Plastic Deformation of Textured Zircaloy 2

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Abstract

The present study deals with deformation behaviour of textured Zircaloy 2 with two dominant orientations: basal and non-basal. During initial stages (<10%) of deformation twinning predominates slip in Zircaloy 2 of non-basal texture. Extensive electron backscattered diffraction (EBSD) analysis showed that twinning is strongly orientation sensitive. Positron annihilation spectroscopy (PAS) analysis also offered some insight towards effect of twinning/slip on positron lifetime. At higher deformations (>20%), two distinct class of grains were observed – non-deforming/non-fragmenting grains and deforming/fragmenting grains. The so-called non-deforming/non-fragmenting grains remain equiaxed even after 50% of deformation. They also have insignificant in-grain misorientation developments and have more residual stresses. Dislocation dynamics simulation showed that the dislocation interactions/mobility is insignificant in basal orientations at room temperature deformations.

Introduction

Understanding the deformation behaviour of a metallic material is always an important subject for a metallurgist/mechanical engineer. For hexagonal Zircaloy 2, the deformation behaviour is expected to be more complex. Both slip and twinning have been reported – as the primary slip systems may not be numerous, and often limited, hence twinning may compete with slip [1]. Twinning depends on a variety of metallurgical & process parameters – temperature, strain rate, grain size, crystallographic texture, alloy composition, etc [2-4]. In this study, it was decided to explore the role of crystallographic texture on the slip-twin activation. Samples with two dominant orientations, basal and non-basal, were produced. These were subjected to uniaxial cold compression (to achieve low deformations) and cold rolling (for higher deformations). The deformed Zircaloy 2 were then characterized through X-ray diffraction (XRD), electron backscattered diffraction (EBSD) and positron annihilation spectroscopy (PAS). Dislocation dynamics (DD) simulations were used to seek out differences, if any, between dislocation activities/interactions.

Experimental Details

Cast and forged Zircaloy 2 sheets were subjected to uniaxial cold compression and cold rolling. Cold rolling (20% and 50% reduction) was performed in a laboratory rolling mill while compression tests (2%, 7.5%, 10%, 15% and 20% reductions) were conducted on a servo-hydraulic MTS (Mechanical Testing System) machine. The chemical composition of Zircaloy 2 is shown in Table 1 and the initial orientations of the samples are shown in Fig. 1. Different characterizations were subsequently conducted on the mid-thickness section of all the samples – see Fig. 1a.

Sn	Fe	Cr	Ni	O	Zr
1.54	0.15	0.12	< 0.05	0.12	Balance

Table 1. Chemical composition, in weight % alloying elements, of Zircaloy 2 used in the present study.

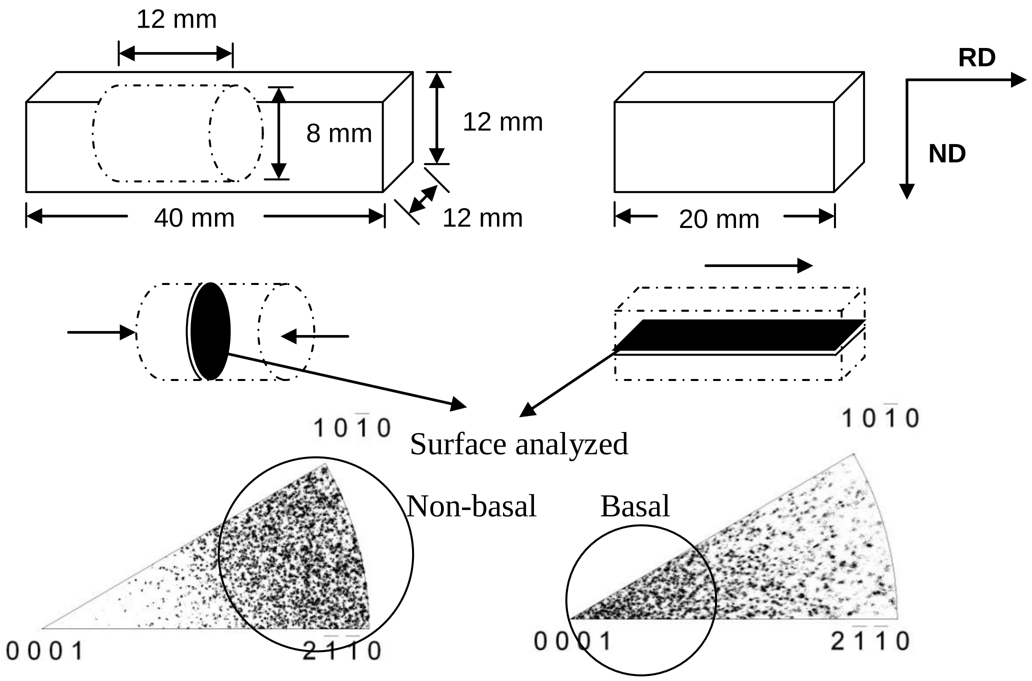


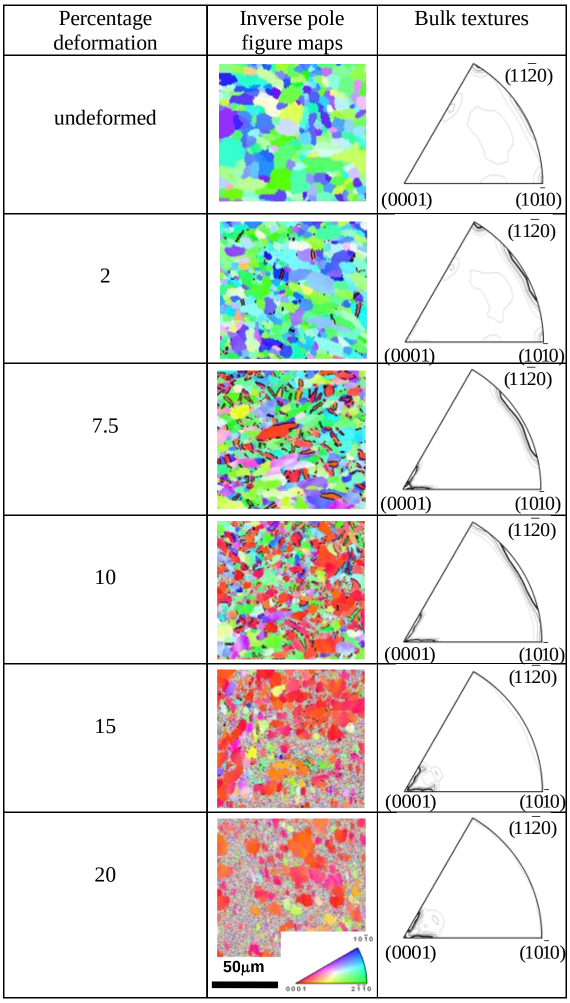
Fig. 1. Schematic showing dimensions and orientation of cylindrical compression samples, rectangular rolling samples and the parent rolled plate. The data of the inverse pole figures (<0001> projection of the respective compression/rolling planes) were taken from individual EBSD (Electron Backscattered Diffraction) scan(s).

A Panalytical MRD system, with CuKα radiation, was used for XRD measrements. The EBSD measurements were taken on Fei Quanta-200HV SEM (scanning electron microscope) using a TSL-OIM EBSD package. A positron source, prepared by ^{22}Na in the form of NaCl deposited in Kapton foil [5-7], was placed between two pieces of Zircaloy 2 samples so that all emitted positrons enter the sample. The mean positron lifetimes [5] were represented as τ_m in the present study. The 3D parallel DD simulation program, ParaDiS (Parallel Dislocation Simulator [8]), developed at the Lawrence Livermore National Laboratory, USA, was also used in the present study.

Results and Discussions

Uniaxial Cold Compression

Fig. 2 shows the microstructural and textural developments during the progressive compressions. At the initial stages of deformation twinning prevails. The twin boundaries are marked as black in the figure. Only tensile twins of $\{10\bar{1}2\} < \bar{1}011 >$ type were observed: identified through appropriate axis angle relationship of $94.8^{o} < \bar{1}2\bar{1}0 >$ [9]. Beyond 10% deformation the twin boundaries were largely absent. In other words, deformation was then dominated by slip. This effect is brought out, quantitatively, in Fig. 3. Twinning was dominated by non-basal orientations and no role of grain size was apparent. It may be noted that twinning parents were of non-basal orientations, while twinning daughter/products were of basal. In other words, the starting texture, basal or non-basal, decided the dominant deformation mode as slip and twinning respectively. At and beyond 15% compression, the microstructure showed fragmented and non-fragmented grains. This point is discussed latter in the section of rolled microstructures. τ_m data showed interesting patterns: (i) increase till 2%, (ii) drop during 2-7.5%, (iii) increase from 7.5-10% and (iv) gradual drop beyond 10% deformation – see Fig. 4. These can be tied up with twin generation, decay and grain fragmentation [10].



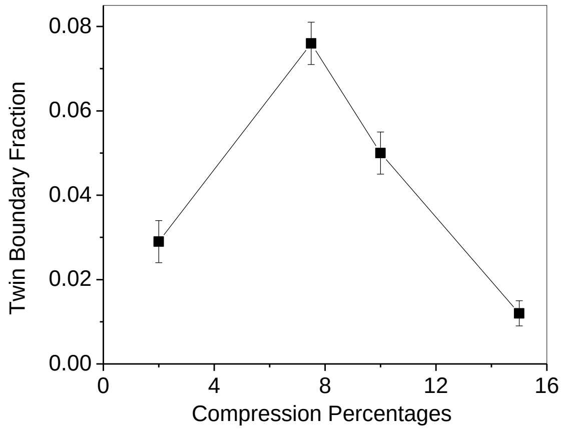


Fig. 3. Twin boundary fractions at different compression percentages.

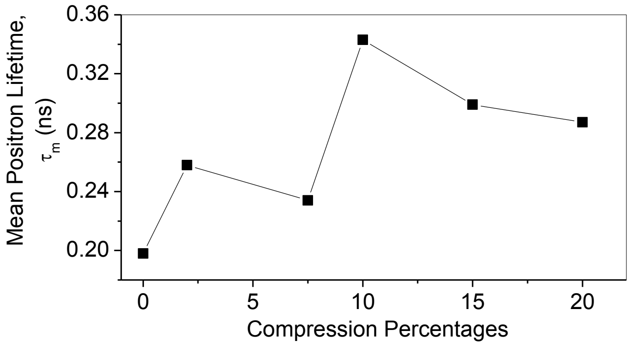
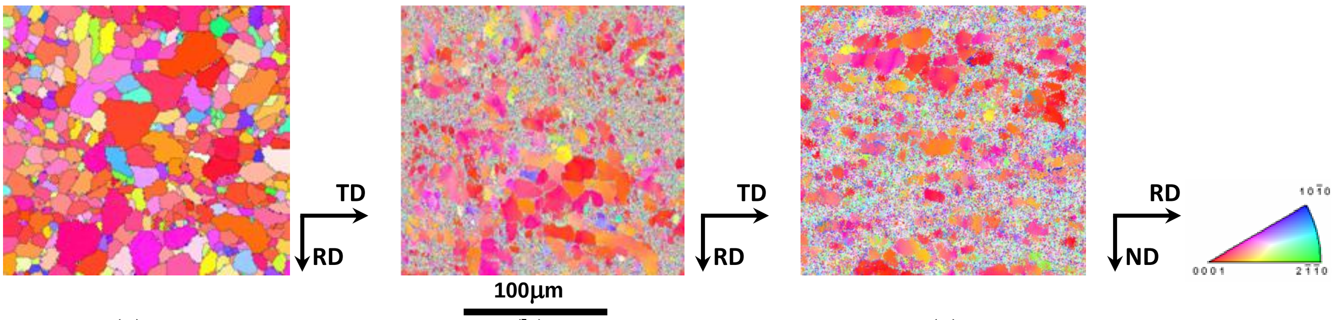


Fig. 4. Mean positron lifetime (τ_m) as a function of compression percentages.

Fig. 2. MIcrostructural and textural developments of Zircaloy 2 with progressive compressions. Inverse pole figure maps were obtained from EBSD while textural results were obtained by XRD. The contour levels in XRD inverse pole figures were 6, 5.5, 4, 3, 1.5 times random.



(a) (b) (c)

Fig. 5. IPF maps of rolled Zircaloy 2 before (a) and after (b & c) 20% deformation. (b) represents the rolling plane while (c) represents the long transverse plane.

Cold Rolling

Fig. 5 shows the microstructural developments during 20% cold rolling of Zircaloy 2. The figure clearly shows two classes of grains: deforming or fragmenting grains and non-deforming or non-fragmenting. More importantly, as shown in Fig. 5(c), in the long transverse section of the rolled Zircaloy 2 the grains remained equiaxed. Similar observation was made after 50% rolling as well.

The EBSD scans were analyzed extensively and had shown that the non-fragmenting grains (i) near basal (more specifically $(01\bar{1}5)$<uvtw>) orientations, (ii) low/insignificant grain misorientation developments and (iii) were elastically harder. X-ray residual stress measurements estimated significantly higher compressive residual stresses for such orientations. DD simulations could capture the differences in deformation behaviour between the crystallographic orientations – see fig. 7. As shown in the figure, there basal single crystals showed almost no change in dislocation density and configuration. This indicates strong pinning through dislocation interactions: a topic for on-going investigation.

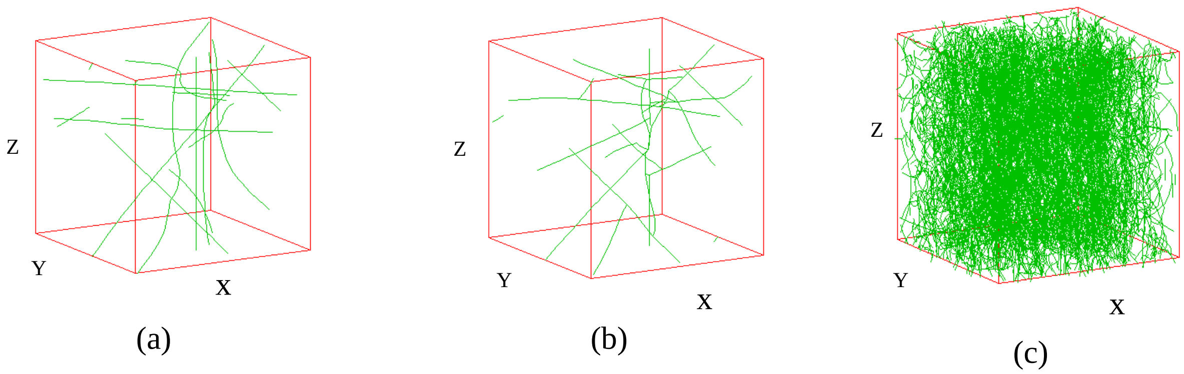


Fig. 7. (a) Starting dislocation structure, (b) & (c) Dislocation structure developments in basal (0001) and non-basal $(10\bar{1}0)$, orientations.

Conclusions

- Deformed Zircaloy 2, used in the present study, had two important microstructural features: fragmenting & non-fragmenting grains and generation & decay of deformation twins. Grain fragmentation, is expected to take place through realignment and recovery of dislocations and creation of high angle boundaries. Twins, on the other hand, are special grain boundaries of very specific orientation relationship: $94.8^{o} < \bar{1}2\bar{1}0 >$.
- Non-basal and basal grains were noted as twinning parents and products respectively; while the non-fragmenting grains were dominated by near-basal orientations. PAS mean lifetime (τ_m) could capture, effectively, signatures of twin generation/decay and grain fragmentation.

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