TRIBOLOGICAL EVALUATION OF SURFACE MODIFIED ZR-BASED FUEL CLADDING WITH CORROSION RESISTANT COATING

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ABSTRACT: *Surface-modified Zr-based fuel claddings are one of the primary candidates for Accident-Tolerant Fuel (ATF) claddings because of their excellent high-temperature strength and resistance to high-temperature steam oxidation under simulated accident conditions. In this study, two types of coated Zr-based claddings have been prepared focusing on the evaluation of fretting wear resistance against current Zr-based spacer grids: FeCrAl alloys with Cr layers (FCA/C) and FeCrAl alloys with Mo layers (FCA/M) on Zr-based cladding using a cold spray coating. This study aims at evaluating the characteristics of the inner layer dependences of the fretting wear mechanisms to provide the possibilities of current Zr-based spacer grids as support structures. Friction coefficients of the both cladding candidates were strongly influenced by surface roughness regardless of the inner layer types. The wear depth results for some FCA/M exceed the outer layer of the coating materials at a given number of cycles. Based on the test results, the fretting wear behaviors of surface-modified cladding for ATF were examined focusing on the application of current Zr-based spacer grids without or minimum changes of their tribological characteristics.*

KEYWORDS: *Accident-tolerant fuel, surface modification, spacer grid, grid-to-rod fretting, friction coefficient*

I. INTRODUCTION

After a failure of the outer containments by the hydrogen explosions at the Fukushima power plants, new fuel systems with enhanced corrosion resistance to high-temperature steam (i.e., accident-tolerant fuel, ATF) have been proposed for mitigating the hydrogen generation by replacing current Zr-based fuel claddings [1-6]. Recent progresses in ATF development indicate that irradiation tests in in-reactor environments have started to qualify the irradiation performance of various ATF cladding candidates, including corrosion, creep, and irradiation growth [7, 8]. However, such research has focused on the corrosion resistance during accident conditions, and there remains a lack of data under normal operating conditions. For example, a grid-to-rod fretting (GTRF) failure is known as one of the severe failure mechanisms under normal operation. Above all, the proposed ATF cladding candidates have different surface conditions such as completely different materials or surface modification of current Zr-based claddings [9]. This means that tribological compatibilities between ATF cladding candidates and the current Zr-based spacer grid should be examined during the initial development stage. In this paper, fretting wear behaviors of two types of coated Zr-based claddings have been examined against the current Zr-based spacer grid in room-temperature water focusing on the reliability of the coated layer on Zr-based claddings.

II. EXPERIMENTS

Two kinds of surface-coated cladding on Zr-based alloy were manufactured using a cold spray coating method: FeCrAl alloys with Cr layers (FCA/C) and the same alloys with Mo layers (FCA/M) on Zr-based claddings. In addition, Zr-based spacer grid specimens were prepared, as shown in Fig. 1(a). Before the fretting tests, FCA/C cladding maintained its original coating layer, but FCA/M cladding was post-polished to compare the wear behavior of Zr-based cladding. Thus, the initial contact between the cladding and grid is made by the FCA coating layer and Zr-based spacer grid with different coating thicknesses and roughness values. The fretting wear tests were carried out under a normal load of 10 N, a relative slip amplitude of 100 μm, a number of cycles of 10^5 to 10^6, and a frequency of 30 Hz in room-temperature water. As shown in Fig. 1(b), the ATF cladding specimen vertically vibrates with lateral contact force by the spacer grid spring. During the fretting wear tests, normal force, shear force, and displacement were measured to evaluate the supportability of the current Zr-based spacer grid and its characteristics of frictional behavior.

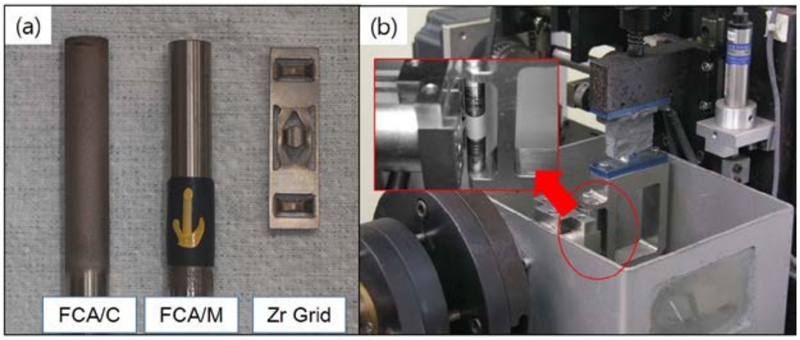


Fig. 1. (a) Surface-modified cladding and Zr-based spacer grid, and (b) fretting wear tester used in this study.

III. RESULTS AND DISCUSSION

III.A. Wear behavior

After the fretting wear tests, wear marks of each cladding specimen were analyzed using a visual measurement system, and typical results are shown in Fig. 2. In the worn surface of FCA/C cladding, it is apparent that the coated layer has a rough surface, and wear damage is difficult to define because of its high roughness value (i.e., R_a=4.68 μm). Thus, the coating layer of FCA/C cladding still adheres to the Zr matrix after the fretting tests. However, the Zr spacer grid shows severe wear damage and irregular contact by the coated particles on the FCA/C cladding surface. The results of FCA/M cladding show a significantly different behavior, which is a remarkable effect of post-polishing treatment. The coating layer seems to be removed by localized contacts, and severe oxidation is dispersed around the periphery of the wear scar, which is expected by the wear debris oxidation. Owing to this localized wear, the coating layer of FCA/M cladding is removed, and Zr-matrix is exposed to a test environment. Thus, the rough surface of the FCA coating layer is effective in increasing the wear resistance, but accelerates the fretting damage of the Zr spacer grid. In contrast, the post-polished FCA coating with a relatively thin layer was removed through localized wear. Therefore, a sufficient coating layer thickness should be considered to maintain the wear resistance against a Zr spacer grid after post-polishing treatment.

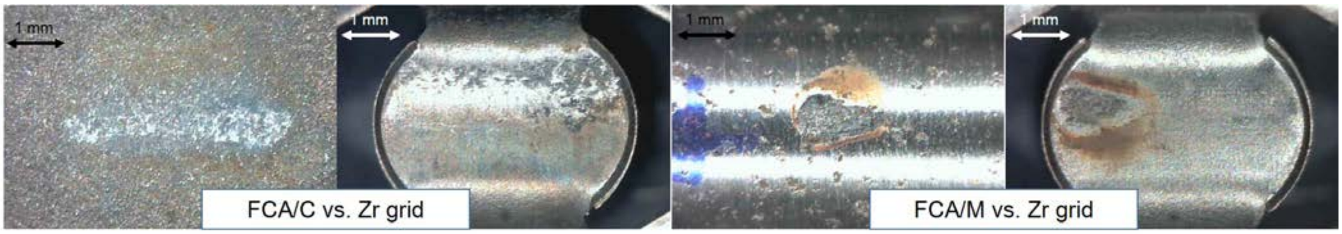


Fig. 2. Typical results of worn surface for each cladding and spacer grid specimen.

III.B. Contact force

Fig. 3 shows the variation of contact force with an increasing number of cycles. In this study, the initial contact force between the cladding and grid was fixed by a spring force with elastically deformable contact. If this contact force is decreased during the fretting tests, it is due to the material removal at the contacting surfaces and/or relaxation of the grid spring. Under the same Zr grid specimen, the rapid decrease in FCA/C cladding against the Zr grid indicates an excessive wear progression at the Zr spacer grid. When considering the supportability of ATF cladding with a Zr-based spacer grid, a rapid drop of initial contact force means the strong possibility of severe wear damage or the formation of a fatigue crack on the coating layers during normal operation. Thus, the wear resistance of a spacer grid for ATF cladding candidates should be considered to maintain the reliability of the coating layers.

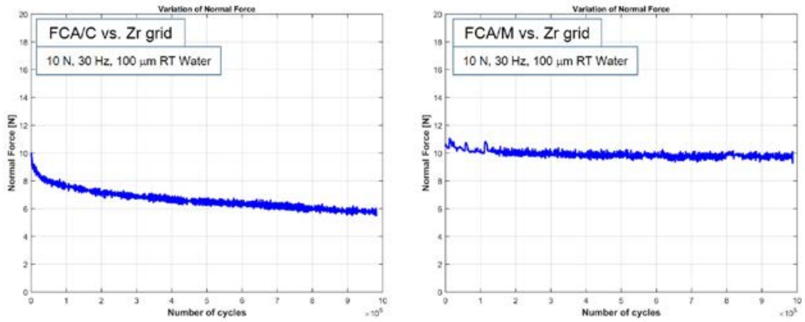
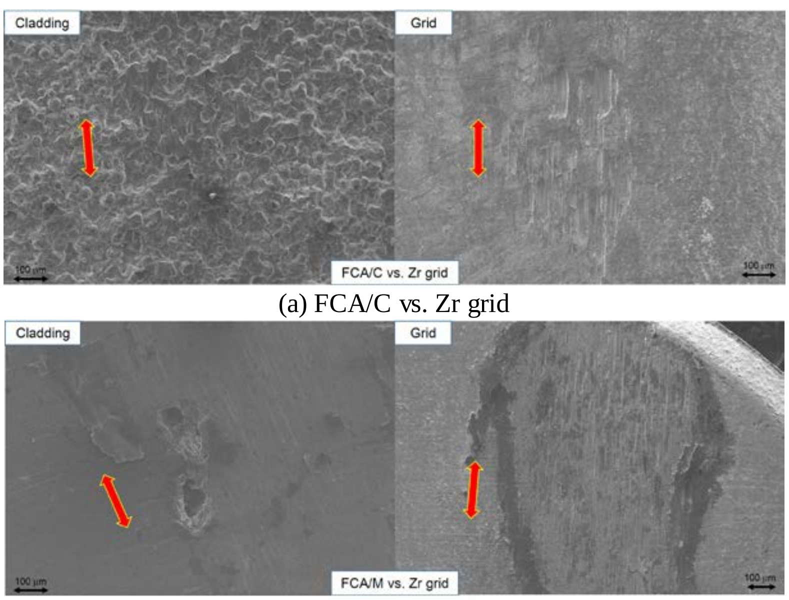


Fig. 3. Variation of contact force with increasing number of cycles under each test condition.

III.C. Wear mechanism

Fig. 4 shows the results of the worn surface morphologies for each test condition. It is apparent that the surface of the FCA/C cladding has irregularly round-shaped dimples, which are strongly adhered to the base cladding materials. In Fig. 4(a), there is negligible wear damage of the FCA/C cladding surface, and these dimples play an important role as a load-bearing layer for reducing the frictional behavior. However, severe wear damage to a Zr grid occurred, and the predominant wear mechanism seems to be abrasive wear by these hard dimples. In the FCA/M result, however, these dimples are removed after post-polishing treatment, which results in a different wear mechanism, as shown in Fig. 4(b). In both the cladding and grid specimens, severe deformed layers were well-developed, and wear debris was removed by the fracture of these deformed layers. In particular, the worn area of FCA/M cladding shows localized spallation of the coating layer. These thin layers failed with the Zr cladding matrix by a locally cohesive failure after the formation of a deformed layer, crack propagation, and wear debris generation because of the hardening difference between the coating layer and Zr-based cladding. Thus, the adhesion strength of FCA coating layers is enough to prevent delamination or adhesive failure, but their thickness should be increased for accommodating the severe plastic deformation of the contacting surfaces.



(a) FCA/C vs. Zr grid

(b) FCA/M vs. Zr grid

Fig. 4. Typical results of worn surface morphologies in room temperature water.

IV. CONCLUSIONS

In this study, the fretting wear behaviors of the FeCrAl coating layer on Zr-based cladding have been examined using a Zr-based spacer grid focusing on the application of current Zr-based spacer grids with minimum or no changes of their tribological characteristics. The as-received FeCrAl coating layer on Zr-based cladding is effective for increasing its wear resistance, but accelerates the fretting damage of the Zr spacer grid owing to their differences in hardness. However, a post-polished FeCrAl coating was removed by localized adhesive wear after severe plastic deformation. Thus, the adhesion strength of FeCrAl coating layers is sufficient to prevent delamination or adhesive failure, but their thickness should be increased to accommodate severe plastic deformation under fretting wear conditions.

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