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Texture evolution in titanium on complex deformation paths: Experiment and modelling

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ABSTRACT

Texture evolution in commercially pure titanium deformed by equal-channel angular pressing (ECAP) and extrusion with forward–backward rotating die (KoBo) is studied both experimentally and numerically. New results are provided that demonstrate the effects of distinct and complex deformation paths on the texture in the ultra-fine grained (UFG) material obtained after severe plastic deformation (SPD). The numerical simulations are based on the self-consistent viscoplastic method of grain-to-polycrystal scale transition. A recently proposed modification of the probabilistic scheme for twinning is used that provides consistent values of the twin volume fraction in grains. The basic components of the experimentally observed texture are reasonably well reproduced in the modelling. The numerical simulations provide an insight into the internal mechanisms of plastic deformation, revealing substantial activity of mechanical twinning in addition to the basal and prismatic slip in titanium processed by ECAP.

1. Introduction

The concept that mechanical properties of metallic materials can be considerably improved by refinement of their microstructure has contributed to rapid progress in development of various methods of severe plastic deformation (SPD) by which ultrafine-grained (UFG) materials are produced, cf. the extensive reviews [1–4]. UFG structure tends towards a class of nanostructure and is characterized by a number of beneficial properties. The mechanical strength of UFG metals can be increased two (or more) times, they have good machinability and improved fatigue resistance, better biocompatibility (titanium alloys), the possibility of further forming by superplastic flow at lower temperatures and with increased speed (by greatly increasing the contribution of grain boundaries), and also higher corrosion resistance (caused by the ease of obtaining a smooth surface). On the other hand, the SPD procedures induce not only substantial changes of materials microstructure but also an evolution of their texture [5–9], which in turn modifies the elastic and plastic anisotropy of the material.

In this paper, texture evolution is investigated in commercially pure titanium extruded by two techniques of producing materials with UFG structures, namely, the equal-channel angular pressing (ECAP) [10,2] and extrusion with forward–backward rotating die (KoBo), e.g. [11,12]. While classical ECAP is a well-established method, the KoBo requires an explanation. The KoBo device is a press with a forward–backward rotating die, Fig. 6a, enabling extrusion of ingots under conditions of permanent destabilization of their microstructure. A cyclic change of deformation path increases the ductility of the material and inhibits the formation and propagation of cracks.

Most of the studies in the literature concerning prediction of texture in ECAP process deal with fcc materials, cf. [13]. Hcp materials, cf. [14], received relatively less attention. For a Mg alloy, simulations for routes A, C and Bc and the channel angle 90° can be found in [15–17]. Similar studies for titanium or its alloys were performed in [18,6]. In all cases the visco-plastic self-consistent (VPSC) model was used and twinning was accounted for by using the predominant twin reorientation scheme, except [17] where the volume transfer scheme was used. Both schemes were proposed in [19]. The stable texture components after ECAP process of hexagonal close packed (hcp) material have been investigated in [20], where different relative values of critical shear stresses were considered. However, since the study was performed under the Taylor assumption, which is questionable for hcp materials with a smaller number of 'easy slip' systems, these results seem to be less meaningful than similar results obtained for fcc polycrystals [21].

Only few published results on modelling the KoBo process are available [22–24]. In reference to this non-conventional extrusion

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process, modelling of texture evolution has been been performed in [25] for an idealized process of tension or compression assisted by cyclic torsion, in which the strain path is, however, significantly different than in the actual KoBo extrusion process. Recently, the KoBo deformation paths, determined using the finite element (FE) method, have been applied to model texture development in fcc materials [26]. Some results concerning hcp AZ31B alloy have been presented in [27].

To model the texture evolution it is necessary to determine the actual deformation path imposed on the material volume. For certain well-known SPD processes, such as the above-mentioned ECAP, the macroscopic deformation path is easily determined with a good accuracy by basic kinematics, e.g., [10,28,2,13]. There exist more refined descriptions of deformation in the ECAP process: the fan model [29], the flow lines resulting from the upper bound analysis [30] or obtained by finite element method, e.g. [31,32]. However, such processes as KoBo, where the plastic deformation field is complex and position-dependent, must be analysed numerically. In the present work, the procedure is employed that enables determining the deformation paths directly from FE computations as proposed in [24]. Following [27], the deformation paths can be visualized by changes of ellipsoidal shape of a deformed initial sphere along a trajectory of a material point.

In this paper, new experimental and simulation results describing texture evolution in commercially pure titanium extruded by both the ECAP and KoBo techniques are provided that demonstrate the effects of applying different deformation paths on the resulting texture.

2. Experimental procedures

The investigated material both for ECAP and KoBo was grade-2 titanium. The initial samples for ECAP with the cylindrical shape were prepared from as-delivered sheet of material. The average grain size of the as-received material was 35 μm with the standard deviation of 24 μm. A relatively high value of the standard deviation reflects a wide spread of grain sizes in the initial material.

For initial and deformed samples the average grain size and the standard deviation for number averages were calculated using the software OIM TSL v. 7.2 [33]. A grain was defined as a set of points with mutual misorientation less than 15° and a grain had to contain at least 5 measurement points (in the case of initial samples this limit is increased to 20 points). For an initial sample the maps of the size 550 μm × 550 μm with the step of 0.4 μm were measured. On the other hand, for the deformed material the maps of the size of 50 μm × 50 μm with the step of 70 nm were determined. A grain was defined as a set of points with mutual misorientation less than 15° and a grain had to contain at least 5 measurement points.

The texture of the input material was roughly described by the ⟨0001⟩ direction lying in the plane perpendicular to the axis of the cylindrical sample. However, distribution of this direction was not uniform (“1” direction – originally normal to the sheet plane – was less coincident with the ⟨0001⟩). Thus the stress–strain curves reveal mechanical anisotropy in the rolling plane, and the stresses fluctuated between 350 and 400 MPa for yield strength, and between 450 and 500 for tensile strength.

During ECAP process the samples were deformed by extrusion through a cylindrical channel of angle 120° by route C, which induces a rotation of the sample by 180° clockwise around its longitudinal axis between adjacent passes. In the present work two deformed samples after 4 and 8 passes were examined. The received billets had the diameter of 10 mm and the length of 70 mm. In order to avoid the segmentation and cracking in the billets the ECAP processes were performed in the temperature of 300 °C.

The initial samples for KoBo were received as hot-rolled bars (ϕ35 mm) with homogeneous, globular microstructure and a mean grain size of 31 μm with the standard deviation of 17 μm. The measurement procedures for the material before and after KoBo differ from those for ECAP only in the sizes of maps and the measurement step. Thus for the initial sample and for the extruded material the sizes of maps and the steps were 960 μm × 960 μm with the step of ~0.80 μm and respectively 100 μm × 100 μm with the step of ~0.09 μm. The texture of the input material was similar to that for ECAP and could be described by the ⟨0001⟩ direction perpendicular to axis of the bar. The yield stress and the tensile strength were about 410 and about 470 MPa respectively. The bar was preheated before extrusion to 450 °C, however, the KoBo process itself was carried out at the temperature of about 400 °C. The bar was extruded to a rod with the diameter of 8 mm at the rate of 0.5 mm/s. The die oscillated by the angle of ± 6° with the frequency of 5 Hz.

The microstructure of the extruded samples was investigated in the transverse “1–2” and longitudinal “1–3” cross-sections (Fig. 1a) by Electron Backscatter Diffraction (EBSD) method in high resolution scanning electron microscopy (SEM/FEG). Textures were recalculated both from the EBSD/SEM/FEG data as well as from X-ray diffraction and presented in classic form of pole figures (0001), (1$\bar{1}$00), (11$\bar{2}$0) projected on the sample planes “1–2” and “1–3” (Fig. 1a).

3. Experimental results

The microstructures of grade-2 titanium after ECAP processing are shown in Fig. 2. The strong fragmentation of microstructure, particularly after 8 passes, is visible, Fig. 2c and d. The average grain size of 35 μm in the initial sample dropped after 4 passes and 8 passes to 0.7 μm and 0.6 μm respectively with the standard deviation correspondingly equal to 1.25 μm and 0.7 μm in ‘number’ measure. Also the material fragmentation inside grains, which can be measured by the average grain orientation spread, increased considerably from 2° in the initial state to about 10° (after 4 passes). And finally, the kernel average misorientation (KAM) increased from 0.5° to 0.8° (after 4 passes), which indicates significant increase of dislocation density.

Using crystal orientations obtained by EBSD technique the (0001), (11$\bar{2}$0) and (1$\bar{1}$00) pole figures were determined. The respective experimental figures are presented later in Section 6 jointly with those predicted in simulations. The projection plane of pole figure was perpendicular to the billet axis (i.e., plane “1–2”) in Fig. 14 or parallel to the longitudinal plane (“1–3”) in Fig. 13. The pole figures measured in “1–2” plane show a statistical symmetry with respect to the vertical axis of pole figures, while those measured in “1–3” plane show a typical shear character (“1–3” was the shear plane in the ECAP process).

The SEM examination of the material processed by KoBo revealed a heterogeneous microstructure consisting of grains shaped like ribbons curled about the extrusion direction ‘3’ (see [34] for more details of curly microstructure after KoBo processing). The grains, strongly elongated along ‘3’, were separated by well-developed high-angle grain boundaries (HAGBs). Most of HAGBs were parallel to ‘3’, Fig. 3. Besides the curly ribbons, there were also areas with equiaxed or cigar-like grains with major axes parallel to ‘3’. The mean grain size was 0.6 μm with the standard deviation equal to 0.6 μm in ‘number’ measure. Mechanical properties of the material were significantly improved; the yield stress and tensile strength increased to 560 and 672 MPa respectively [34].

The pole figures (PFs) measured at the center ($r \approx 0$) of the rod revealed a relatively sharp nearly axial texture with the ⟨0001⟩ axis perpendicular to ED, Fig. 15. Moreover, within the axial texture, the ED was predominantly parallel to ⟨1$\bar{1}$00⟩ direction. The PFs obtained from the edge of the rod ($r \approx 4$) show some deviation