Advancements in FeCrAl Alloys for Enhanced Accident Tolerant Fuel Cladding for Light Water Reactors

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INTRODUCTION

Advanced FeCrAl alloys are being considered as an enhanced accident tolerant fuel (ATF) cladding for light water reactor (LWR) applications as they can exhibit slower reaction kinetics with high temperature steam and have a reduced production of hydrogen during accident scenarios compared both to historic 304L cladding and Zircaloy [1,2]. Both of these attributes are key towards producing a fuel-form with enhanced accident tolerance over the current Zr-based-UO_2 fuel form in deployment.

A multi-year, multi-laboratory effort has been established to rapidly advance FeCrAl alloys as an ATF concept. This effort has focused on optimizing the microstructure and composition of these alloys in an attempt to provide performance on-par with or better than the current Zr-based cladding in both normal operating conditions and under accident scenarios. To date, a significant database supporting key performance factors in both scenarios has been developed. Based on this database, a compositional and microstructural window has been identified providing the insight for an optimized, advanced nuclear-grade FeCrAl alloy for LWRs.

This work will provide a comprehensive overview of the systematic effort to advance FeCrAl alloys as an enhanced ATF cladding in commercial LWRs.

DESCRIPTION OF ACTUAL WORK

Base Properties

A wide range of different alloys have been developed including model FeCrAl alloys and more complex engineering grade FeCrAl alloys. These different alloy variants span the Fe-rich corner of the Fe-Cr-Al ternary phase diagram with nominal Cr contents between 0-20 wt.% and Al contents between 0-10 wt.%. Minor additions including Y, Mo, Si, C and Nb have also been introduced. A wide range of different thermomechanical treatments (TMT) have been applied to form microstructures with varying grain size and secondary phase dispersions. Parallel to these alloy development efforts, other commercial FeCrAl alloys have been assessed.

As part of the program, all alloys have been evaluated using tensile tests at room temperature (RT) and a select set at elevated temperatures. Generally, all alloys developed for strength criteria showed excellent tensile properties with yield strengths at RT between 500-800 MPa and total elongations between 5-30% [1]. Several developed alloys with optimized compositions and microstructures showed tensile properties that exceeded commercial FeCrAl alloys while retaining the excellent workability required for thin-tube drawing. No significant negative effect was found on tensile properties with varying either the Cr or Al content of the alloys.

Evaluations on the ability to fabricate FeCrAl alloys into thinned walled cladding has also been completed. Tube drawing efforts have seen success but have been proven to be extremely sensitive to the starting condition (composition and microstructure) of the alloy and selected drawing parameters. Contrary to the tube drawing sensitivities, the weldability of FeCrAl alloys has little to no dependence on the starting condition of the alloy as long as controlled fusion-welding techniques such as laser welding are deployed. Given this, fusion-based weldments typically have lower strength parameters compared to non-welded specimens [3], typical of stainless steel alloys.

Performance Under Normal Operation

Corrosion tests with immersion up to 1 yr. have been completed in pressurized water reactor (PWR) water chemistry, boiling water reactor hydrogen water chemistry (BWR-HWC), and boiling water reactor normal water chemistry (BWR-NWC) conditions at LWR temperatures. These tests have shown that with sufficient levels of Cr and Al (>10 wt.% and >3 wt.%, respectively). corrosion properties of the alloys are satisfactory with performance near or better than Zr-based alloys [4].

Testing by Rebak [2] has shown that even under aggressive conditions, that BCC-ferritic alloys with high-Cr including APMT have excellent stress corrosion cracking (SCC) resistance. These alloys consistently showed lower crack growth rates compared to other Fe-based alloys historically used in LWRs such as 300 series austenitic stainless steels.

The neutronic penalty of FeCrAl alloys has been assessed by George et al. [5] for a typical PWR system. It was shown that FeCrAl alloys, due to their inherent composition, will have a higher thermal neutron absorption cross section than typical Zr-based alloys. Two viable strategies were proposed to offset the penalty: decreasing the cladding thickness which in turns provides for a larger pellet diameter and/or increasing the enrichment of the ^{235}U in the fuel.

Neutron radiation tolerance evaluations have been completed up to 13.8 dpa at LWR relevant temperatures. Model and commercial alloys showed classical radiation hardening behavior, similar to the behavior in literature for other high-Cr, Fe-based alloys. Saturation in hardening occurred above 2 dpa. The hardening behavior was linked to the formation of Cr-rich α' precipitates, dislocation loops, and small defect clusters [6]. The hardening response was found to be composition dependent primarily due to variances in the number density of Cr-rich α' precipitates after irradiation [6].

In-pile swelling and creep measurements are also being conducted at the Halden Reactor. Negligible swelling and modest irradiation creep rates have been measured to date, which is consistent with the literature on ferritic alloys [7]. A significant thermal creep component is present, particularly at the high stress levels (~300 MPa) examined so far in this ongoing experiment.

Performance Under Accident Scenarios

Several different screening tests for high temperature steam oxidation have been evaluated including isothermal exposures [1,8], ramp testing, and step-ramp testing. Performance under these tests varied depending on the tested alloy's composition. Generally, lean FeCrAl compositions (<10 wt.% Cr and/or <5 wt.% Al) under performed compared to non-lean compositions when subjected to the same test. A clear observation was made from these tests: a critical amount of Cr and/or Al is needed to form a protective alumina scale when tested in high temperature steam [8]. Furthermore, other variables such as minor alloying additions also vary the oxidation resistance of a given alloy.

Cladding burst tests have been completed on several model FeCrAl alloys by Massey et al. [9]. These tests show that FeCrAl alloys have nearly a 10% higher temperature at burst onset compared to Zr-based alloys. The burst criterion for the FeCrAl alloys is dictated by the thermomechanical instability and the generally good oxidation resistance meaning the mechanisms for burst are uniquely different than Zr-based alloys.

In-situ isothermal annealing small angle neutron scattering (SANS) experiments on irradiated specimens has shown the radiation-induced microstructure would have little effect at temperatures greater than 500°C during accident scenarios.

CONCLUSIONS

Efforts undertaken by this multi-year, multi-laboratory program have shown the viability of using FeCrAl alloys as an ATF cladding in LWRs. Most importantly, it has been shown the oxidation resistance, decreased hydrogen production, and reduced heat generation of FeCrAl alloys strongly contribute to its ATF capability. Furthermore, it has been shown that the normal operational performance of a FeCrAl cladding can rival that of Zr-based alloys. Finally, it was found that optimizing the performance of FeCrAl cladding materials requires balancing the starting composition and microstructure in order to satisfy key performance indicators such as oxidation resistance and radiation tolerance.

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