Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 374 (2008) 138–146
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Examination of residual stresses and texture in zirconium alloy cladding tubes after a large plastic deformation: Experimental and numerical study

D. Gloaguen *, T. Berchi, E. Girard, R. Guillén

GeM, Institut de Recherche en Génie Civil et Mécanique, Université de Nantes, Ecole Centrale de Nantes, CNRS UMR 6183, 37 Boulevard de l'Université, BP 406, 44 602 Saint-Nazaire, France

Received 11 May 2007; accepted 25 July 2007

Abstract

X-ray diffraction is used to assess the development of residual stresses within the grains of Zr alloy tubes processed via cold pilgering. A modified elastoplastic self-consistent model was used to simulate the texture and the internal stresses developments. The influence and the role of elastoplastic anisotropy were also studied and explained in this work. The contribution and the magnitude of the first- as well as the second-order residual stresses were correctly evaluated using information from the model. Comparison between the X-ray diffraction results (texture *and* residual strains) and the simulations confirms that prismatic slip is the main active deformation mode in this alloy under large strain.

PACS: 46.35.+z; 61.10.Nz; 62.20.Fe; 81.05.Bx; 83.60.−a

1. Introduction

Zirconium alloys are extensively used in various types of fission reactors. The development of zirconium alloys is essentially due to the nuclear industry, where zirconium alloys have been regarded as the proven structural material [1]. In this work, we are concerned by the manufacturing process of M5™ alloy cladding tubes by cold pilgering. This process is a tube forming operation where the inner radius and wall thickness are both progressively reduced between a fixed axisymmetric mandrel and forward- and backward-rolling grooved dies [2]. This process consists in a sequence of three rolling passes. After each pass, the tube is heat treated at a certain annealing temperature, which is sufficient to induce recrystallization, except for the last heat treatment, which is done just for stress relieving.

Zr alloys have a hcp crystal structure and exhibit high anisotropic plastic properties at mesoscopic (grain) and macroscopic levels with various active deformation modes. These properties and the crystallographic texture explain the appearance and development of important residual stresses when an elastoplastic deformation is introduced. These stresses are termed intergranular or second-order stresses. They depend on initial and induced crystallographic textures. The engineering consequences of second-order stresses with strong texture may be severe. The texture and stresses at a given step in the fabrication process will influence the formability with which the next mechanical process might be realised. The texture of the material will have a significant effect on its in-service performance because irradiation creep, yield strength, stress corrosion cracking resistance, for example, are strong functions of texture. During the process, internal stresses can also induce defects such as transverse cracks or surface damage [1,3].

* Corresponding author.
E-mail address: david.gloaguen@univ-nantes.fr (D. Gloaguen).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.07.017

Therefore, metal forming processes optimization such as rolling requires knowledge of the evolution of the material's anisotropic elastoplastic behaviour during the deformation operations. Polycrystal models for numerical prediction of deformation processes have undergone an important development during the last years. The modelling of the plastic deformation of metallic polycrystals can be carried out by deductive methods based on strain mechanisms and scale transition methods like self-consistent (SC) models [4–6]. Polycrystal models are typically evaluated by their ability to simulate the mechanical behaviour. For large deformations (>20% strain), model predictions are readily compared to textures determined experimentally by X-ray or neutron diffraction.

Hexagonal materials are characterised by a wide variety of possible deformation systems. It is necessary to know both the texture and the deformation mechanisms to be able to model these mechanical properties. This requires, in particular, a proper knowledge of the deformation mechanisms with their corresponding CRSS (critical resolved shear stresses). Only few data are available for CRSS in the literature. Moreover, the CRSS generally depend significantly on the contents of alloying elements. In spite of this very basic knowledge of these data, many authors have tried to model the mechanical properties of hexagonal materials after large deformation. In these cases, the approach consists in finding the set of material parameters offering the best agreement with crystallographic texture by applying a polycrystalline model. Realistic simulations of deformation texture development of Zr alloys can be done using the viscoplastic SC model [7–9]. The cold pilgering texture of zirconium alloy has been also studied with this kind of approach [3,10]. The confrontation between simulations and experimental texture shows that the prismatic slip is probably the most active system for this process.

In the present work, a different approach is proposed to validate the accuracy and the relevance of theoretical model for hexagonal material in a large deformation framework. *Both texture and residual stresses* characterisation by diffraction have been used simultaneously to evaluate polycrystal models for non-cubic material. A confrontation between experimental observations (X-ray diffraction) and predictions of an elastoplastic self-consistent (EPSC) model has been made in order to obtain more information about the different factors responsible for the appearance of residual second-order stresses and determine with more accuracy the set of deformation systems. This comparison allows a better understanding and interpretation of diffraction and mechanical results.

The aim of the present study is the analysis and understanding of the anisotropic elastoplastic behaviour evolution during the cold pilgering operation of zirconium alloy. A modified EPSC model was used to predict the behaviour of zirconium alloy cladding tubes during the last rolling pass. This approach is well suited to study anisotropic materials with multiple slip and twinning modes because it allows for different deformation depending on the relative orientation between the grain and the average medium. X-ray diffraction results (texture and residual stresses) obtained at the initial and final states provide an accurate experimental base for determining the appropriate model parameters and find a realistic combination of deformation systems. The theoretical stresses are compared with the experimental results obtained by X-ray diffraction. The results predicted by the SC model are discussed. In hexagonal alloys, like those of zirconium, plastic anisotropy induces plastic incompatibility stresses. These intergranular plastic stresses must be taken into account for a proper interpretation of X-ray experimental data. Consequently, a specific study concerning the influence of these second-order stresses, as well as the first-order (macroscopic) stresses, has also been performed.

2. Experimental procedure

The analysis was performed for the last cold pilgering pass. In this work, we analysed the texture and residual stresses in two states: before and after the third pass cold work. At the initial state, tubes have been submitted to a recrystallization treatment at 700 °C. At the initial state, the dimensions of M5™ tubes are: 17.8 mm external diameter and 2 mm thickness. The dimensions after forming (195% total strain) are 8.37 mm and 0.6 mm. The chemical composition is (Wt%-balance = Zr): Nb(1.0), Fe(0.035) and O(0.13).

2.1. Texture analysis

X-ray diffraction analysis was performed with four circles XRD3003PTS SEIFERT goniometer. Kα copper radiation was used. The X-ray beam output collimator had 0.5 mm diameter. The diffraction peaks were recorded with a position sensitive detector (PSD). We measured incomplete pole figures (PF) on a $5 \times 5°$ grid with tilt and azimuth angles ranging from 0° to 60° and 0° to 360°, respectively. For each experimental direction, the diffraction pattern was adjusted, using a nonlinear least squares analysis and assuming pseudo-Voigt peak profiles for each peak, to evaluate background noise and to obtain peak intensities. The study of samples having a curved geometry not only requires an accurate positioning of the samples but also take into account the geometric effects induced by XRD directional feature. A theoretical model based on a ray-tracing method was used to take into account the geometric effects, which modify the collected intensities. More details of this approach can be found in [11]. Correction coefficients accounting for the 'geometrical texture' of the samples as well as absorption corrections are calculated. The obtained results are used to correct experimental pole figures. The orientation distribution function (ODF) calculation has been performed with experimental PF $\{0002\}$, $\{10\bar{1}1\}$, $\{11\bar{1}0\}$ and $\{10\bar{1}3\}$ with help of WIMV algorithm implemented in the BEARTEX program package [12].