Three-Point Bending Test for Metal-Ceramic Hybrid Fuel Cladding Tubes

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1. Introduction

Since 2012, the Korea Atomic Energy Research Institute (KAERI) has launched a national R&D project to develop suppressed hydrogen-release fuel cladding tubes. A metal-ceramic hybrid cladding tube is one of these concepts. The tube forms composite ceramic layers on the zirconium alloy cladding tubes to enhance their stability during all accidents, as well as to prevent them from generating hydrogen gas under severe accidents (see Fig. 1).

The new tubes can be made in the following two stages: first, producing zirconium alloy tubes, and second, forming ceramic composites on the tubes [1,2]. The first stage of the fabrication is the same as a conventional manufacturing process for zirconium fuel cladding tubes. The inner tube was produced from a Zr-alloy ingot by repeating the pilgering and annealing. The second stage covers the fabrication of a SiC ceramic fiber composite. The SiC-fiber filament is wound on the Zr tube. The hetero interface between Zr metal and SiC ceramic can be adjusted with compliant media to minimize the material incoherence. The empty space within the fiber-wound perform is then filled with SiC-based preceramic polymer. Finally, the cladding tube is completed with surface coating.

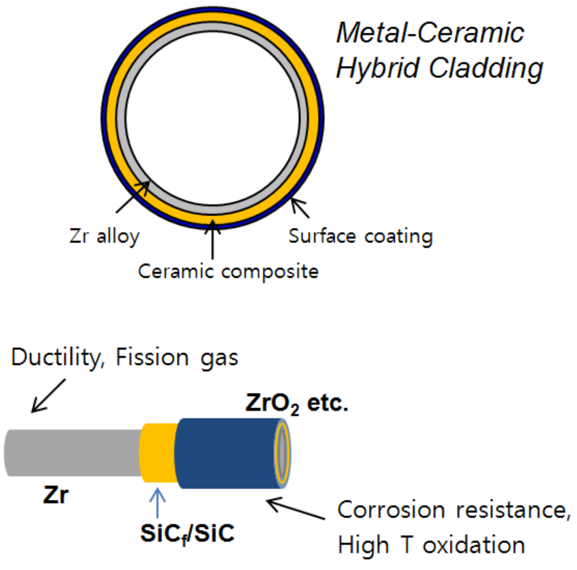

Fig. 1. Schematic illustration of metal-ceramic hybrid fuel cladding tubes.

In the current study, mechanical properties of the metal-ceramic hybrid cladding tube were analyzed using a three-point bend test. Strengthening by the ceramic composite layer was realized. However, the effect was offset due to the additional heat-treatment process for the fabrication of the ceramic composite layer.

2. Methods

The developed Zr tubes of HANA-2 with dimensions of 9.5 mm in outer diameter and 0.57 mm in thickness were filament wound by a commercial SiC fiber of Tyranno-S (Ube industry, Japan). The band-width of one filament wound on the Zr tube was 3.5–3.7 mm. The average thickness of the fiber-wound layer was about 0.81 mm after two complete spans of filament winding. The filament winding was performed under either dry or wet condition. For the impregnation, a synthesized preceramic polymer of polycarbosilane (ToBeMTech, Korea) was used to fill the open space within the fiber-wound layer. The prepared filament wound Zr tube was dipped in a polycarbosilane-dissolved *n*-hexane and divinylbenzne mixed solution. Polymer impregnation was performed under a low vacuum of 60–70 kPa. The immersed composite tube was dried and cured in air at 600°C. The samples were prepared by repeating the impregnation and pyrolysis process three times. (additional information in [3]) Several tubes were coated by Zr using a physical vapor deposition to form an interphase (prior to the matrix formation) and/or a surface layer. Fig. 2 shows the fabricated samples. Then, three-point and four-point bend tests were performed as shown in Fig. 3. The span length for the three-point bend test was 125 mm (L), and those for the four-point bend test were 35 mm (Li) and 110 mm (L). The bending stress was calculated as

$$\sigma = \frac{P(L - L_i)r_o}{\pi(r_o^4 - r_i^4)}$$

where P is the bending load, and r the dimension of the cladding tube. Bending was applied within an elastic range in the case of a four-point bend; however, it was induced to cause a permanent deformation in the case of a three-point bend.

3. Results and Discussion

Fig. 4 demonstrates the test results for the flexural load and stress for the bending. The behavior was compared with the claddings without a composite layer: one is fresh and the other is the cladding undergoing identical heat-treatment for the fabrication of the composite layer. In terms of the flexural load, metal-ceramic hybrid tubes showed a higher bending strength as compared to the Zr-only tube with the same thermal history (green curves to red curves in Fig. 4(a) and 4(c)). This suggests that the composite layer attributed to the strengthening of the metallic tubes. However, this effect disappeared when stress other than the load was considered. Since the hybrid cladding tube is thicker than the fresh cladding tube, it is no wonder the load for bending was increased in the hybrid cladding tubes. The flexural stress of the hybrid tube was lower than that of the existing tubes (green curves to red and blue curves in Fig. 4(b) and 4(d)).

For the hybrid tubes, additional heat-treatment should be accompanied. The heat-treatment reduced the stiffness of the fresh cladding tube (red curves to blue curves in Fig. 4). Although the reduced strength was recovered by the composite layer, the overall effect of strengthening should be reconsidered.

Fig. 2. Specimens for a three-point bend test that were fabricated differently: i) wet process, ii) wet process followed by a Zr surface coating, iii) wet process with a Zr interphase coating, and iv) wet process with a Zr interphase coating followed by a Zr surface coating.

Fig. 3. Specimen loaded on a three-point bend test.

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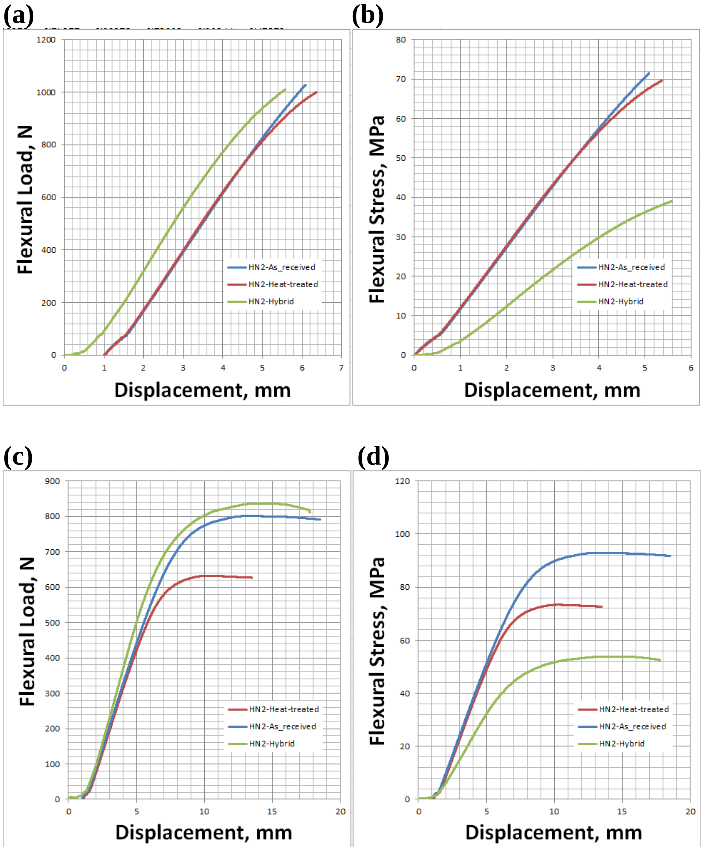

Fig 4. Test results of the four-point bending ((a)-(b)) and three-point bending ((c)-(d)) for the fabricated hybrid cladding tubes (green lines) and reference tubes (blue lines for fresh tubes and red lines for heat-treated metallic tubes), demonstrating flexural loads ((a) and (c)) and flexural stresses ((b) and (d)), respectively.