Evaluation of Multi-Metallic Layered Composite (MMLC) Accident-Tolerant Fuel Cladding

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ABSTRACT*: After Fukushima-Daiichi accident, accident-tolerant fuel(ATF) claddings which have resistance to severe accident such as loss of coolant accident(LOCA) have been researched. Under environment of lead-bismuth eutectic(LBE), multi-metallic layered composite (MMLC) fuel cladding has been shown to have good properties. In order to apply this cladding to the light water reactor, we have designed this cladding to have good characteristics for the light water reactor environment. In order to evaluate the characteristics of this cladding, we will conduct high temperature oxidation test, ring tensile test at room temperature and high temperature, observation of microstructure etc. Before the MMLC cladding is conducted high temperature oxidation test, in order to determine the optimal composition and performance level of Fe-Cr-Si specimen in the LWR environment, high temperature oxidation test is conducted by composition of Fe-Cr-Si specimen.*

KEYWORDS*: Fuel Cladding, Accident-tolerant, Multi-Metallic Layered Composite(MMLC), CRUD, High Temperature Oxidation Test*

I. INTRODUCTION

In situation of beyond design basis accidents, similar to Fukushima-Daiichi accident, the zirconium alloy fuel claddings are rapidly heated because of nuclear decay heating and rapid oxidation of zirconium with steam. Under this situation, the zirconium alloy fuel cladding rapidly reacts with steam, decrease strength, burst or rupture. And it generates large quantities of hydrogen gas and cause hydrogen explosion. In order to avoid this situation, accident tolerant fuel(ATF) design is researched. The ATF is required to have resistance to steam oxidation and decrease to hydrogen generation, be enough mechanical strength. Therefore, many materials such as Fe-Cr-Al, Mo alloy and SiC/SiC composite have been studied (Ref 1.) (Ref. 2).

II. CONCEPT OF MMLC FUEL CLADDING

Multi-metallic layered composite (MMLC) is a new concept for ATF cladding. There is not attempt to manufacture the MMLC fuel cladding for the Light Water Reactor (LWR). The previous MIT has already undergone trial and error and developed the optimized process variable and technology. This test is processed under static lead-bismuth eutectic(LBE) have been investigated at low(600–615°C) and high (700–715°C) temperatures, at oxidative and reductive oxygen potentials with respect to iron oxide formation (Ref 3.). We apply this experiment to the LWR.

In the case of Fe-Cr-Al, which is researched for ATF cladding, Al_2O_3 is formed during oxidation. And it is known that the oxidation resistance is much better at higher temperatures (>1000°C) than Zr alloy. (Ref 4.) Fe-Cr-Si in the outside of MMLC cladding is predicted to SiO_2 formation during oxidation. As the Fig 1, SiO_2 is predicted that oxidation resistance is much better at higher temperatures (>1000°C) than Al_2O_3.

MMLC is mainly consisted of zirconium alloy and Fe-Cr-Si alloy. The inside layer is composed of zirconium alloy that has high neutron irradiation resistance. The outside layer is composed of Fe-Cr-Si, which has high resistance to steam oxidation. The diffusion barrier layer between them is composed of Cr, Ti that prevent the reaction between Zr and Fe. And surface is coated with a material such as ZrN to improve the CRUD (Chalk River Unidentified Deposits) resistance of the cladding. In order to evaluate high temperature oxidation feature of fuel cladding, oxidation tests are conducted in steam conditions. A schematic of the MMLC is shown in the Fig 2.

In order to fabricate the MMLC cladding having such the structure, Ti, Cr and others behaving as barrier layer are welded on the zirconium alloy TREX. And then Fe-Cr-Si alloy is welded on the barrier layer. After finishing this process, the TREX is made a 50 mm diameter tube by co-extrusion. By proceeding pilgering process, the tube is made a 10 mm diameter tube which is similar to the current zirconium cladding. The fabrication process of MMLC cladding is shown in the Fig 3.

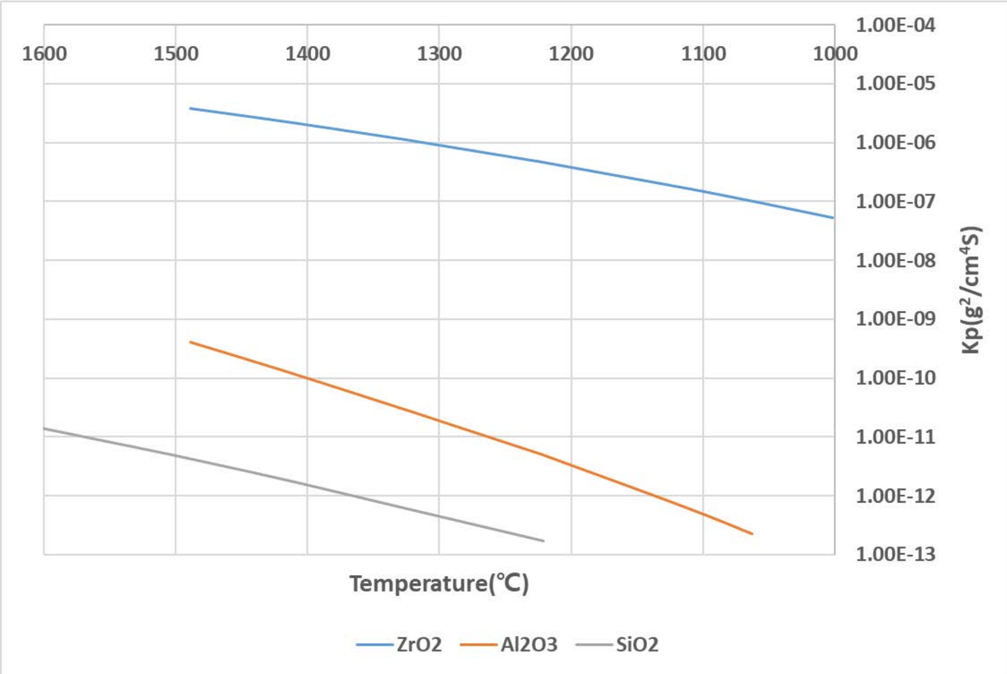

Fig 1. A rough comparison of parabolic rate constants of Zr, Al and Si (Ref 4.)

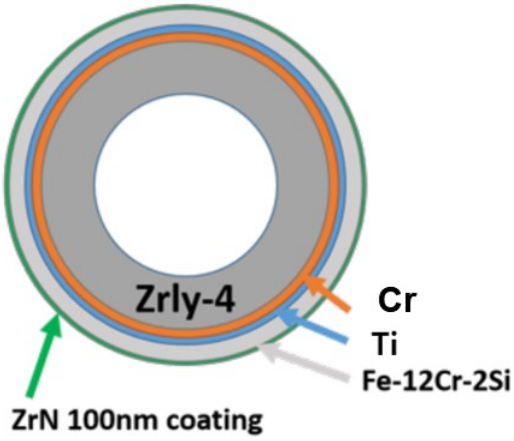

Fig 2. Schematic of the proposed MMLC

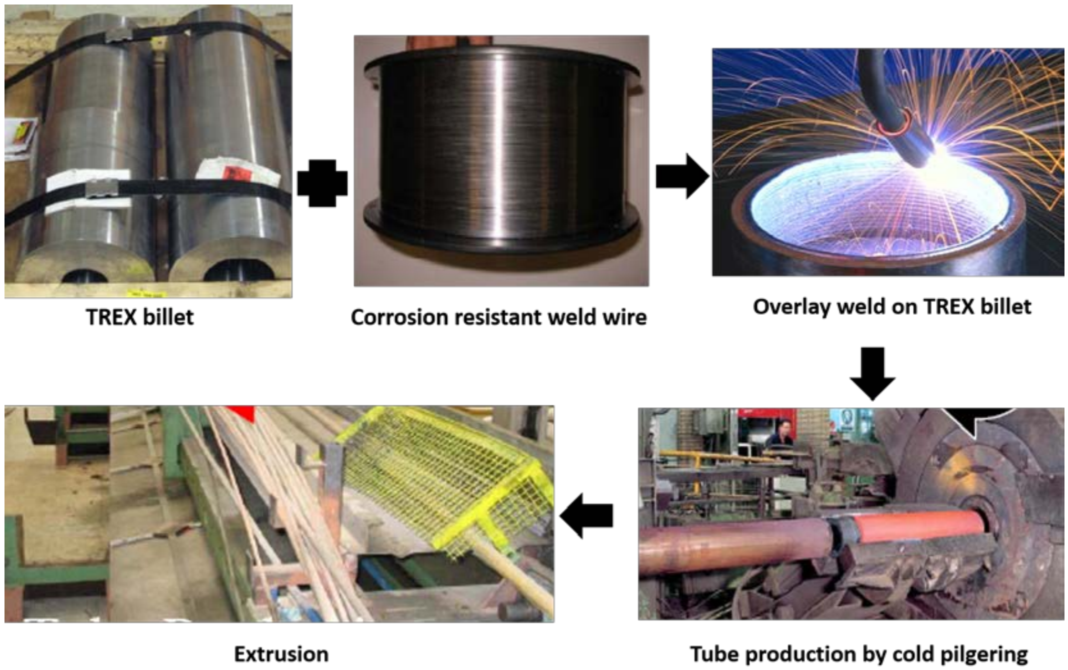

Fig 3. Example of MMLC cladding production process fabricated from welding and pilgering

III. EXPERIMENTAL PROCEDURE

III.A. High Temperature Oxidation Test

III.A.1. Design and Set-up of High Temperature Oxidation Steam Furnace

In order to self-evaluate high temperature oxidation feature of fuel cladding, we designed the high temperature steam furnace. Two-sided steam oxidation tests in 1000°C, 1100°C, 1200°C are conducted in flowing steam conditions between 0.8 to 30 $mg/cm^2 \cdot s$ according to NRC Reg. guide DG-1262(Ref 5.). When steam is supplied, dry Ar gas is used for smooth supply of steam. Also to evaluate the performance of cladding in severe environments, it is conducted under temperature above 1200°C. To compare MMLC cladding with zirconium alloy cladding, oxidized samples are analyzed by using scanning electron microscopy (SEM), scanning transmission electron microscopy (STEM) and X-ray diffraction (XRD), as well as basic weight gain measurements. A schematic of the high temperature steam oxidation furnace is shown in the Fig 4. and Fig 5.

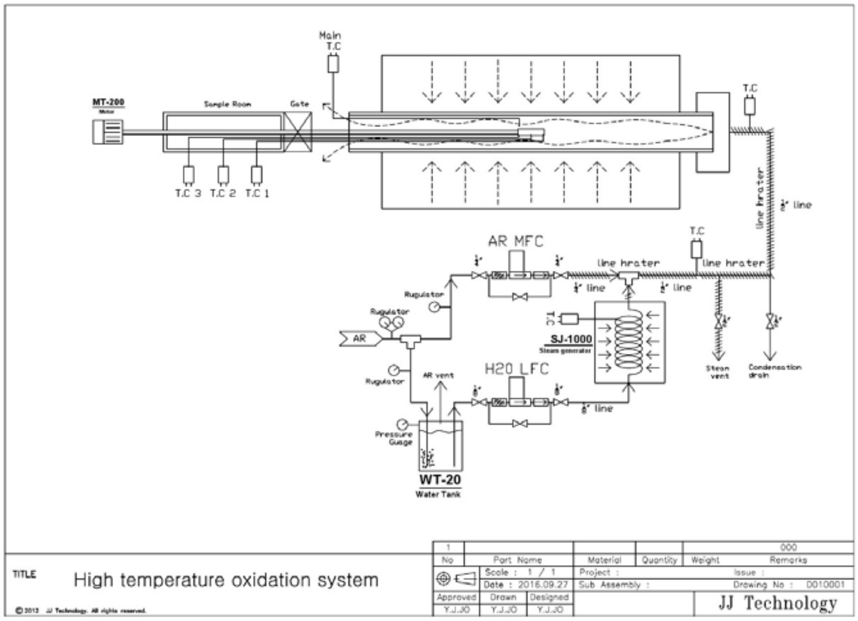

Fig 4. Schematic of high temperature oxidation steam furnace

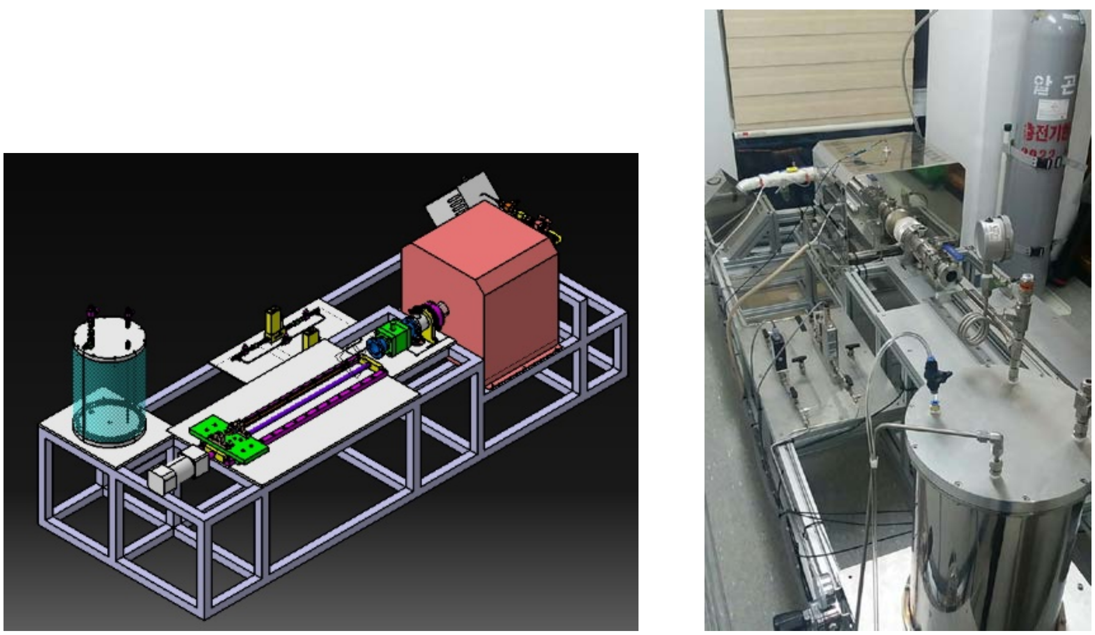

Fig 5. High temperature oxidation steam furnace schematic(left) and reality (right)

III.B. Ring tensile Test

Ring tensile test is conducted with zirconium alloy and MMLC cladding specimens. MMLC cladding is possibility that welding point of the cladding is separated in severe environment, because it is consist of multi-layer. So, the strength of this cladding needs to be checked. In order to checking the strength, ref. zirconium alloy and MMLC cladding are conducted ring tensile test in same condition. Because Shape of ref. zirconium alloy is tube type, we test ring tensile test. In reference to preceding literature, sample holder and ring type samples were fabricated as shown in Fig 6. (Ref 6.)(Ref 7.)(Ref 8.)

Fig 6. Ring tensile test sample holder(top) and samples before and after tensile test(bottom)

IV. RESULT & DISCUSSION

IV.A. High Temperature Oxidation Test

IV.A.1. Design and Set-up of High Temperature Steam Furnace

Before proceeding with the high temperature oxidation test of the MMLC cladding, the Fe-Cr-Si specimen that constituting the outer surface of the MMLC cladding was prepared. In fact, when the MMLC cladding is applied to the LWR reactor, The Fe-Cr-Si layer which forms the outer part of the MMLC cladding contacts the primary water. Checking the high temperature oxidation level of Fe-Cr-Si alloy, we think that confirm the high temperature oxidation level of MMLC cladding. Fe-12Cr-2Si, which showed good performance in the static lead-bismuth eutectic (LBE) test environment of the previous research (Ref. 4), was fabricated with ref. specimen. In order to find the composition of Fe-Cr-Si optimized in the LWR environment, Fe-16Cr-2Si and Fe-20Cr-2Si specimens were prepared. We will conduct high temperature oxidation tests on these three specimens to confirm the high temperature oxidation resistance depending on the Cr content. In addition, in another previous paper, there is a result of testing the change of Fe-15Cr alloy by Si content in Ar-15% O_2 950 °C atmosphere. (Ref 9.). According to this paper, when 0 - 1% Si is added in Fe-15Cr alloy, the optimum composition is shown as Fe-15Cr-0.5Si. With reference to this precedent, after the high temperature oxidation resistance by Cr content is evaluated, the high temperature oxidation resistance by Si content will be evaluated.

After the optimum condition of Fe-Cr-Si is found in the LWR environment, we will apply to MMLC cladding, this cladding will be conducted the high temperature oxidation test and the ring tensile test. After the test, we will compare the performance of MMLC cladding with ref. zirconium alloys.

IV.B. Ring tensile Test

Before testing the MMLC cladding samples, in order to ensure the reliability of the self-test results, ring tensile test of ref. zirconium alloy are conducted in third-party certification company. It was conducted that three times in the third-party certification company and five times in the self-test equipment. The progress is shown in Fig 7. and TABLE 1.

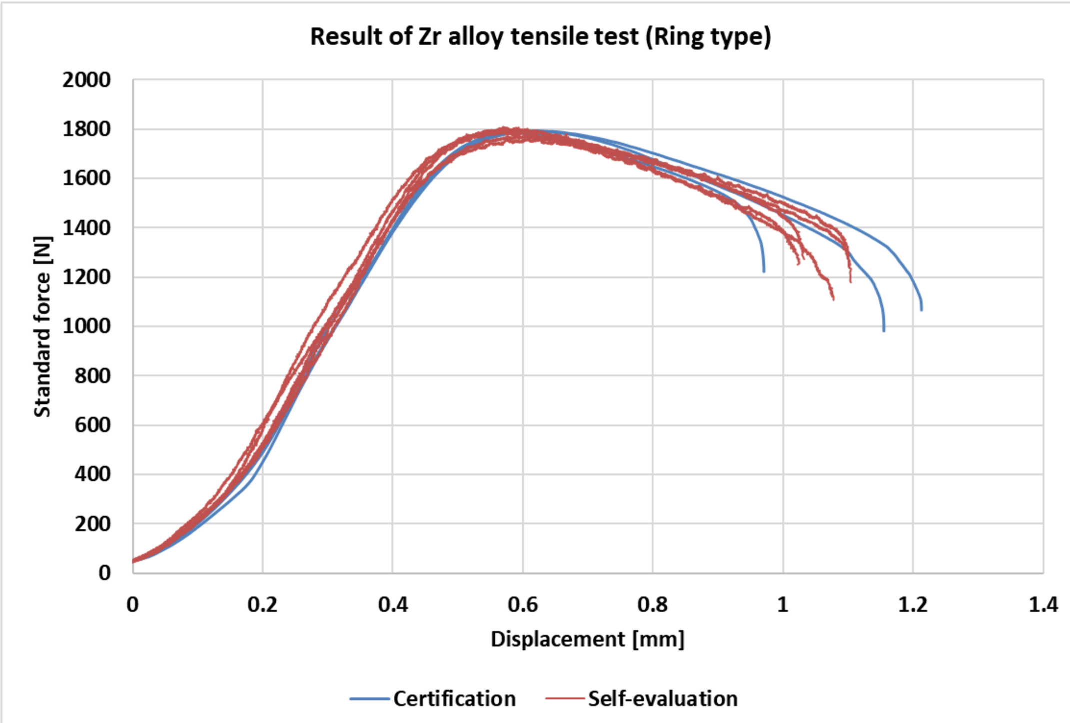

Fig 7. Result of ring tensile test of ref. zirconium alloy (at room temperature)

TABLE 1: Comparison of ring tensile test of third-party certification company and self-test

	Maximum Load		Final Elongation	
	Certification	Self-test	Certification	Self-test
Avg	1790 N	1788 N	1.11 mm	1.07 mm
STDEV(σ)	4	19	0.13	0.04
2σ deviation	8	37	0.25	0.08
Max. value(2σ)	1798 N	1825 N	1.37 mm	1.14 mm
Min. value(2σ)	1782 N	1751 N	0.86 mm	0.99 mm

When the STDEV is compared with the evaluation result, the result of third-party certification company is 4 and the result of self-test is 19, and the self-test result is higher than third-party certification company. However, the average value of the maximum load is similar with 1790N (third-party certification company result) and 1788N (the self-test result). When the final elongation is compared, the STDEV of the self-test result is 0.04 and the STDEV of third-party certification company is 0.13. It is shown that the self-test result is lower than the third-party certification company result. In fact, when we look at Fig 9., we can see that all self-test graphs are inside the third-party certification company result graphs. Therefore, we think that there is no problem in data reliability when conducting the self-test.

V. SUMMARY

MMLC cladding which are predicted to have better properties than zirconium alloy cladding in severe environments such as LOCA is fabricated. It is predicted to have high neutron irradiation resistance, high resistance to steam oxidation. In order to evaluate the performance of this cladding, the high temperature oxidation experiments will be conducted. After proceeding the experiment, to compare with zirconium cladding alloy, the material was analyzed.

Before proceeding with the high temperature oxidation test of the MMLC cladding, the Fe-Cr-Si specimen is conducted high temperature oxidation test. In order to confirm the high temperature oxidation resistance depending on the Cr content, we prepared the three specimen. After checking the high temperature oxidation resistance of the three specimen, the high temperature oxidation resistance by Si content will be evaluated. Finally, we will conduct the high temperature oxidation test and ring tensile test of MMLC cladding that have the outer layer of Fe-Cr-Si optimized in the LWR environment.

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