Research Status Of Accident Tolerant Fuel Cladding For Improving Accident Resistance : Do We Have Any Alternative For Current Approaches ?

Dae Yoon Kim, Yu Na Lee and Young Soo
Gachon University, Department of Materials Science and Engineering, Bokjung dong Seoungnam Si, Gyunggi do Korea
*Corresponding author: benedicto@gachon.ac.kr

1. Introduction

One of the most noteworthy features in recent nuclear power research is the accident tolerant fuel (ATF) cladding. This has become even more important after the Fukushima nuclear power plant accident in 2011. Research on accident-resistant cladding is very broad, because it can increase the safety margin of nuclear power plants in case of a serious accident, and it is also diverse in the way of research. In the harsh environment of space and marine medical science, the intention to adopt new materials has been very active so far, but nuclear power has taken a very conservative stance in adopting it relatively. Nonetheless, there is general consensus that the adoption or partial adoption of new materials must be carried out in the ATF cladding. This is because, as shown in Equation 1, the Q value must be reduced in order to have a technical response time in the event of a severe accident.

$$\rho Cp\frac{\partial T}{\partial t} = k\nabla^2 T + Q \qquad (1)$$

where,
C_p : Heat capacity of core material
K : Thermal conductivity
Q : Heat generation rate

This presentation will present not only the scientific approach to ATF clad development, but also the technical features that need to be overcome for actual application. Also, new alternative research method that might solve the problems and limitations of existing researches and future research directions will be presented. This is because the development of the ATF clad from a commercial viewpoint is a technical task to be solved by the nuclear industry as a top priority.

The technical approach for ATF clad development has been divided into three major areas: (1) coating of a functional thin film or thick film on a Zr alloy clad surface, (2) a new composition alloy - an alloy containing ODS such as Alumina – and (3) SiC composite or SiC / SiCf composite based on SiC fiber. Each case has both material advantages and disadvantages. Nevertheless, the most important engineering feasibility for commercialization is still unclear. Among these, the development of new alloys is recognized as being the easiest to manufacture at a practical commercial level. However, applying new materials completely different from existing materials has a considerable problem, which means significant modification, supplementation or substitution of most hardware and codes related to existing nuclear power generation.

2. Research trend of ATF

Table 1 shows the research methods and institutions related to ATF clad development, which is currently underway. A wide variety of institutions such as academia, corporations and research institutes have been studying and developing ATF clad using the three typical methods mentioned above or a combination of these methods.

2.1 Functional thin film or thick film and coating

This is a concept to coat a functional film to improve the surface characteristics on the surface of a conventional Zr alloy cladding tube, and it is recognized that it is very useful because it utilizes the cladding material currently used. That is, even if the functional layer to be coated is a thin film or a thick film, there is not a large change in the macroscopic mechanical properties appearing in the cladding tube, so the psychological threshold for actual application is not high. This has attracted considerable attention at the beginning of the ATF clad study. In fact, coatings of ceramic functional films such as SiC and CrN have been actively studied. In recent years, attempts have been made to coat single metal films such as Cr.

The most widely used process is sputtering, which is technically verified and relatively simple compared to other coating processes. Nevertheless, there is no report on the commercialization level yet. This is due to problems such as non-uniformity of the coating film when the sputtering method is applied to a three-dimensional curved surface such as a clad. In addition, the uniform coating of long tubes requires a very long process time and excessive cost for system design for such processes. This aspect appears to be a greater problem in ceramic coatings than in metals.

2.2 Alloy of new composition

Assuming that the optimum alloy is finally developed, it is believed that this technique is most suitable for producing commercial grade clad. Nevertheless, no breakthroughs have been reported on alloys or ODS alloys with a new composition composed of the optimum material for the environment similar to the operation of the nuclear power plant. In particular, the feasibility of applying this approach is unclear, especially because of the economical weakness of the material and the generation of helium during use.

2.3 SiC or SiC / SiC_f composite

SiC is a material having excellent properties in terms of neutron irradiation effect and chemical corrosion. For this reason, the development of SiC based clad was accepted as a very positive view at the beginning of development. However, the reliability of the mechanical properties of SiC, which is one of the ceramics, is not high. In fact, manufacturing of the tube has technically difficult problems. For this reason, studies have been made to fabricate a clad by combining SiC fiber and SiC. However, SiC fiber is still an expensive material that is difficult to apply in practice, and its chemical integrity is still incomplete in a high-temperature steam atmosphere.

3. Is there an alternative?

The three technological approaches described above have their advantages and disadvantages. Although these methods have completeness from the material point of view, it is very questionable whether it can be realized from the Engineering point - can it be manufactured at commercial level? – of view. Therefore, alternatives that are likely to replace these three methods must satisfy at least the following four conditions. (1) to overcome the objection to the application of new materials in nuclear energy, (2) to be easy to implement in engineering, (3) to be acceptable from an economic point of view and (4) the reproducibility of each worker should be very high. In this presentation, we propose a new process that can satisfy these four conditions. It is true that the proposed process still requires much verification from its fabrication and user perspectives, but I hope that it will be another alternative to demonstrate new possibilities in the development of a rather stagnant ATF clad.

Table 1 ATF clad research status

Lead Organization	Category – Major Technology Area	Team Members
AREVA [1]	Protective materials, MAX phase, Coated Zr cladding, SiC/SiC composites	U. Wisconsin, U. Florida, SRNL, TVA, Duke
Westinghouse [2, 3]	Cladding coating (near) SiC cladding (mid)	General Atomics, MIT, EWI, INL, LANL, TAMU, Southern Nuclear Operating Company
ORNL [4]	FeCrAl alloy	GE
General Electric Global Research [5]	Advanced steels for cladding	Global Nuclear Fuels, LANL U. Michigan
University of Illinois [6]	Modified Zr-based cladding	U. Michigan, U. Florida, INL U. Manchester, ATI Wah Chang
MIT [7]	SiC/SiC_f composite cladding	-
University of Tennessee [8]	Ceramic Coating for clad	Penn state, U. Michigan, UC boulder, LANL, Westinghouse, Oxford, U. Manchester, U. Sheffield, U. Huddersfield, ANSTO
INL [9]	Zr liner + SiC hybrid	-
EPRI [10]	Zr-Mo alloy	EPRI, INL, GE
HRP[11]	CrN phase coating	-
KAERI [12., 13]	Surfuace modified cladding metal - ceramic hybrid cladding SiC cladding	-

4. References

[1] Bischoff, J., Delafoy, C., Vauglin, C., Barberis, P., Roubeyrie, C., Perche, D., ... & Nimishakavi, K. (2018). AREVA NP's enhanced accident-tolerant fuel developments: Focus on Cr-coated M5 cladding. *Nuclear Engineering and Technology*, Vol. *50*(2), p. 223, 2018

[2] Hallstadius, L., Johnson, S., & Lahoda, E. (2012). Cladding for high performance fuel. *Progress in Nuclear Energy*, Vol. *57*, p.71-76, 2012.

[3] Ševeček, M., Gurgen, A., Seshadri, A., Che, Y., Wagih, M., Phillips, B., ... & Shirvan, K. (2018). Development of Cr cold spray–coated fuel cladding with enhanced accident tolerance. *Nuclear Engineering and Technology*, Vol. *50*(2), p.229-236, 2018.

[4] Terrani, K. A., Parish, C. M., Shin, D., & Pint, B. A. (2013). Protection of zirconium by alumina-and chromia-forming iron alloys under high-temperature steam exposure. *Journal of Nuclear Materials*, Vol. *438*(1-3), p. 64, 2013.

[5] Rebak, R. B. (2018). Versatile Oxide Films Protect FeCrAl Alloys Under Normal Operation and Accident Conditions in Light Water Power Reactors. *JOM*, Vol.*70*(2), p.176, 2018.

[6] Heuser, B., Stubbins, J., Kozlowski, T., Uddin, R., Trinkle, D., Downar, T., ... & Phillpot, S. (2017). *Engineered Zircaloy Cladding Modifications for Improved Accident Tolerance of LWR Nuclear Fuel* (No. 12-4728). Battelle Energy Alliance, LLC, Columbus, OH (United States), 2017.

[7] Auguste, R. (2017). *Quantifying the fouling resistance of Accident-Tolerant Fuel (ATF) cladding coatings with force spectroscopy* (Doctoral dissertation, Massachusetts Institute of Technology), 2017

[8] Sickafus, K. E., Wirth, B., Miller, L., Weber, B., Zhang, Y., Patel, M., ... & Plunkett, K. (2017). *Ceramic Coatings for Clad (The C3 Project): Advanced Accident-Tolerant Ceramic Coatings for Zr-Alloy Cladding* (No. 12-4722). Univ. of Tennessee, Knoxville, TN (United States), 2017.

[9] Griffith, George W. *US Department of Energy Accident Resistant SiC Clad Nuclear Fuel Development*. No. INL/CON-11-23186. Idaho National Laboratory (INL), 2011. tube for nuclear fuel cladding applications." *Journal of Nuclear Materials* Vol. 458 p. 29, 2015.

[10] Bragg-Sitton, S. (2014). Development of advanced accident-tolerant fuels for commercial LWRs. *Nuclear News*, Vol. *57*(3), p. 83, 2014.

[11] Van Nieuwenhove, R., Andersson, V., Balak, J., & Oberländer, B. (2018, January). In-Pile Testing of CrN, TiAlN, and AlCrN Coatings on Zircaloy Cladding in the Halden Reactor. In *Zirconium in the Nuclear Industry: 18th International Symposium*. ASTM International, 2018

[12] Kim, D. J., Lee, H. G., Park, J. Y., & Kim, W. J. (2015). Fabrication and measurement of hoop strength of SiC triplex tube for nuclear fuel cladding applications. *Journal of Nuclear Materials*, Vol. *458*, p. 29, 2015.

[13] Kim, J. J., Kim, H. G., & Ryu, H. J. (2018, March). High Temperature Oxidation Behavior of Zirconium Silicides and Their Coating by Laser Cladding on the Zircaloy-4 Tube. In *TMS 2018*. TMS, 2018.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF2016R1A5A1013919).