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Frictional Behaviors of Surface-treated Zr-based Cladding with Different Coating Thickness

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1. Introduction

As one of the strong candidates of accident-tolerant fuel (ATF) cladding, surface-treated Zr-based claddings have being developed to increase high temperature oxidation resistance and mechanical strength [1, 2]. Various coating methods (i.e., Arc ion plating, cold spray, laser beam scanning, etc.) are applied to form protective layers on current Zr-based cladding surface with high corrosion resistant alloys and oxides. Previous results [3~5] indicated that their outstanding corrosion resistance showed a decrease of corrosion rate by at least two orders of magnitudes at normal operation and simulated severe accident conditions. However, optimized thickness of coated layers on Zr-based cladding should be considered for maintaining the reliability of these layers under both mechanical contacts in normal operation and corrosive environments in severe accident conditions.

Generally, the minor alloying elements such as Zn, Nb in Zr-based alloys influenced grid-to-rod fretting (GTRF) to a lesser degree but has a strong dependence on the grid-to-rod gap as a function of burnup under presence of excessive flow-induced vibration [6]. In this study, simplified GTRF tests have been performed with surface-treated Zr-based claddings using an arc ion plating (AIP) method with high corrosion resistant alloys in room temperature water. The objective is to evaluate the variation of frictional behaviors with the thickness of coating layer against current Zr-based spacer grid.

Table 1. Summary of cladding samples

Label	T10	T40	T55
Average thickness	10 μm	40 μm	55 μm
Surface roughness (Ra)	0.12 μm	0.32 μm	0.29 μm
Cladding OD (mm)	9.52	9.58	9.61

2. Methods and Results

2.1. Samples and Test Conditions

Three kinds of surface-treated Zr-based claddings were manufactured by an AIP method and their properties are summarized in Table 1. The coating layers were formed by CrAl alloy. Also, Zr-based spacer grid was prepared for simulating GTRF contacts in normal operating condition. The tests were carried out under a normal load of 10 N, a relative slip amplitude of 100 μm, number of cycles of 10^5~10^6, and a frequency of 30 Hz in room temperature water. During the fretting wear tests, normal, shear force and displacement were measured for evaluating the variation of contact conditions and its frictional behavior. Details of this tester and sample arrays were illustrated in Fig.1.

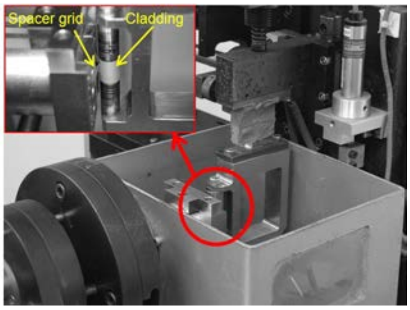

Fig. 1. Schematic view of tester and samples used in this study.

2.2. Wear Results & Frictional Behavior

After fretting wear tests, wear amounts were measured and their results are summarized in Table 2. Regardless of coating thickness, wear volume gradually increased with number of cycles and there is no significant difference at $1x10^6$ cycles even though transition cycles are dependent on the coating thickness. However, higher maximum wear depth appeared in T10 conditions, which has the thinnest layer on Zr cladding. In this test, coating thickness of T10 has ~10 μm. So, this layer are removed by interacting with Zr-based spacer grid under the fretting condition.

Table 2. Wear measurement results

No. of cycles	T10	T40	T55
	Mean wear volume [x 10^{-3} mm^3]		
1 x 10^5	1.7	2.5	2.0
5 x 10^5	6.2	11.4	8.0
1 x 10^6	14.8	14.0	14.8
	Max. wear depth [μm]		
1 x 10^5	5.9	7.1	6.4
5 x 10^5	6.8	8.6	10.6
1 x 10^6	18.4	12.7	13.8

Fig. 2 shows the variation of coefficient of friction (COF, μ_{rms}) at each test condition. The results indicated that the variations of COF values have a strong dependence on the coating thickness. At T40 and T55 conditions, it is difficult to find repeated drops and shows saturated values with increasing number of cycles. At initial cycles, increasing COF values means relatively high roughness effects and these effects are disappeared up to $1x10^5$ cycles and then show gradually stable. However, T10 condition shows no initial roughness effect due to its lower roughness value and repeated COF drops can be distinguished at middle cycle region. So, failure of coating layer at T10 condition are expected to initiate after $2x10^5$ cycles.

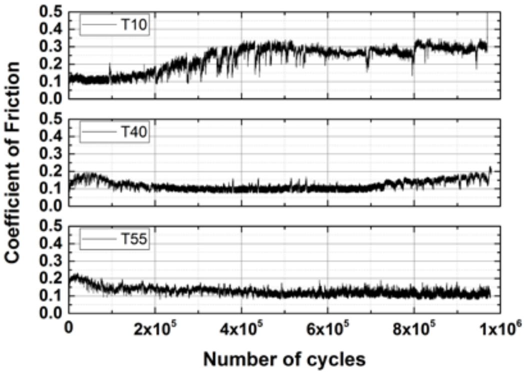

Fig. 2. COF variation of surface-treated Zr-based claddings at room temperature water against Zr spacer grid.

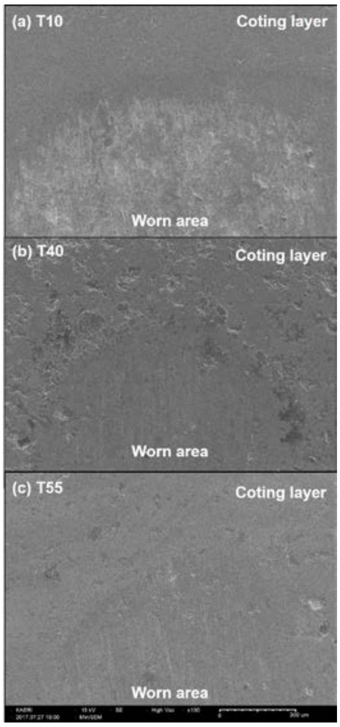

Fig. 3. Typical results of worn surfaces (Top region) of surface-treated Zr-based claddings.

2.3. Worn surface

Fig. 3 shows typical results of worn surfaces at 10^6 cycles. For comparing wear mechanism, top region of each worn surface are observed. At T10 condition, coating layers are partially removed, and distinct reciprocating motion on wear tracks and wear debris are detached from repeated deformation of coating layer. However, there are some grooves on coating layers of T40 and T55 conditions, which are expected to generate during post-polishing process. These are act as load-bearing layers for both decreasing COF value and trapping wear debris under fretting condition. In addition, it is difficult to find the severe wear marks and cracking behavior of coating layers regardless of localized contact region. Thus, both the initial surface conditions and their lower COF values showed negligible wear damages with increasing the number of cycles.

3. Conclusions

Frictional behaviors of surface-treated Zr-based fuel rod using an arc ion plating method with CrAl alloys are examined against Zr spacer grids in room temperature water. Thin coating layer was easily failed by simulated fretting wear condition but coating thickness above 40 μm showed relatively outstanding effects for preventing mechanical contact damages due to the initial surface conditions and their lower coefficient of friction values.

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