Evaluation of the Hoop Tensile Behavior of Cr-coated Zircaloy-4 Fuel Cladding by Advanced Expansion Due to Compression (A-EDC) Test

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Abstract

This research evaluates the mechanical behavior and strength of Cr-coated Zircaloy-4 cladding tubes under hoop tensile stress. Cr coatings were applied to Zircaloy-4 rings using the pulsed laser deposition (PLD) method. Advanced expansion due to compression (A-EDC) tests were conducted on the as-deposited specimens at room temperature (RT) and 573K. To determine the coating's strength accurately, mechanical properties including Young's modulus and residual stress were measured using nano-indentation and XRD methods. Analyzing the crack density-local strain relationship established a quantification method for the coating's cracking behavior. The results demonstrated superior crack resistance for the thin Cr coating with a nanocrystalline/amorphous structure.

Keywords: Accident Tolerant Fuels, Cr coating, Advanced Expansion due to Compression (A-EDC) Test, Hoop strength, Crack propagation

1. Introduction

Chromium (Cr) coated zirconium-based alloy (Zry) is considered as the nearest candidate for accident-tolerant fuel (ATF) cladding materials. These coatings are likely to face axial and hoop tensile stresses, temperature variations, and other factors that can degrade the cladding and cause cracks to form on the outer layer. The Advanced Expansion-Due-to Compression (A-EDC) test, which can assess the hoop tensile mechanical properties of cladding materials, is a potential method for evaluating the hoop tensile behavior of coated cladding, particularly regarding the coating's adhesion and fracture strength.

This research qualitatively and quantitatively evaluates the mechanical behaviors of Cr-coated Zircaloy-4 cladding tubes under hoop tensile stress using the A-EDC test.

2. Experimental

Pulsed laser deposition (PLD) was used to apply Cr coatings on the outer surface of Zircaloy-4 rings. The cross-sectional structure of the as-received coatings was examined using transmission electron microscopy (TEM), with sample foils prepared via the focused ion beam (FIB) technique. Advanced Expansion-Due-to Compression (A-EDC) tests were conducted on the as-deposited specimens, using cylindrical pellets of Cu and stainless steel 316L, at RT and 573K, respectively. Young's modulus and nano-hardness were measured by nano-indentation at various indent depths. Residual stress at RT was determined using the d-$\sin^2(\psi)$ method by X-ray diffraction (XRD).

3. Results

The Cr coatings, 350 nm thick, have a bi-layer structure: a 130 nm amorphous layer and a 220 nm nano-crystalline layer. Their Young's modulus and residual stress are 227 GPa and -1.4 GPa, respectively. In A-EDC tests, transverse surface cracks perpendicular to the tensile direction and slanted cracks at a 45° angle appeared, indicating strong adhesion and strain transfer from the Zry-4 substrate. The crack density-strain relationship shows three stages: no cracking, rapid crack increase, and saturation, with slanted cracks forming after transverse ones. At 573K, the first crack forms at a strain of 0.07, higher than at RT (0.03), suggesting increased ductility due to a brittle-to-ductile transition. This implies superior fracture strength (~5.9 GPa) for the Cr coating with the nature of brittleness of Cr at RT, though determining its exact behavior remains challenging due to the unclear DBTT window for the nano-crystalline/amorphous structure.