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Deep-Notch Type Micro Tensile Test of Cr-Coated Zircaloy-4 for Interface Characterization

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1. Introduction

Zirconium-based alloy is an important material for cladding, owing to its low neutron absorption cross section. However, a major limitation is their poor oxidation resistance. To mitigate this, extensive research has focused on applying chromium (Cr) coatings to the cladding surface to enhance oxidation resistance under both normal operating conditions and accident scenarios. Sustained oxidation resistance performance requires that the Cr layer remain well bonded and resist delamination; accordingly, adhesion has often been assessed at the macroscopic scale. For example, Kim et al. (2015) investigated 3D laser–deposited Cr on Zircaloy-4 and reported higher strength than uncoated specimens along with excellent interfacial adhesion under ring-compression and tensile loading [1].

In this study, microtensile testing, which contains a bilateral deep-notch, was employed to evaluate the zirconium-chromium interface, such as interface failure stress and fracture toughness characteristics, on a micron scale.

2. Methods and Results

2.1 Sample preparation

In this study, microtensile specimens were manufactured using a Zircaloy-4 tube coated with a Cr layer of approximately 10 µm in thickness, deposited by arc ion plating (AIP). Microtensile specimens were fabricated by focused ion beam (FIB), and the detailed geometries are shown in Figure 1 (a). To promote the interfacial failure, a deep sharp notch was added on the middle section of the gauge, which is the Zr/Cr interface region. After the final fabrication, the SEM images in Figure 1 (b).

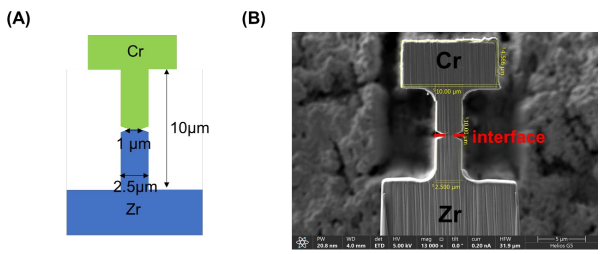

Fig. 1. (a) Schematic of the deep-notch interface (DN – interface) microtensile specimen and (b) SEM image

2.2 Microtensile test results

Microtensile specimen tests were conducted under displacement-controlled loading at 10^{-3} /s using the nanoindenter (InSEM, KLA). In this study, 4 specimens were tested. Figure 2 shows the SEM images of the fractured specimens after testing. As shown in Figure 2 (a), a fracture occurred in the notched part of the specimen, with delamination at the Zr/Cr interface, and this was consistent for all 4 samples. It can be confirmed clearly from the top view with the precence of a notched surface in Figure 2 (b). A load-displacement curve was obtained, and the results are shown in Figure 3. From the obtained load-displacement curve, nominal failure stress and strain to fracture were evaluated by Equation 1. Also, analytical fracture toughness was evaluated by Equation 2, which is derived for the ideal sharp bilateral notch hypothesis [2].

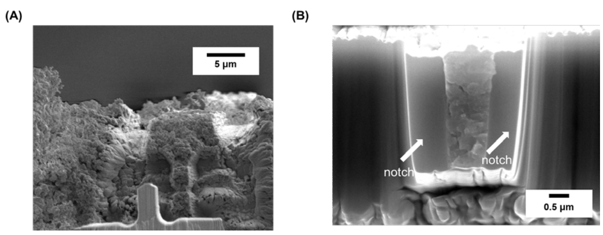

Fig. 2. SEM image of fractured microtensile specimen after tensile test of (a) front view and (b) top view

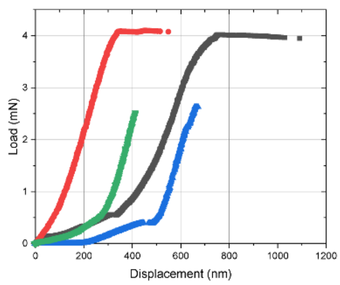

Fig. 3. Microtensile test raw load-displacement results

$$\varepsilon = \frac{\Delta L}{L}$$

$$\sigma_{nominal} = \frac{load}{gauge\ width\ * thickness}$$

$$\sigma_{failure} = nominal\ failure\ stress$$

Eq. 1. Strain to fracture and failure stress of DN - interface

$$K_{IC} = \sigma_{failure}\sqrt{\pi a} \times F\left(\frac{2a}{b}\right)$$

$$F\left(\frac{2a}{b}\right) = \frac{1.122 - 0.561\left(\frac{2a}{b}\right) - 0.205\left(\frac{2a}{b}\right)^2 + 0.471\left(\frac{2a}{b}\right)^3 - 0.190\left(\frac{2a}{b}\right)^4}{\sqrt{1 - \frac{2a}{b}}}$$

a : $crack\ length$
b : $gauge\ width$

Eq. 2. Analytical fracture toughness with ideal sharp notch hypothesis by Tada et al [2].

3. Conclusion

In this study, microtensile tests were conducted to investigate the interfacial characteristics of Cr-coated Zircaloy-4 cladding, focusing on the adhesion behavior and mechanical performance at the microscale. Microtensile specimens were fabricated using a Zircaloy-4 tube coated with a Cr layer deposited by arc ion plating.

The test results showed that fractures consistently occurred in the notched region, which is the Zr/Cr interface. From the deep-notch type microtensile test, interfacial failure stress and fracture toughness of the Zr/Cr interface could be evaluated. Future work will focus on FEM based fracture toughness evaluation to validate the current results and detailed fracture surface analysis.

ACKNOWLEDGMENT

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