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Scratch Hardness Evaluation of CrAl-Coated Cladding for Accident-Tolerant Fuel

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1. Introduction

Surface-modified claddings for accident-tolerant fuel have being developed to increase their oxidation resistances and mechanical strength in high temperature considering postulated (beyond) design-basis accident scenarios [1,2]. These protective layers on conventional Zr-based claddings by various surface modification techniques are great steps forward in introducing lead test rods or assemblies in commercial reactors. Kim and Jung [3~5] demonstrated their outstanding corrosion resistance and mechanical properties of surface-modified cladding candidates in normal operation and corrosive environments in severe accident conditions. In normal operations, the reliability of these coating layers should be maintained as a starting point for successful applications of accident-tolerant fuel cladding. Thus, the mechanical behaviors of these coating layer should verified with reasonable methods regardless of their outstanding corrosion resistance in high temperature steam. In this study, scratch hardness tests have been performed to evaluate adhesion strength and deformation behavior of coating layers with CrAl-coated cladding candidates by an Arc Ion Plating (AIP) method.

2. Methods and Results

2.1. Scratch hardness

A scratch hardness is defined as resistance of a solid surface to penetration by a moving stylus [6] and expressed as follows;

$$HS_p = kP/w^2 \qquad (1)$$

where, HS_p is scratch hardness number, k geometrical constant, P applied normal force and w scratch width. Thus, HS_p means the ability of a material to resist plastic deformation, usually scratches and abrasion.

2.2. Samples, Tester and Conditions

Four kinds of CrAl-coated cladding samples were prepared by AIP method with different bias voltage. After coating process, cladding surface was polished to maintain suitable roughness level of commercial Zr-based cladding. Their characteristics are summarized in Table 1 and Zr-based cladding also prepared as reference data.

Table 1. Summary of cladding samples

Label	Zr	1-250V	2-150V	3-100V	4-130V
T [μm]	N/A	40~50	40~60	10~30	40~60
Ra [μm]	0.3	0.324	0.212	0.127	0.292
Bias V[V]	N/A	250	150	100	130

In this study, a scratch tester for evaluating the deformation behavior of coating layer was specially designed [7] and modified for applying constant force shown in Fig. 1. This system has a hard stylus in the form of a 83º cone with a spherical tip of radius 120 μm. Normal loads was applied to cladding specimen with 10~50 N by adjusting dead weight. Three kinds of scratching speed (i.e., 0.1, 1.0 and 5 mm/s) was applied with stroke length of 5 mm. For each test, a minimum three scratches were made.

Fig. 1. A specially-designed scratch tester for evaluating CrAl -coated cladding layer on conventional Zr-based alloys.

2.3 Stylus Drag Coefficient (D_{sc})

Stylus drag coefficient (D_{sc}) can be defined as the dimensionless ratio of the scratching force to the normal force applied to the stylus [6] as expressed in (2).

$$D_{sc} = F_{scr} / P \qquad (2)$$

where, F_{scr} is average scratching force along the length of the scratch and P is normal force. This value is quite similar with the kinetic friction coefficient, but difference is that D_{sc} is the resistance to the surface deformation, not to sliding against the test specimen. Fig. 2 shows typical result of D_{sc} measurement during the scratching tests. In this study, CrAl-coated layer were fabricated with different bias voltage, which influence on hardness. The value of D_{sc} increased as the bias voltage increased (i.e., 3-4-2-1). The lower D_{sc} value of CrAl coating at 3-100V condition explained by diminution of grain size and the induction of residual stress. Thus, 3-100V condition expects to have high bulk hardness of coating layer and more resistance to plastic deformation.

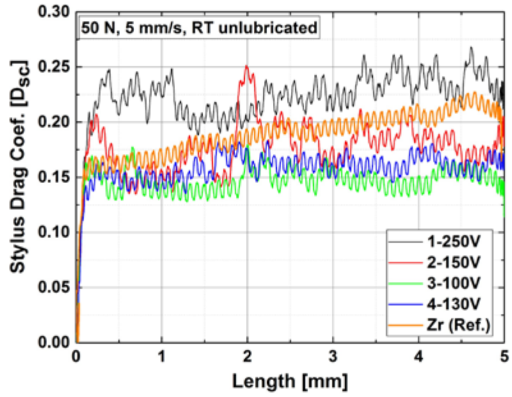

Fig. 2. Variation of D_{sc} at each specimen at 50 N of dead weight and 5 mm/s of stroke speed.

2.4 Scratch Hardness (HS_p)

HS_p values of each coating condition were determined by measurement results of scratch width and applied dead weight as shown in Fig. 3. Although 1-250V condition shows repeatedly fluctuation with dead weight, HS_p gradually decreased with further increase of negative bias voltage above -100V. This behavior seems to be attributed to the microstructural change of CrAl coating. With increasing dead weight, as expected, HS_p gradually increased due to the change of stress state, which depends on the contact geometry and the normal load. Fig. 4 shows typical deformation behavior of 3-100 V condition and no cracking occurred during the scratching tests. Based on above result, relatively lower bias voltage is more desirable to increase bulk hardness of CrAl coating layer on Zr-based cladding.

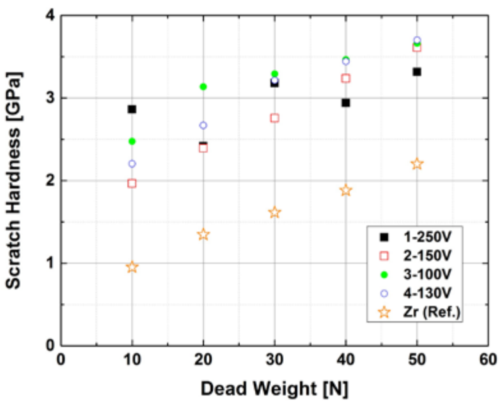

Fig. 3. Results of HSp evaluation with CrAl-coated cladding and comparison with commercial Zr-based cladding.

3. Summary

Scratch hardness tests have been performed to evaluate adhesion strength and deformation behavior of coating layers with CrAl-coated cladding candidates by an Arc Ion Plating (AIP) method. Application of lower bias voltage results in a high bulk hardness of coating layer and more resistance to plastic deformation. Further study will be focused on relationship between bulk hardness and microstructural changes of CrAl coating layer.

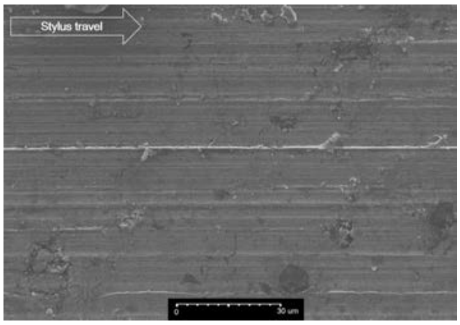

Fig. 4. Typical result of deformed trace of 3-100V condition at 50 N, 5 mm/s, unlubricated scratching test.

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