Qualitative approach to understand fatigue behavior of CrAl-ODS-Zr alloy ATF cladding

Jong-Dae Hong*, Jae Yong Kim
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Korea
**jongd@kaeri.re.kr*

1. Introduction

The cladding fatigue by repetitive fatigue strain (or stress) causes the failure of fuel assembly during normal operation, including anticipated operational occurrences. Fatigue stresses may be induced in the fuel assembly co mponents due to, e.g. the turbulent coolant flow and ther mal cycle. To avoid this risk, the acceptance criteria in r egulatory standard review plan (SRP) 4.2 limited that th e cumulative number of strain fatigue cycles should be s ignificantly less than the design fatigue lifetime, which i s based on appropriate data and includes a safety factor of 2 on stress amplitude or a safety factor of 20 on the n umber of cycles (or other proposed limits must be justifi ed) [1,2]. Also, it should be presumed the existence of w ear on the fatigue limits.

O'Donnell and Langer's conservative design curve (**Fig. 1**) [3] for Zr-based cladding based on the extensive database including irradiated test data has been used. However, O'Donnell and Langer's design curve couldn't be simply applied to coated accident tolerant fuel (ATF) cladding fatigue analysis because the relevant knowledge is lack due to limited data. In this paper, the fatigue behavior of ATF cladding is qualitatively studied and its effect on fuel in-reactor behavior is discussed for the phenomenon identification and ranking table (PIRT) development study. They are performed for the development of the ATF nuclear fuel performance model and code. The type of the ATF cladding to be covered in this study is Zr-alloy cladding with the partially oxide dispersion strengthened (ODS) and CrAl alloy coated layer, as shown in **Fig. 2**.

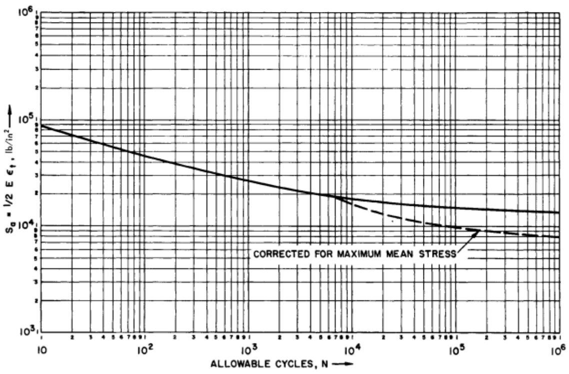

Fig. 1 Fatigue design curve of irradiated Zircaloy component by O'Donnell and Langer [3]

2. Fatigue behavior of CrAl-ODS-Zr alloy ATF cladding

2.1. CrAl-ODS-Zr alloy ATF cladding [4]

The surface modified Zr cladding concept in KAERI has been developing as a one of the candidates for ATF cladding because the corrosion/oxidation resistance and the high-temperature strength of Zr alloy can be improv ed by applying a surface modified technology, as shown in **Fig. 2**. Two technologies of outer surface coating an d a partial ODS structure at the intermediated region bet ween the outer CrAl coated layer and Zr alloy tubes are applied in this concept. In detail, the corrosion/oxidatio n resistance during normal operation and under accident conditions can be increased by the surface coating meth od (arc ion plating, AIP), and the high-temperature stren gth of the cladding can be increased by the partial ODS method with Y_2O_3 particles.

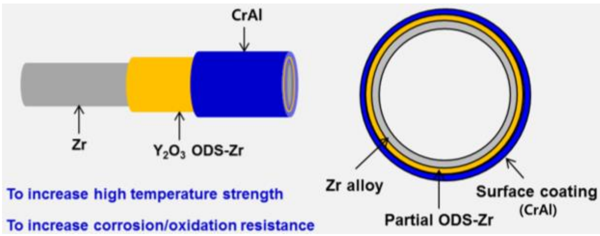

Fig. 2 Structure of CrAl-ODS-Zr alloy cladding [4]

2.2. Existing study for coated ATF cladding

There is limited fatigue data for coated ATF cladding, especially no data for CrAl-ODS-Zr alloy. In KAERI, CrAl coated Zry-4 cladding (200 ppm hydrogen charged with air oxidation at 400°C for 60 days) has 498 cycle under at hoop stress of 450 MPa, which is 4.8 times longer than uncoated Zry-4 cladding. Cr coated Zry-4 has significant improved fatigue resistance in vacuum environment, as shown in **Fig. 3** (Ma et al) [5]. On the contrary, M. Ševeček et al [6] reported that fatigue failure observed significantly earlier in Cr-coated cladding samples by cold spray under normal water chemistry environments. They presumed decreased fatigue life of in Cr-coated cladding resulting from stress concentration in the coating caused by the inhomogeneity created during the coating process, but these problems could be solved by the optimization of manufacturing process and setting of appropriate limits.

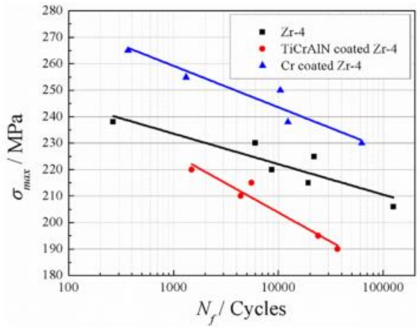

Fig. 3 Improvement in the fatigue resistance of Cr coated ATF cladding [5]

Additional studies related to fatigue behavior for Cr coating not on Zr-alloy, cold spray coating could give a beneficial effect inducing a compressive residual stress [7]. Cr coating for plated steel could improve or significantly worsen the fatigue lifetime due to different microstructures produced and especially the fatigue life with chromium coatings with columnar (dendritic) structure significantly decreased resulting from crack propagation along the grain boundaries (**Fig. 4**) [8].

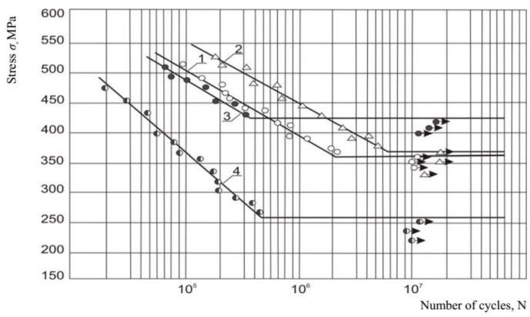

Fig. 4 Fatigue characteristics for Cr-coated plated steel (1 - uncoated, 2 - coatings with homogeneous structure, 3 - coatings with horizontal-layered structure, 4 - coatings with columnar (dendritic) structure) [8]

2.3. Fatigue behavior of CrAl-ODS-Zr alloy ATF cladding

Based on the existing studies for Cr coating which is similar to CrAl, fatigue resistance of CrAl-ODS-Zr alloy cladding would be improved by hard CrAl and ODS layers to the limit that the intact coating layer is maintained. Because CrAl layer of CrAl-ODS-Zr alloy cladding is not columnar structure, the fatigue resistance would not deteriorate by coating layer. But the fatigue cracking in CrAl coating layer could occur by small repetitive strain (e.g. 0.01%-0.1%) in normal operation and propagate through the cladding. Therefore, coating cracking should be evaluated. Due to uncertainties resulting from limited data and cracking issues, it couldn't be concluded whether the fatigue resistance of CrAl-ODS-Zr alloy cladding is superior to that of existing Zr-alloy cladding to date. Based on the extensive irradiated test database for CrAl-ODS-Zr alloy ATF cladding, the new fatigue design curves including a safety factor of 2 on stress amplitude or a safety factor of 20 on the number of cycles should be presented.

3. Summary

The fatigue behavior of CrAl-ODS-Zr alloy ATF cladding has been studied by qualitative approach. The cracking which is inherent concerns for coating should be evaluated. Meanwhile, based on the existing studies for Cr coating, fatigue resistance of CrAl-ODS-Zr alloy cladding would be improved by hard CrAl and ODS layers. But in regulatory or design point of view, current design curve for Zr-alloy is inapplicable for CrAl-ODS-Zr alloy ATF cladding. Because it couldn't be concluded whether the fatigue resistance of CrAl-ODS-Zr alloy cladding is superior to that of existing Zr-alloy cladding due to limited database and cracking issue. Throughout the extensive irradiated tests, the new fatigue design curves considering a safety factor should be presented.

Acknowledgement

This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science and ICT (NRF-2017M2A8A5015064).

REFERENCES

[1] KINS, Safety review guidelines for light water reactors. (Revision 6), KINS/GE-N001
[2] US NRC, Standard review plan 4.2, NUREG-0800
[3] W.J. O'Donnell, B.F. Langer, Fatigue design basis for Zircaloy components, Nuc. Sci. Eng. 20 (1964) 1-12
[4] H.G. Kim et al, Development of surface modified Zr cladding by coating technology for ATF, Top fuel 2016, 17526
[5] X. Ma et al, Benefit or harm of accident tolerant coatings on the low-cycle fatigue properties of Zr-4 cladding alloy: in-situ studies at 400°C, J. Nucl. Mater. 545 (2021) 152651
[6] M. Ševeček et al, Fatigue behavior of cold spray-coated accident tolerant cladding, Top fuel 2018, A0126
[7] P. Cavaliere, Fatigue behaviour of cold sprayed metals and alloys: critical review, Surf. Eng. 32 (2016) 631-640
[8] V. Kvedaras, Fatigue strength of chromium-plated steel, Mater. Sci. 12 (2006) 16-18