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Investigating the impact of mechanical post-processing on HT9 cladding material for annular metallic fuel manufacturing

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1. Introduction

The use of metallic fuel offers advantages such as capability of recycling through pyro-processing, high thermal conductivity, low coefficient of thermal expansion, excellent proliferation resistance, good compatibility with sodium, and ease of manufacturing. However, there are several issues that need to be solved, including Fuel Cladding Chemical Interaction (FCCI) and Fuel Cladding Mechanical Interaction (FCMI) phenomena caused by fission products during operation. One possible solution to these issues is the use of annular metallic fuel, which induces swelling towards the center hole of the fuel, thereby mitigating FCMI and FCCI issues [1]. Additionally, using annular fuel can minimize the gap between the cladding and the fuel, resulting in a bond sodium-free nuclear fuel [2]. Our research team is currently focused on exploring the manufacturing and mechanical post-processing techniques of annular metallic fuel, with the goal of minimizing the gap between the fuel and cladding. In this study, we used U-10Zr surrogate to manufacture the assembly of annular metallic fuel and cladding using mechanical post-processing such as swaging. We evaluated the effect of the process on the cladding through microstructural analysis and mechanical property evaluation.

2. Experimental procedure

2.1 Selection of U-10Zr surrogate material

We selected a surrogate material to simulate U-10Zr, a metallic fuel component, for mechanical post-processing. The surrogate material was chosen based on its mechanical properties, including yield strength, tensile strength, elongation, modulus of elasticity, and surface hardness, in comparison to U-10Zr. Referring to several evaluations of U-10Zr mechanical properties [3-5], we determined the properties of U-10Zr as yield strength of 1,000 MPa, tensile strength of 1,400 MPa, elongation of 9%, modulus of elasticity of 180 GPa, and surface hardness of 400 HV. Table 1 shows the selected candidate surrogate materials in comparison to the properties of U-10Zr.

Table 1. U-10Zr surrogate materials list [6]

Composition (wt%)	YS (MPa)	UTS (MPa)	El (%)	E (GPa)	Hardness (HV)
Fe-(1.6~1.9)Mn-(0.38~0.43)C	910	979	18.8	200	301
Fe-(0.7~0.9)Cr-(0.65~0.85)Mn-(0.2~0.3)Mo-(1.65~2)Ni-(0.38~0.43)C	1170	1255	13.7	200	384
Fe-(0.7~0.95)Mn-(1.8~2.2)Si-(0.51~0.59)C	1007	1170	14.9	200	350
Fe-(1~1.4)Cr-(0.45~0.65)Mn-(0.08~0.15)Mo-(3~3.5)Ni-(0.08~0.13)C	993	1238	15.3	200	397
Fe-(1~1.4)Cr-(0.45~0.65)Mn-(0.08~0.15)Mo-(3~3.5)Ni-(0.08~0.13)C	1010	1227	15	200	384
Fe-(0.7~0.9)Cr-(0.7~0.9)Mn-(0.2~0.3)Mo-(0.85~1.15)Ni-(0.38~0.43)C	1105	1240	15	200	382
Fe-20Cr-11Ni-2Mn-0.08C	860~1070	1030~1170	5~10	195	340
Fe-(11.5~13.5)Cr-0.15C	1005	1085	13	200	344
Fe-(0.75~1.5)Al-(13.75~15)Cr-1Mn-(2~3)Mo-(7.75~8.75)Ni-0.05C	1034	1227	8	200	396
Fe-14.8Cr-1Mn-3.5Cu-4.5Ni-0.07C	1140	1170	12	200	372
Fe-22Cr-5Mn-2.25Mo-12.5Ni-0.06C	1000	1105	25	200	316
Fe-20Cr-9Mn-6Ni-0.23N-0.08C	1115	1235	28	200	388
Fe-18Cr-13Mn-3.13Ni-0.3N-0.08C	1150	1270	10	200	399
Fe-11.8Cr-2Cu-8.5Ni-2Nb-1.1Ti-0.05C	930	1105	8	200	323
Fe-(20~22)Cr-1.5Mn-(6~7)Mo-(23.5~25.5)Ni-0.03C	1095	1200	4	200	325
Ti-6Al-2Sn-4Zr-2Mo	990	1010	3	120	333
Ti-8Al-1Mo-1V	910	937	18	120	349
Ti-5.5Al-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si	820	930	9	125	320
Ti-5.8Al-0.5Mo-0.7Nb-4Sn-3.5Zr	925	1050	12	120	350
Ti-8Mo-8V-2Fe-3Al	1150	1200	8	120	350
Fe-(14~16)Cr-(1.25~1.75)Cu-(0.5~1)Mo-(5~7)Ni-0.05C	1165	1193	17	200	376
Co-(19~21)Cr-(11.25~20.5)Fe-(1.5~2.5)Mn-(6~8)Mo-(14~16)Ni	1040	1310	-	189	343
Ti-4.5Al-2.5Fe	1081	1375	16	110	300~400
Fe-18Cr-13Mn-1.5Ni-0.33N-0.15C	1090	1310	18.5	200	316
Fe-(15~17.5)Cr-(3~5)Cu-(3~5)Ni-0.07C	1117	1158	16	197	367

Although Ti-based alloys exhibited mechanical properties similar to U-10Zr, they were not utilized due to their low modulus of elasticity. Additionally, instead of using a type of stainless material that requires cold working to manifest certain properties, we utilized a type of precipitation hardening stainless steel material that can be induced with specific properties through simple heat treatment as a surrogate material.

2.2 Mechanical post-processing (swaging)

Swaging was employed as a mechanical post-processing method to mechanically join the annular metallic fuel and cladding tube. A surrogate annular metallic fuel with an outer diameter of 6 mm was inserted into the HT9 cladding material with an inner diameter of 6.4 mm, followed by swaging. The process was carried out by gradually decreasing the diameter of the swaging die to bond the outer cladding tube to the surface of the inner metallic fuel. Specifically, three units of the surrogate material, each 100 mm in length, were inserted into a 300 mm length of the cladding tube. Fig. 1 shows the swaging equipment used in this study.

Fig.1. Swaging equipment for post mechanical processing

2.3 Microstructural/property analysis of cladding

As mechanical post-processing involves mechanical deformation of the cladding tube, it is essential to evaluate the integrity of the tube. In particular, if degradation of the HT9 cladding material occurs as a result of mechanical post-processing, it can lead to issues with the performance of the cladding itself, making the process practically unusable. Therefore, in this study, Micro-CT was used to detect internal bonding defects in HT9 after mechanical post-processing, and OM/SEM was used for microstructural analysis. Furthermore, the impact of mechanical post-processing on the micro hardness distribution of the cladding tube was analyzed.

3. Results and Discussion

To simulate the mechanical post-processing before its implementation, we conducted a simulation of the swaging process using Deform software based on the properties of U-10Zr. Fig.2 presents the simulation results, showing that the swaging process applies strength and strain at the level of elastic region to the cladding. We concluded that there is little plastic deformation occurring in the cladding during the mechanical post-processing, and hence, it does not significantly affect the performance of cladding. However, to verify these fact, changes in microstructure and mechanical properties before and after processing will be discussed in this paper. Furthermore, we acknowledge that evaluating the performance of cladding based solely on the micro hardness assessment used in this study is challenging. Therefore, it is necessary to confirm the integrity of the cladding through ring tensile test and high-temperature creep test in future studies. Fig. 3 shows the Micro-CT results after the mechanical post-processing, revealing some gaps between the surrogate fuel segments within the cladding. We presume that this is due to the vibrations occurring during the swaging process or the different mechanical properties of the surrogate fuel and cladding. The presence of gaps between the fuel segments can lead to the uneven distribution of thermal energy during operation and inefficient heat transfer. Thus, we plan to conduct further studies on not only the swaging process but also the drawing and pilgering processes to solve this issue.

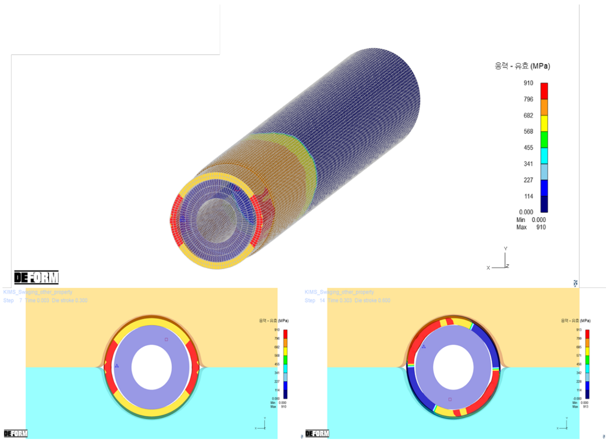

Fig.2. Stress/Strain distribution of HT9 cladding after post mechanical process

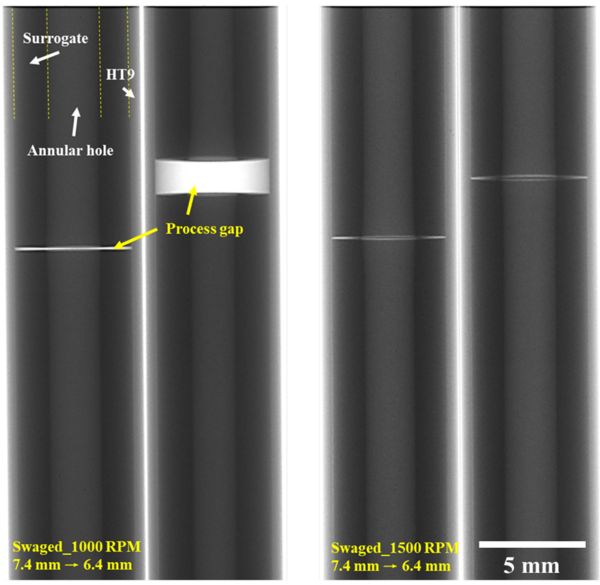

Fig.3. Micro-CT analysis of HT9 cladding after post mechanical process

4. Conclusion

In this study, we investigated the post-mechanical processing for bonding metallic fuel cladding to the tube, and the following results were obtained:

1) PH stainless steel is a promising surrogate material for U-10Zr.

2) The stress/strain levels induced in the cladding during swaging were limited to the elastic region.
3) Swaging resulted in gaps between the fuel segments in the cladding unit.
4) Further research is necessary to evaluate the integrity of the cladding using tests such as ring tensile and creep, and to investigate other processes such as drawing and pilgering

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