NON-DESTRUCTIVE TECHNIQUES ON ZIRCONIUM ALLOY E110 WITH CHROMIUM COATINGS FOR THE PRODUCTION OF EMERGENCY-RESISTANT CORE COMPONENTS OF NUCLEAR REACTORS

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Abstract

This study evaluates the effectiveness of chromium coatings on zirconium alloy E110 in nuclear reactor core components. Various NDT methods were used to assess structural soundness and effectiveness. Results showed that increasing the chromium coating thickness improves electrical conductivity and thermoelectric properties, making it suitable for nuclear reactor applications. This enhances the long-lastingness and dependability of zirconium alloy components.

Keywords: Non-destructive testing (NDT); Zr1%Nb; Chromium coatings; magnetron sputtering; corrosion resistance; nuclear reactors.

Introduction

The safety and efficiency of nuclear reactors rely heavily on the performance of their core components, which are often subjected to extreme conditions. Zirconium alloys, particularly E110, are widely used due to their favorable nuclear properties but face challenges due to their susceptibility to oxidation and hydrogen embrittlement under high-temperature conditions. Chromium coatings have emerged as a promising solution to enhance corrosion resistance and mechanical integrity of these alloys [1,4]. Zr1%Nb alloy (grade E110) is widely used in the Russian Federation for emergency-resistant core components due to its low thermal neutron capture cross-section, corrosion resistance, acceptable mechanical characteristics, and resistance to radiation swelling. Research and development have focused on creating protective coatings to reduce hydrogen absorption in zirconium alloys. Chromium-based coatings demonstrate a unique set of physicochemical and mechanical properties that prevent hydrogen penetration into the alloy, reduce hydrogen-induced defects, and significantly increase corrosion resistance while maintaining mechanical properties [2]. This study focuses on non-destructive testing methods to evaluate the effectiveness of chromium coatings on Zirconium alloy E110 for developing emergency-resistant core components for nuclear reactors.

Materials and methods

The material for this work is zirconium alloy Zr1%Nb (grade E110), presented in the form of plates 2 mm thick and 15 × 15 mm in size. The samples were grinded and polished using a water-based diamond suspension with a grain size of 3 μm and 1 μm; and finishing polishing using a colloidal silicon suspension. The chromium coating was deposited at the Tomsk Polytechnic University using a specially designed ion-plasma setup [3].

The experimental setup includes a vacuum system with cryogenic and turbomolecular pumps, three magnetron sputtering systems with 90 mm diameter disk targets, an ion source with closed electron drift for finishing plasma cleaning of substrates, a resistive heater (up to 300 °C), a gas ion implanter (ion energy up to 25 keV), a planetary substrate holder (8 positions), and a system of bias supply to the substrates (up to -1 kV). Deposition of chromium coatings was carried out on substrates preheated to a given temperature using a resistive heater after plasma cleaning in vacuum.

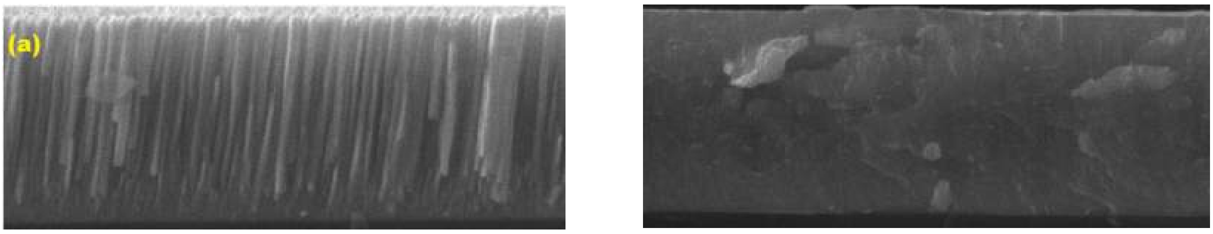
Samples of the studied material were cut on the equipment "Accutom 5" of "Struers" company with a diamond cutting disk with a thickness of 0.5 mm and pressed by cold pouring method using SpeciFix-40 epoxy resin.

Viewing and photographing areas near the oxide film were carried out at 1000x magnification using an Olympus GX51 optical microscope. Image acquisition was performed using SIAMS 800 software.

A Shimadzu XRD 7000S X-ray diffractometer was used to study the patterns of changes in the structural and phase states of the material before and after hydrogenation. The diffractometer is equipped with a wide-angle 1280-channel high-speed detector.

Results

The results of metallographic studies of the initial samples of Zr1%Nb and Zr1%Nb zirconium alloy with a Cr coating applied using magnetron sputtering (hereinafter Zr1%Nb-Cr) are shown in Figure 1.

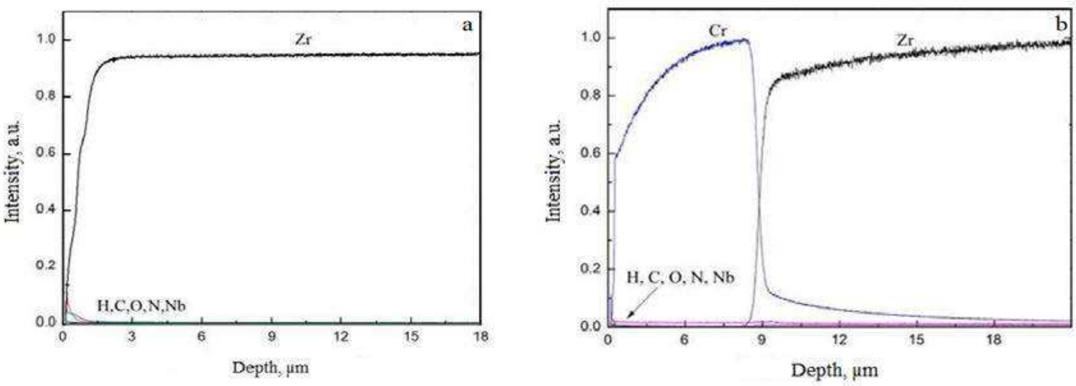


(a) (b)

Figure 1. Image of metallographic sections of samples of Zr1%Nb zirconium alloy with chrome coatings obtained using MPC with “hot” (a); and in cooled targets(b)

Microscopic image analysis revealed grain sizes of 2–3 microns and 3–4 microns in the main matrix, and uniform chromium plating of 6 microns and 9–10 microns on the studied zirconium alloy Zr1%Nb.

Figure 2. Shows the stoichiometric depth distribution in zirconium alloy samples Zr1%Nb and Zr1%Nb-Cr.



(a) (b)

Figure 2. Depth distribution of chemical elements in the alloy Zr1%Nb (a) and Zr1%Nb-Cr (b)

All alloy samples are free of gaseous impurities, including hydrogen, and the thickness of the chromium coating is 6 microns, and approximately (9±1) microns.

The results of X-ray diffraction analysis of the Zr1%Nb-Cr system are presented in Figure 3, Figure 4 and Table 1.

Analysis of diffraction patterns of samples of the Zr1%Nb-Cr with thickness of the chromium coating 6 microns in figure 3, and approximately (9±1) microns in figure 4. revealed significant changes in the phase composition.

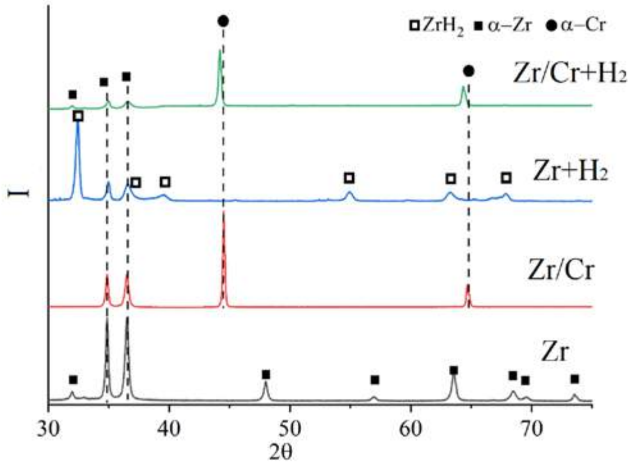


Figure 3. Diffraction patterns of the studied material of the Zr1%Nb-Cr with thickness of the chromium coating (6) microns

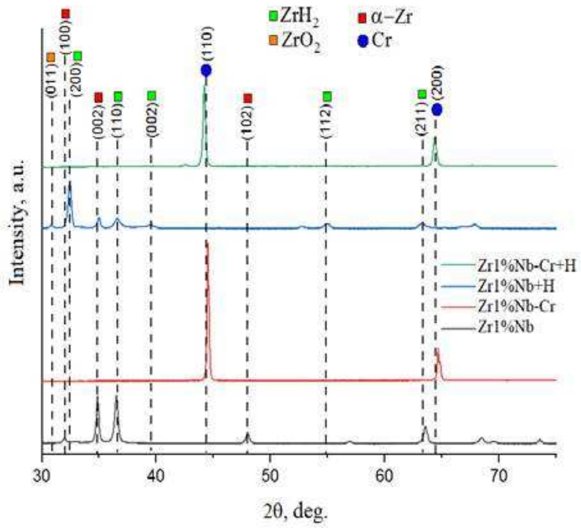


Figure 4. Diffraction patterns of the studied material of the Zr1%Nb-Cr with thickness of the chromium coating (9±1) microns

Table 1 – Results of X-ray diffraction analysis of the Zr1%Nb-Cr system

Sample	Phase	Phase content, vol.%	Lattice parameter	Crystallite size according to CSR, nm	Microstrain, $\Delta d/d \cdot 10^{-3}$
Zr1%Nb	Zr	100	a: 3.2357 c: 5.1465	42	1.9
Zr1%Nb-Cr 6 microns coating	Cr	100	*a*: 2.8864	49	0.9
Zr1%Nb-Cr (9±1) microns	Cr	100	a: 2.8869	54	0.4

To understand the reasons for the observed effects, further research is needed, in particular structural studies –in situ X-ray diffraction, four-probe resistivity measurements, and thermal electromotive force (EMF).

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