Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Enhanced ATF Cladding Thermal Stability in LOCA-like Simulations of PSTD

Unho Lee [a], Jong-Woo Kim [a], Ji-Hyeok Choi [a], and Young Soo Yoon [a]*
[a]Department of Materials Science and Engineering, Gachon University, Gyeonggi-do,13120
[*]Corresponding author: benedicto@gachon.ac.kr

1. Introduction

Nuclear power is difficult to accept socially and culturally due to safety issues. There have been many studies to realize the safety of nuclear reactors, such as the use of accident prevention fuels (ATFs) and extreme-situation simulations to maintain the safe operation of nuclear reactors. To solve the problem of safety in a nuclear reactor, a Stainless steel 316 (SUS316) tube is drawn outside the Zr-alloy cladding as Pseudo-Single Tube with Double layer (PSTD). Swaging-drawing is a very simple and operable process at room temperature. In particular, the strength of SS316L does not decrease significantly compared to Zr-alloys, which decrease in strength with increasing temperature. However, the thermal conductivity is low, and the thermal neutron absorption cross-sectional area is 10 times larger than that of the Zr alloy. In addition, due to the high strength and ductility, the cladding can be relatively thin and the manufacturing processability is excellent. Therefore, the Zr-alloy SUS316 cladding exhibits maximum performance during bonding. The Swaging-drawing process was used to improve the mechanical strength under high-temperature conditions Loss-of-Coolant Accident (LOCA). Swaging drawing applies a physical force toward the center of a tube with a large outer diameter. A tube of the desired size is formed by compression and tension. In this way, the multilayer fuel cladding increases the maximum allowable combustion and operating temperature of the fuel. Therefore, hydrogen generation is reduced, and stability and economy are improved.

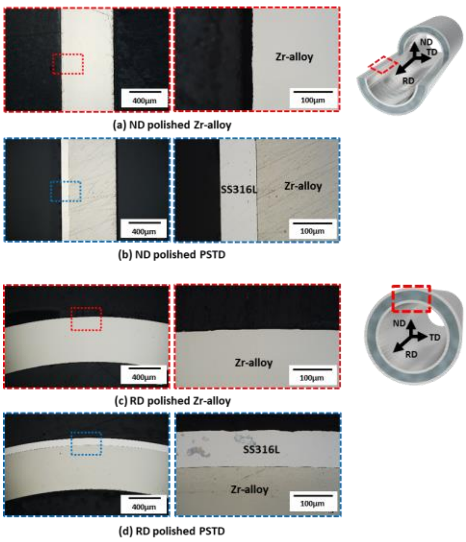

Fig. 1. Schematic of the PSTD drawing process with the sample placed in the die and the draw bench machine.

2. Methods and Results

2.1 Swaging and drawing process

The PSTD consists of a double-layer tube. The drawing process is carried out outside the Zr-alloy tube (outer diameter: 9.50mm, inner diameter 8.35mm, length 2.0m). The outer tube has SUS316 (outer diameter: 10.0mm, inner diameter: 9.60mm, length: 2.0m). Fig. 2. shows tube diameter, length, and size comparison. The PSTD was prepared by inserting the outer SUS316 tube in the Zr-alloy. Then drawing, adjust the size of the dies and draw to the desired outer diameter. The swaging process should be preceded, about 15cm in length of the multi-walled tube to hold the front part when drawing. The first was drawn once with 9.60Φ, 9.55Φ die, and the second the other was drawn with 9.50Φ. In order to secure the inner diameter, put a metal bullet of the desired size inside the tube. The 8.35Φ diameter cylindrical metal bullet was used to secure the inner diameter. The PSTD after double-walled tube drawing. It is confirmed that the length of the external SUS316 tube is about 1~2mm became longer than the length of the Zr-alloy tube.

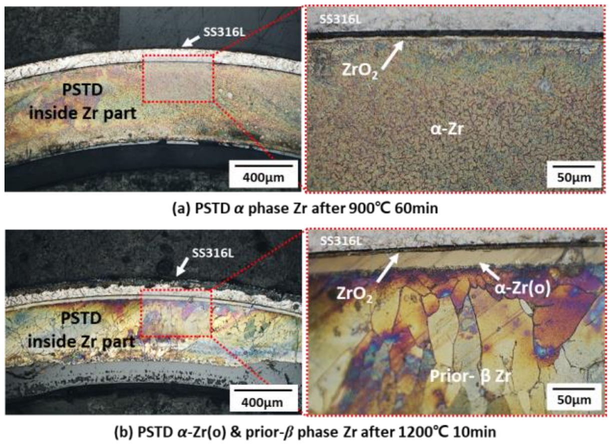

Fig. 2. Optical micrographs of etched PSTD showing the microstructure change after heat treatment.

2.2 Heat treatment test

Zr-alloy outer 9.5Φ and inner 8.35Φ PSTD cut into 1.5cm were prepared and a furnace was used for heat treatment. The three specimens were exposed to 600℃, 900℃, and 1200℃ respectively in air condition. Each condition was increased at a rate of 300℃/h, at room temperature. Each specimen was maintained at 600℃, 900℃, and 1200℃ for 10 min and decreased temperature naturally to room temperature.

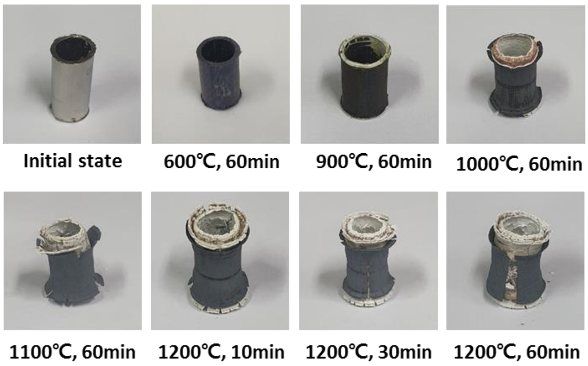

Fig. 3. 15mm machined cladding heat treatment results.

2.3 Results and discussion

The PSTD of oxidation resistance the properties under heat treatment at 600 ℃ was maintained for 60 min. There was a little different after the heat treatment at temperatures of 900 ℃ or higher the appearance of the PSTD was deformed into a short, curved surface that turned black because of the breakaway phenomenon. Under the heat treatment at temperatures of from 1000 ℃, 1100 ℃, and 1200 ℃, oxidation proceeded inside and outside the PSTD, resulting in brittleness and spallation visible to the naked eye. The PSTD on heat treatment had the formation of ZrO_2 along the rim of the sample, where the Zr-alloy part was exposed to the outside of SUS316 and hence oxidation. In the PSTD, subjected higher the inside of the specimen was also oxidized and turned dark gray in the same manner as the Zr-alloy. The SUS316 on the exterior surface was also oxidized, and it was observed that the color changed to a darker gray than before due to the formation of Fe-rich oxide film. Cracks occurred on the surface of the SUS316 layer of the specimen maintained at 1200 °C for 30 min, and when the SS316 layer was broken in the PSTD maintained for 60 min, rapid oxidation of the Zr-alloy part proceeded. Therefore, it is concluded that PSTD is oxidized more slowly compared to raw Zr-alloy up to the temperature of 1200 °C, but on the development of cracks in SUS316, the oxidation resistance rapidly decreases as the Zr alloy is exposed to the outside.

Table 1. Comparison of mechanical properties of metal materials for cladding

Property	Zr-alloy	SUS316
Tensile strength [Mpa]	514	558
Yield strength [Mpa]	381	290
Elastic Modulus, E [Gpa]	89	205
Poission's ratio, γ	0.35	0.28
Neutron absorption cross section [barn]	0.22	3.10
Melting point [°C]	1,850	1,450
Thermal conductivity [W/m·K]	21.5	17.0

3. Conclusions

In this study, we successfully fabricated an ATF cladding with the desired thickness using a SUS316 tube, which is thinner than that used in previous studies. The swaging and drawing process used applies to the production of cladding with 4 m length, which is difficult to access by the general coating process, and the process can be used to surface treat the inside of the PSTD as well. Although SUS316 is not an optimal material as a protective layer for ATF cladding, it has the advantage of easy processing and supply; therefore, it is used to verify the feasibility of the swaging and drawing process. As the next steps of this study, heterogeneous tubes other than SUS316, the formation of internal and external protective layers with a thickness of 50 µm or less, sample production of 4 m length, and various evaluations in the LOCA environment can be considered. Further analysis of the swaging and drawing process and additional studies on the interfacial integrity of heterogeneous tubes and Zr alloy are needed, but because ATF cladding with a length of approximately 2 m can be manufactured in large quantities, there is great potential for ATF in the future.

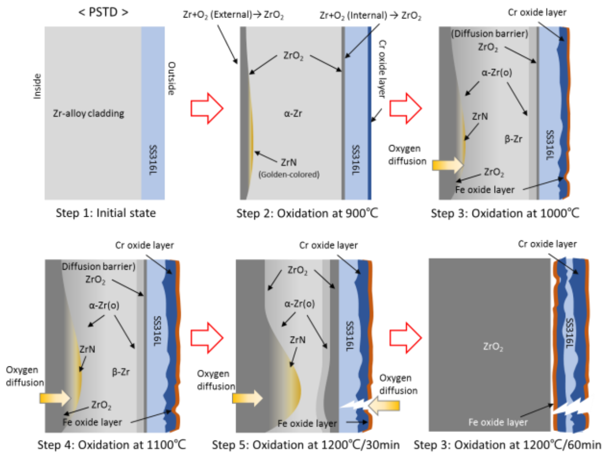

Fig. 4. PSTD oxidation mechanism schematic diagram.

REFERENCES

[1] Kim, Jong Woo, et al. "Study of structural stability at high temperature of pseudo-single tube with double layer as an alternative method for accident-tolerant fuel cladding." Journal of Nuclear Materials (2022): 153800.

[2] Ko, Jaehwan, et al. "Review of manufacturing technologies for coated accident tolerant fuel cladding." Journal of Nuclear Materials (2022): 153562.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2021M2D2A2076384)