Materials Chemistry and Physics 173 (2016) 12–25

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

An investigation of deformed microstructure and mechanical properties of Zircaloy-4 processed through multiaxial forging

Devasri Fuloria [a], P. Nageswararao [a], R. Jayaganthan [a, b, *], S. Jha [c], D. Srivastava [d]

[a] Department of Metallurgical and Materials Engineering & Centre of Nanotechnology, IIT Roorkee, Roorkee 247667, India
[b] Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India
[c] Nuclear Fuel Complex Limited, Hyderabad 501301, India
[d] Materials Science Division, Bhabha Atomic Research Centre, Mumbai 40085, India

HIGHLIGHTS

- Zircaloy-4 was subjected to MAF at cryogenic temperature.
- Microstructural evolution was studied through EBSD and TEM.
- Deformed microstructure was marked with various types of twinning and shear banding.
- Twins formations are responsible for effective grain refinement and enhanced mechanical properties.

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
31 August 2015
Accepted 16 September 2015
Available online 25 January 2016

Keywords:
Cold working
Electron diffraction
Electron microscopy (TEM)
Mechanical testing

ABSTRACT

In the present work, the mechanical behavior of Zircaloy-4 subjected to various deformation strains by multiaxial forging (MAF) at cryogenic temperature (CT) was investigated. The alloy was strained up to different number of cycles, viz., 6 cycles, 9 cycles, and 12 cycles at cumulative strains of 2.96, 4.44, and 5.91, respectively. The mechanical properties of the alloy were investigated by performing the universal tensile test and the Vickers hardness test. Both the test showed improvement in the ultimate tensile strength and hardness value by 51% and 26%, respectively, at the highest cumulative strain of 5.91. The electron backscattered diffraction (EBSD) measurement and transmission electron microscopy (TEM) were used for analyzing the deformed microstructure. The microstructures of the alloy underwent deformation at various cumulative strains/cycles showed grain refinement with the evolution of shear and twin bands that were highest for the alloy deformed at the highest number of cycles. The effective grain refinement was due to twins formation and their intersection, which led to the improvement in mechanical properties of the MAFed alloy, as observed in the present work.

1. Introduction

Zirconium alloys belong to the class of hexagonal closed packed metals (HCP), with a c/a ratio (1.593) less than ideal ratio. In the nuclear industry, they have broad applications as structural materials in the cores of nuclear reactors because of their superior mechanical properties, high temperature creep resistance, corrosion resistance in water at 300 °C, and low neutron absorption cross section [1]. Consistent performance under hostile reactor surroundings inflicts rigorous demand for higher–grade physical properties, mechanical properties, and dimensional allowances. The operating performance of Zircaloy-4 tubes, used as fuel element cladding, depends on the microstructural features like grain size distribution, grain morphology, crystallographic texture, morphology, and dispersal of precipitates, etc. As a result, it is imperative to have an efficient processing method that enables the formation of desirable microstructures, so as to acquire the finest transient and longstanding mechanical and corrosion properties with indispensable dimensional tolerances [2].

Zircaloy-4, a Zr–Sn system alloy, is extensively used as a nuclear fuel pellets cladding element. It has been observed that at service temperature, it is in α phase, and between 800 °C and 1000 °C, it transforms into β phase with a BCC structure [3]. The

* Corresponding author. Department of Metallurgical and Materials Engineering & Centre of Nanotechnology, IIT Roorkee, Roorkee 247667, India.
E-mail address: rjayafmt@iitr.ernet.in (R. Jayaganthan).

http://dx.doi.org/10.1016/j.matchemphys.2015.09.025

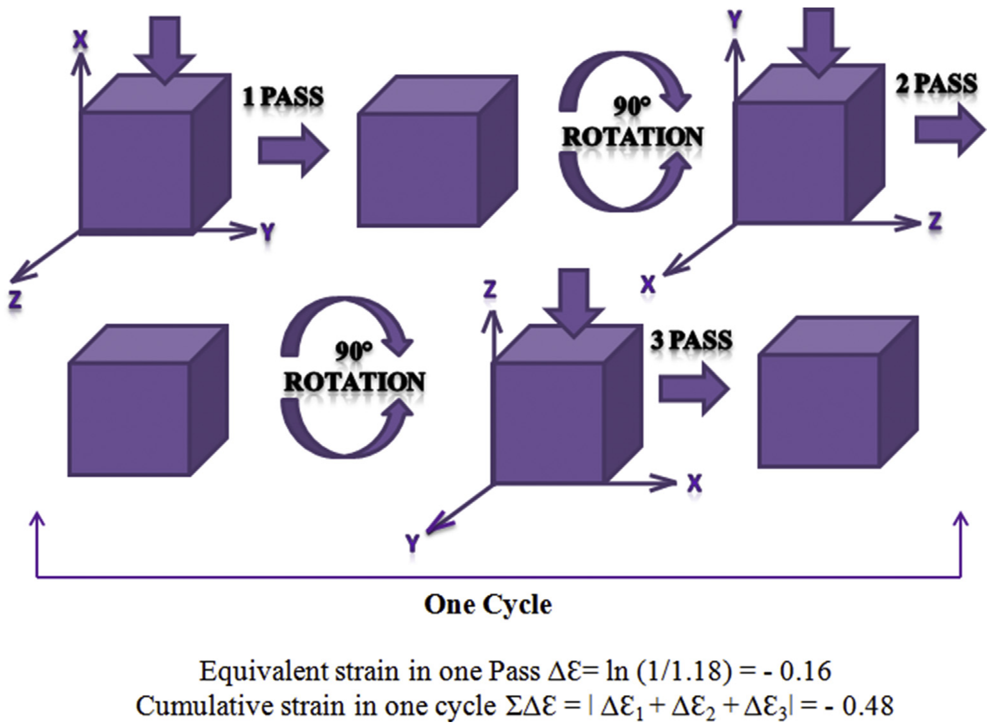

Fig. 1. Schematic of Multiaxial Forging (MAF) corresponding to one cycle.

thermomechanical processing route usually comprises extrusion to pilgering or tube drawing followed by several stages of annealing [4–6], which renders HCP grains of the alloy to be elongated or equiaxed with submicron level intermetallic precipitates [4,7,8]. The operable deformation modes are slip and twinning in this alloy

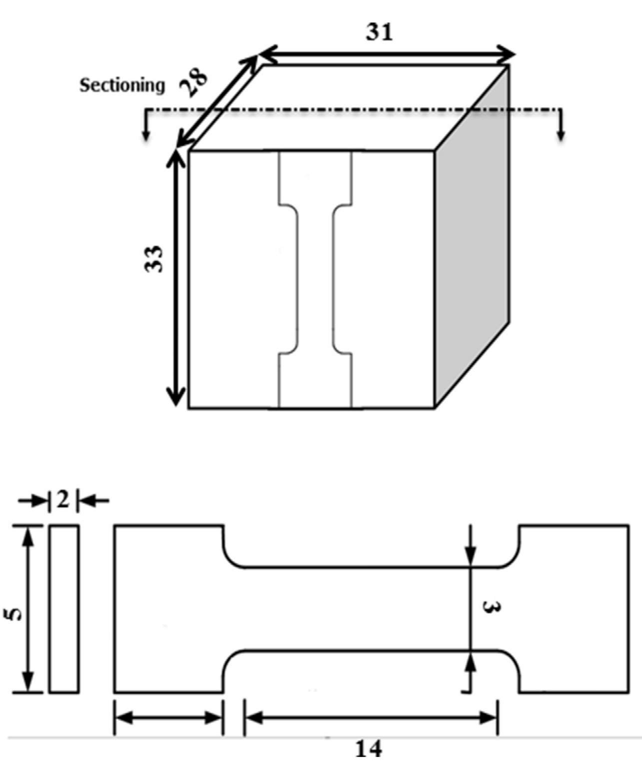

Fig. 2. Schematic of the cutting procedure of Tensile sample from the MAFed block. All the dimensions are in mm.

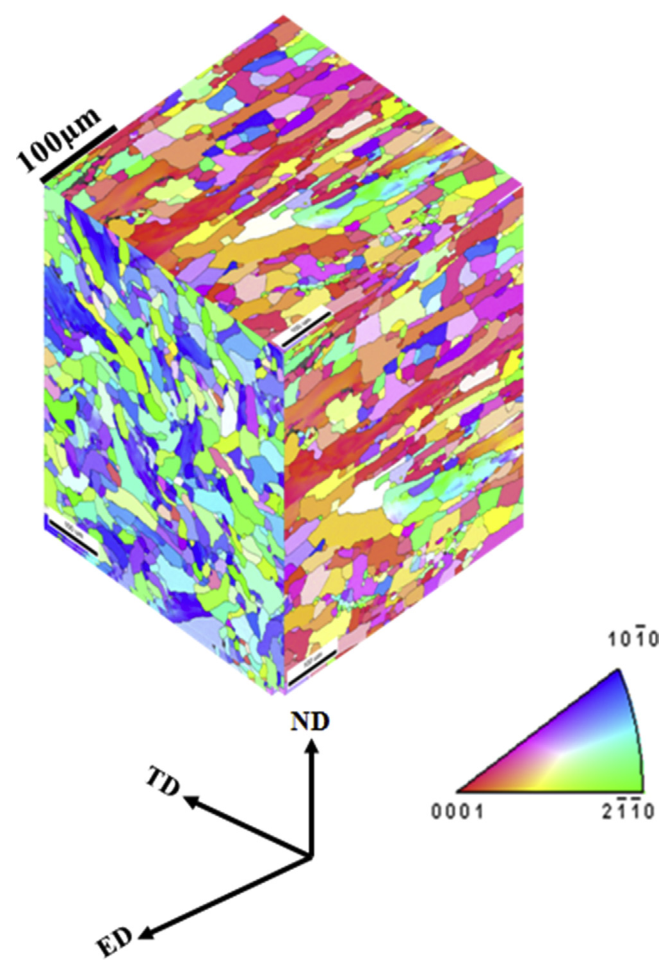

Fig. 3. EBSD (IPF) map of as-received alloy.