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An investigation of effect of annealing at different temperatures on microstructures and bulk textures development in deformed Zircaloy-4

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ABSTRACT

In the present work, the effect of various annealing temperatures on the microstructural and textural evolution in deformed Zircaloy-4 has been investigated. Zircaloy-4 was subjected to a rolling reduction of 90% corresponding to a true strain of 2.3 along the ND - ED and ND - TD planes of the as-received Zircaloy-4 bar at room (298 K) and cryogenic (77 K) temperatures. Following this, the various deformed conditions of the samples were subjected to annealing treatment at various temperatures such as 400°C, 450°C and 500°C. The deformed samples were characterized by a high dislocation density and nano scale subgrains, which after annealing at various temperatures were marked with annealing twins of nano - size along with some other dislocation configuration. A higher dislocation density and hardness (258.54 ± 2.91 HV) values were observed after annealing the cryorolled alloy along the ND - TD plane at 450°C. This high cold work energy provided by cryorolling along the ND - TD plane, after annealing at 450°C produced an optimum twin growth, which impeded the dislocation motion and slightly increased the hardness along this plane. Finally, the textures evolved after annealing indicated the role of annealing twins combined with < a > prismatic, < c + a > pyramidal & basal glide activity.

1. Introduction

Zirconium and its alloys are used widely in nuclear industry as pressure tubes and cladding materials due to their good mechanical properties, excellent resistance to high temperature corrosion and creep and low neutron absorption cross section [1–3]. Zirconium alloys generally display anisotropic mechanical and physical properties owing to their hexagonal close packed structure, which depends upon the level of thermomechanical processing of the alloy and the crystallographic texture developed [4]. Zircaloy-4 belongs to a Zr—Sn system alloy, exists in α phase at service temperature while, it transforms into β phase having a BCC structure between 800°C and 1000°C [5]. The core components of nuclear reactor from Zr alloys are fabricated by processes such as forging, swaging, extrusion and hot and cold rolling. The formability of the material along with the intricacy of the part being fabricated decides a particular or combination of the various fabrication processes to be adopted. The formability of Zirconium alloys depends mainly on their crystallographic textures developed as a result of preceding thermomechanical treatment [6].

Because of the restricted number of slip systems, the deformation behavior of Zirconium alloys is more complex than cubic materials. The plastic deformation in Zirconium alloys is reported to proceed by the combination of twinning, prismatic slip and pyramidal slip in order to fulfill the requirement of five independent slip/twin systems to accommodate polycrystal plasticity [7]. Deformation by the activation of extensive deformation twinning plays an important role in hexagonal materials than in the case of cubic metals. Twinning is assumed to activate in conditions where slip is difficult [8,9], such as at high strain-rate or low temperature. Twinning can lead to drastic changes in mechanical properties and texture.

Further, deformation at low temperatures has been observed to play an important role in the fabrication of UFG materials due to the suppression of dynamic recovery [10], which by accumulating the high density defects in the deformed material can lead to the improvement in mechanical properties. Cryorolling of Zirconium and its alloys has exhibited a significant enhancement in mechanical properties because of grain refinement, which is in accordance with the Hall-Petch relation [11]. Yet, the main problem associated with this method is that high strength is obtained at the expense of ductility, which has critically prohibited them from real-world usefulness. Therefore, annealing

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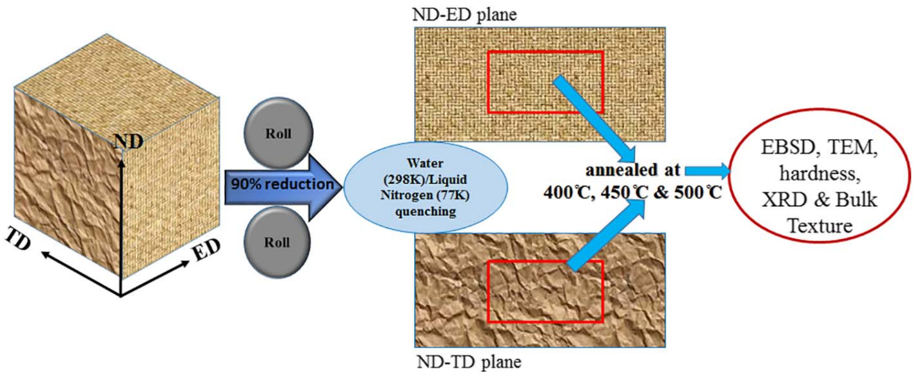

Fig. 1. Schematic representation of the rolling followed by annealing process.

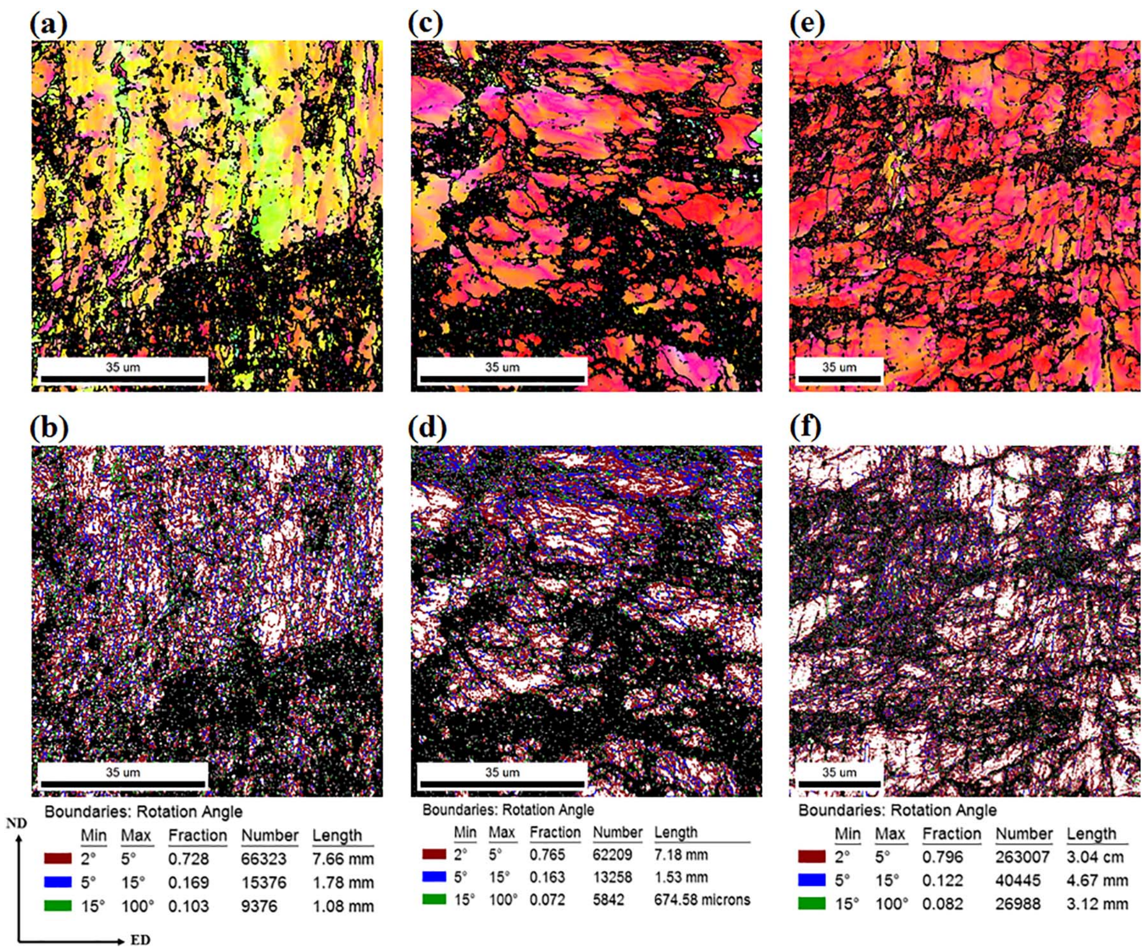

Fig. 2. Orientation maps of Zircaloy-4 after RTR followed by annealing at various temperatures along the ND - ED plane at (a, b) 400°C annld, (c, d) 450°C annld, and (e, f) 500°C annld. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

treatment after the deformation is generally adopted to modify the microstructures and textures in order to make it suitable for practical utility.

Over the years', texture development in hexagonal structural materials has been of significant interests because of the use of Zircaloys for cladding nuclear fuel pellets [12,13]. It is observed that in the sheet rolling process of Zircaloy, the normal direction of the sheet is under compression and the rolling direction is under tension whereas causing small changes in the transverse direction. Thus, as a result of this, the basal poles favorably align parallel to the compressive force i.e. parallel to the normal direction with a slight spread of around ± 20°–40° towards the transverse direction. The spread in the basal poles in the transverse direction is attributed to the evolution of small compressive force. The similarity in the evolution of stress - strain conditions in case of tube reduction processes for $R_W/R_D > 1$ with the normal rolling process leads to the similar texture development as that in rolling process. Further, twinning also rotate the basal planes normal along the direction of deformation which after recrystallization annealing rotates by 30° around the c-axis thus making $\langle 11\bar{2}0\rangle$ directions parallel to the rolling direction [2]. The microstructure, texture and properties of various alloys developed after various heat treatments have potential for industrial application. The investigations on deformation followed by annealing treatment of various Ti alloys have been reported [14–16]. However, an investigation on the microstructural and textural evolution of Zircaloy-4 during rolling at room and cryogenic temperatures following annealing at different temperatures