diffraction pattern is fitted by the sum of a background spline and the convolution of the theoretical line profiles related to crystallite size and dislocations. The theoretical line profile functions used in this fitting procedure were based on a model of the microstructure where the crystallites (or coherently scattering domains) have spherical shape and a log-normal size distribution. The following parameters of the microstructure were determined by the CMWP fitting procedure: the mean crystallite size ($< x >$), the average dislocation density (ρ) and the dislocation arrangement parameter M. The dimensionless parameter M is calculated as $R_e\rho^{1/2}$ where R_e is the effective outer cut-off radius of dislocations. The value of M reflects the arrangement of the dislocations. Thus, a smaller value of M relates to a more shielded strain field of dislocations and the arrangement of dislocations into low energy configurations, such as low angle grain boundaries (LAGBs) or dipoles, yields a consequent decrease in M. The mean crystallite size ($< x >$) was calculated as $< x > = m \cdot \exp.(0.5\,\sigma^2)$, where m is the median and σ^2 is the log-normal variance of the crystallite size distribution.

For EBSD, samples were prepared through metallographic polishing with final stage of polishing being done with colloidal silica (particle size: 0.05 μm). In the case of Ti, a second step of polishing was also applied using a mixture of 70% colloidal silica (particle size: 0.05 μm) and 30% hydrogen peroxide. The analysis of the microstructure was carried out on the central region of the RD-ND plane (see Fig. 1) for the rolled samples. In the case of the torsion-tested samples, the microstructure was studied at the locations of the Z-R section which correspond to the ε_{VM} values achieved in rolling (see Fig. 1). From the above measurements, the IPFs corresponding to the RD-TD section and Z-θ section were obtained by making suitable rotations. EBSD for both Ni and Ti deformed samples was carried out by FEGSEM (FEI made Inspect F model) equipped with high-speed HIKARI camera using TSL OIM™ data acquisition and post-processing software (version 7.2). The EBSD scans for the initial state of Ni and Ti were performed with a step size of 1 μm. The EBSD scans were performed with a step size of 50 nm for the Ni samples deformed to the strain of 2.65 while for other deformed samples a step size of 300 nm was used. The grain boundary