Impact and Fretting Wear Behaviors of Cr-coated Multi-layer Fuel Cladding for Accident-Tolerant Fuel

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1. Introduction

During the development of accident-tolerant fuel (ATF) cladding, an oxide-dispersion-strengthened (ODS) treatment was proposed by modifying surface characteristics with introducing Yttrium oxide (Y_2O_3) particles to improve mechanical strength of Zr-based nuclear fuel rod at high temperatures [1,2]. From the previous results, the ODS layer by laser beam scanning (LBS) treatment was stably formed on the Zr cladding surface without any significant defect, which confirmed that its mechanical strength considerably improved about 20% at high temperatures even though there are little changes in room temperature [3]. After the LBS treatment, however, corrosion resistance of the ODS layer was significantly reduced under the influence of unintended microstructures (i.e., HAZ by welding process) due to melting and rapid solidification. Therefore, additional coating is required to prevent these corrosion-sensitive surfaces in operating PWR environments. This multi-coated fuel cladding is one of the representative ATF candidates which can improve the resistance to corrosion in high temperature steam as well as mechanical strength. The key factor determining the enhanced accident tolerance by applying ATF cladding is to maintain the integrity of applied coating layer without significant degradation during the normal operations. The previous studies showed that Cr or Cr-alloy coating layers show outstanding fretting wear resistance by improved mechanical strength of the coating layer [4,5]. During the normal operations, however, contact conditions between cladding and grid can be changed from fretting to impacting wear due to spring relaxation and irradiation. Thus, the coated cladding should be verified for wear damages or crack formation under the impacting force contact. This is because thin coating layer is vulnerable to impact contact. The objective of this study is to experimentally evaluate the impact wear behavior of the Cr-coated Zr claddings with and without ODS layer.

2. Experiments and Results

Fig. 1(a) shows a multi-layer coating concept, which used in this study. The Zr fuel claddings with and without the ODS treatment were prepared and the outer Cr coating layer was formed by an arc ion plating with a thickness of 15~20 μm. The impact wear test was performed using a specially designed tester as shown in Fig. 1(b). The coated fuel cladding was vibrated in the axial direction with a peak-to-peak amplitude of 100 μm and a frequency of 30 Hz. The grid specimen, which was developed in KAERI, was impacted on the coated cladding at radial direction with a peak impact force of 3 N, a stroke length of 200 μm and a frequency of 30 Hz. For the comparison with conventional fretting wear results, additional test without impact motion under the constant contact force of 3 N also carried out at the same axial vibration condition. All tests were performed in room temperature water up to 2.4 x 10^6 cycles at least 3 times.

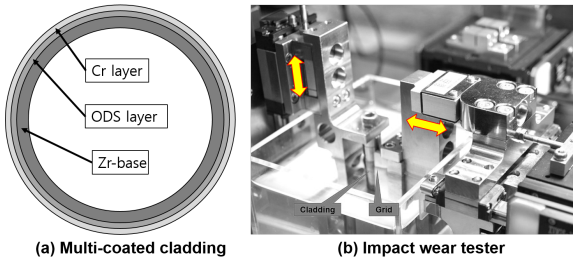


Fig. 1. Multi-coated cladding concept and an impact wear tester used in this study.

Fig. 2 shows the impact wear test results of Cr-coated Zr cladding with and without ODS treatment at each test condition. It can be seen that the wear volume and depth results at constant contact force of 3 N (i.e., no impact) shows different wear behaviors according to the internal ODS layer when compared to the results of the impact wear. In case of Cr-coated ODS cladding under a constant contact force of 3N, its wear volume was negligible, but the Cr-coated Zr cladding (i.e., no ODS layer) was significantly increased. This behavior was similarly observed at the results of the maximum wear depth. Thus, the ODS layer, which was formed on the Zr cladding has a beneficial effect for decreasing wear damages of the outermost Cr coating layer. When the ODS layer is generated by LBS treatment, the surface roughness of the ODS layer gradually increases due to the irregular HAZ distribution under melting and rapid solidification process. Therefore, the adhesion strength between the Cr coating and the ODS layer is relatively increased enough to reduce friction of this thin Cr coating layer if there is no pore at the interfacial region.

When repeated impact force is applied, however, localized wear damages of both Cr coating layers can be generated at random contacts within each worn area, which expected to have similar wear damages at the outermost Cr coating layer. Above all, this impacting contact can generate a rather flat worn surface by plastic deformation of Cr coating layer even though detached wear debris can be rarely found on worn surface.

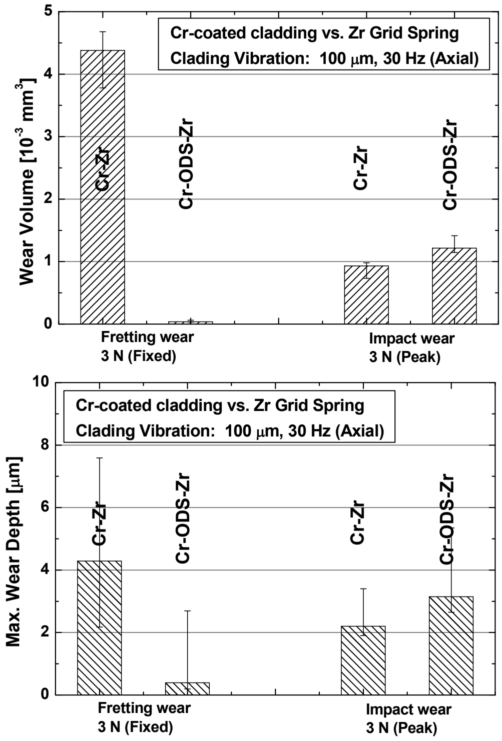
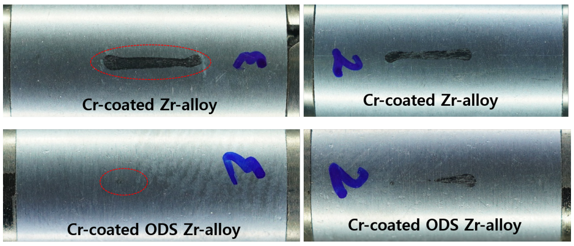


Fig. 2. Measured wear volume and maximum wear depth of Cr-coated cladding with and without ODS treatment against Zr spacer grid.

Fig. 3 shows typical worn surface of Cr-coated Zr cladding with and without ODS layer. As expected, the Cr-coated ODS cladding shows almost no wear damages under constant contact force. In this condition, the plastic deformation of the Cr coating layer could be limited to the thickness direction, which results in a negligible wear damages. In the impact wear condition, however, the ODS layer had little effect on the resistance to wear damage because the localized wear rather than the severe plastic deformation was dominant on the outermost Cr coating layer. From the test results, the ODS-based multi-layer for the ATF cladding has good wear resistance in both fretting and impact wear.



Normal force: 3N, Fixed   Impact force: 3N (Peak)

Fig. 3. Typical results of worn surface of Cr and Cr-ODS coated Zr cladding after fretting and impact wear tests.

3. Summary

The impact wear characteristics of Cr-coated Zr cladding with and without ODS treatment for ATF cladding were experimentally evaluated. The Cr-ODS Zr cladding has a good resistance to fretting and impact wear against Zr-based spacer grid.

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