Accident tolerant FeCrAl fuel cladding: current status towards commercialization

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Abstract

FeCrAl alloys are rapidly becoming a mature concept for accident tolerant fuel applications. The FeCrAl material class has shown excellent oxidation resistance in high-temperature steam environments, a key aspect of any accident tolerant cladding concept, while also being corrosion resistant, stress corrosion cracking (SCC) resistant, irradiation-induced swelling resistant, weldable, and formable. Current research efforts are focused on design, development and commercial scaling of advanced FeCrAl alloys including large-scale, thin-walled seamless tube production followed by a broad spectrum of degradation evaluations in both normal and off-normal conditions. Included in this discussion will be theoretical analysis of the alloying principles and rules, alloy composition design, and overview of the most recent empirical database on possible degradation phenomena for FeCrAl alloys. The results are derived from extensive in-pile and out-of-pile experiments and form the basis for near-term deployment of a lead-test rod and/or assembly within a commercially operating nuclear power plant.

Introduction

Iron-chromium-aluminum (FeCrAl) alloys are currently under investigation as an option for accident tolerant fuel (ATF) cladding in light water reactors (LWRs). FeCrAl alloys represent a family of advanced oxidation resistant alloys with typical Cr contents between 10 and 22 wt.% and Al contents between 4 and 8 wt.%. The Cr and Al contents are primarily within this range as these compositions are known to exhibit enhanced oxidation resistance in elevated temperature steam when compared to Zr-based alloys [1–4]. These fully ferritic, body-centered-cubic alloys have been investigated as part of a multiyear, multifaceted alloy development effort to establish a working materials database to enable full commercialization of FeCrAl alloys for ATF cladding deployment in LWRs [5].

The overall research and development (R&D) effort is broad with primary focuses in accident scenario testing, irradiation materials screening tests, safety/economic analysis, fabrication studies, vendor (commercial) interface, and integral testing such as water loop testing. These activities enable a robust and vast material database to be developed which in-turn provides a fundamental scientific basis for alloy selection and production for commercial deployment. In the case of the R&D effort, the goal is to deploy the selected alloy(s) as part of a Lead Fuel Rod(s) (LFR) in a Lead Test Assembly (LTA). Within this effort, the primary focus is on the development and maturation of the clad, the fuel remains unchanged from the typical commercial standard and hence will remain conventional UO_2.

An overview of the general structure of the R&D program is shown in Figure 1. Figure 1 shows the tiered approach where basic testing, such as oxidation testing, materials irradiation, and neutronics evaluations are used to define the working compositions for viable FeCrAl alloys as ATF cladding. This foundation is then used to develop more robust alloys that are closer in approximation of a commercially produced alloy and used in integral testing such ATF-2 and IFA-796 which are both neutron irradiation water loop tests in materials test reactors. This tiered approach resulted in a multi-phase development program where lower tiered examinations were completed on simple FeCrAl alloys deemed “Generation I” FeCrAl alloys. These alloys typically only contained Fe, Cr, Al, and Y (for enhanced oxidation resistance) and were not fully optimized for nuclear power applications. An overview of the R&D activities related to this generation of alloys can be found in multiple references [5,6]. Testing on Generation I alloys has given way to more complicated testing on more advanced alloys that closely approximate the expected composition and microstructure of the alloy(s) to be deployed within a lead fuel assembly (LFA). These alloys are deemed “Generation II” alloys. Generation II alloys are easily distinguishable from Generation I alloys as the Generation II alloys have optimized microstructures and chemistries. Generation II alloys fall within the “lean-alloy” chemistry class of the FeCrAl family. Typically, Generation II alloys have Cr contents between 10 and 13 wt.% and Al contents between 5 and 6 wt.%. Additionally, Generation II alloys include minor alloying additions such as Niobium and Molybdenum. All Generation II alloys are produced using traditional wrought fabrication techniques to minimize production costs and enable rapid interface with commercial vendors such as nuclear fuel vendors as well as seamless tube production vendors.

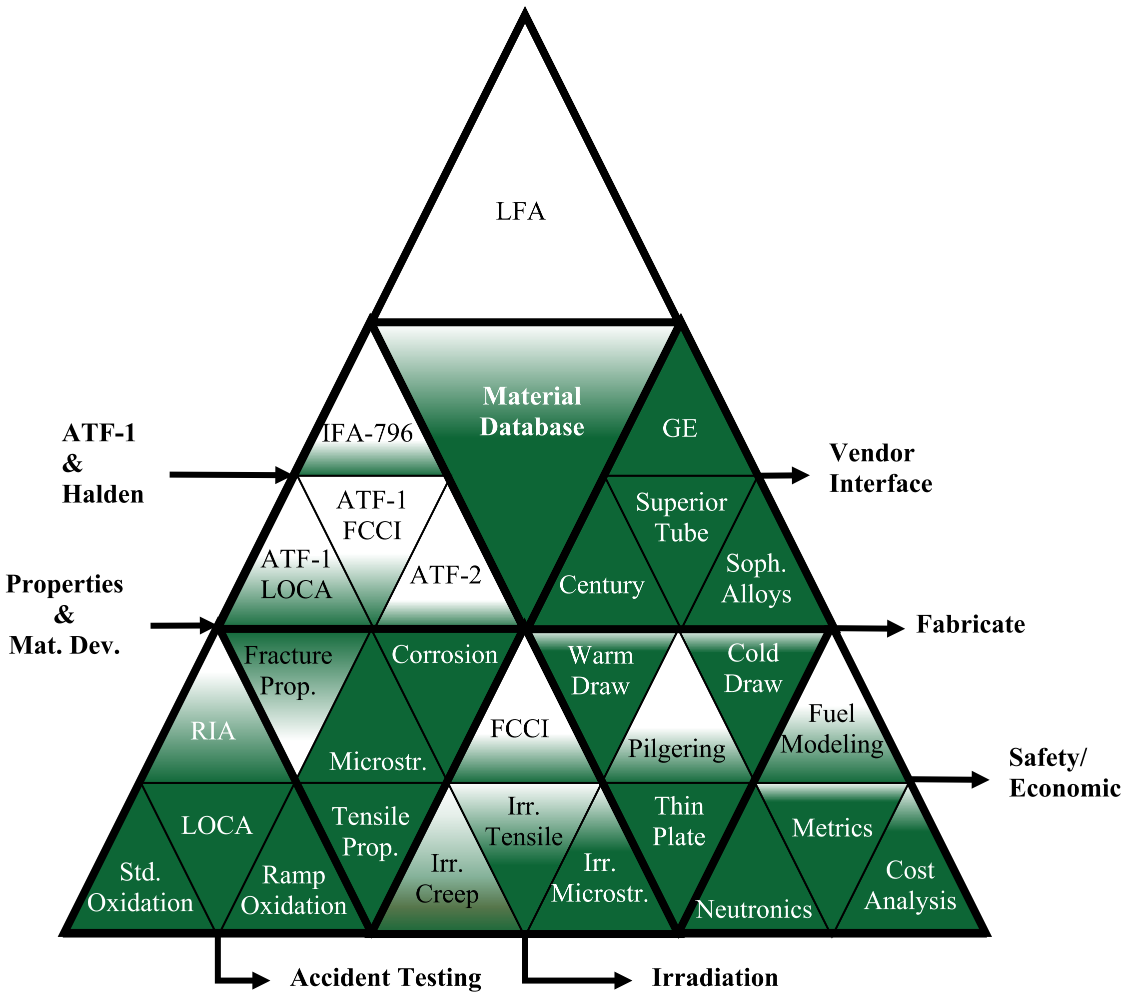

Figure 1. R&D program design strategy. Filled polygons represent a qualitative assessment on the extent of testing completed regarding the specified topic. Definitions: Std: standard; LOCA: loss of coolant accident; RIA: reactivity insertion accident; Irr.: irradiation; Microstr.: microstructure; FCCI: fuel-cladding chemical interaction; Soph.: Sophisticated; LTR: lead test rod; GE: General Electric Corporation.

Figure 1 also provides a qualitative representation of the extent of testing completed regarding a specific topic of interest based on the currently available literature. For example, the irradiation tensile topic within the “Irradiation” group is partially filled at nearly 50%. This assessment is based on the wealth of irradiated mechanical properties for Generation I FeCrAl alloys [7] but only limited low dose (<2 displacements per atom (dpa)) data for Generation II FeCrAl alloys [8]. Another example is from the more complicated integral testing such as the Accident Tolerant Fuel (ATF)-2 test. The ATF-2 test is currently only in the design stage and therefore does not show significant progress within Figure 1. The most important aspect is the material database shown in Figure 1. Significant progress has been made within the R&D effort resulting in a large degree of data on Generation I, Generation II, and commercially available FeCrAl alloys. The reminder of this discussion is orientated to providing an overview of the current materials database for FeCrAl alloys.

Overview of Materials Database

The current understanding of Cr and Al on different material properties and conditions for FeCrAl alloys as well as the wealth of data for a specific topic of interest for ATF cladding is depicted schematically in Figure 2. It should be noted that the topics listed in Figure 2 are not the sole topics/focus areas currently under investigation to enable deployment of a LFA. The topics listed are only a representative cross section of focus areas that were or are under investigation. Additionally, Figure 2 also lists Generation I, Generation II, and commercial alloys. Investigations on all three FeCrAl classes has enabled the understanding of composition effects for a given topic/property. Only a brief discussion on the current materials database and discussion on future directions for the database is discussed as a handbook on material properties which discusses in great detail the topics represented (and not represented) in Figure 2 is forth coming [9].

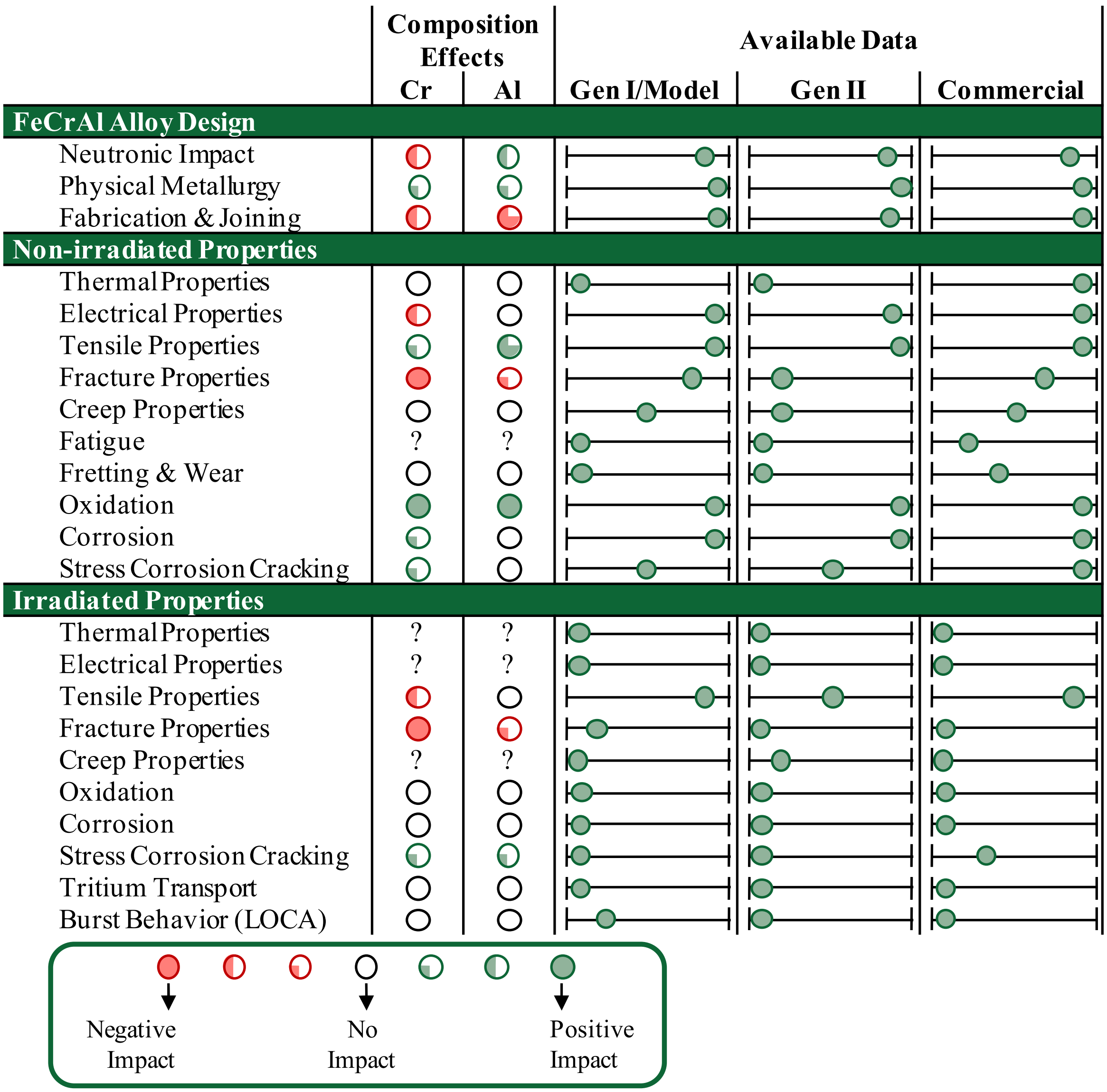

Figure 2. Summary of the materials database on FeCrAl alloys for accident tolerant fuel cladding applications. The amount of polygon fill in the Cr and Al columns is a qualitative representation on the degree of severity on the impact of a property/topic of interest. "?" denotes areas with unknown effects, if any. Available data columns represent degree of data; left: limited data set(s), right: complete data set(s).

Figure 2 shows the inherent complexity in designing FeCrAl alloys for ATF cladding applications. For example, it has been shown that large amounts of Al and to a lesser degree, Cr, has significant impacts on the fabrication and especially joining of FeCrAl alloys. High Al and Cr content FeCrAl alloys have been shown to be susceptible to weld-induced cracking [10,11] as well as have stronger propensity for work hardenability leading to cracking during typical compressive tube-drawing activities [12,13]. Additionally, high Cr additions (>10-12 wt.%) in Generation I FeCrAl alloys are susceptible to α' leading to significant radiation-hardening and potential embrittlement near end of life irradiation doses [7,14–16]. On the other hand, Cr and Al additions, at concentrations where α' is expected to form and weld-induced cracking is an issue, are needed to form a dense passivating α-Al_2O_3 layer during elevated steam exposure [1–4]. In this respect, many of the material properties require a delicate balancing act to optimize the chemistry (and the microstructure) to ensure successful operation of a FeCrAl cladding during normal and off-normal operation within a LWR. Given this, other materials properties, as shown in Figure 2, are rather insensitive to starting composition such an aqueous corrosion, at least within the composition range currently under investigation.

The complex interplay between different material properties is a primary driving factor for the limited studies conducted on more complex material behavior such as stress corrosion cracking and fuel-clad behavior in the presence of an irradiation field, Figure 1 and Figure 2. These integral tests (IFA-796, ATF-1 FCCI, ATF-1, and ATF-2 — Figure 1) require complex designs leading to long experimental development times (on the order of 1-2 years) and due to limited in-core materials testing reactor core space only a limited dataset of alloys can be investigated. Hence, several FeCrAl alloy down-selections have occurred prior to the start of these complicated experiments.

The most significant down selection was within the transition from Generation I to Generation II FeCrAl studies. As noted prior, the Cr content was down selected to only include alloys with 10, 12, or 13 wt.% Cr and Al contents of either 5 or 6 wt.%. This narrow composition band represents alloys predicted to have the best optimization of materials properties and hence are those proposed for use in the advanced, integral tests. The result is future development within the material database, especially for oxidation, corrosion, stress corrosion cracking, and LOCA behavior of irradiated cladding will be completed within this refined alloy space on Generation II alloys.
In the terms of a LFA/LTA, it is anticipated a Generation II FeCrAl alloy will be deployed as the cladding. Therefore, the advanced testing will be directly applicable towards the understanding of the performance of the LFA within a commercial LWR. Finally, it should be noted that insertion of a LFA/LTA only represents the first steps to a fully adopted, commercially deployed ATF FeCrAl cladding for today's current LWR fleet. Zr-based alloys have seen decades of refinement based on lab-scale experimentation and modeling as well as based on operational knowledge. FeCrAl alloys are anticipated to be no different, and the knowledge gained from the first series of LFA(s) within a LWR will enable further refinement of the Generation II alloy class and eventually enable a nuclear fuel vendor to provide an inherently accident tolerant fuel cladding within today's commercial LWRs.

Summary

An extensive R&D program focused on the development of ATF FeCrAl cladding for commercial LWRs that will enhance the inherent safety of nuclear power generation in the United States and abroad is on-going. The focus of the program is identifying FeCrAl alloy(s) that perform well in both normal and off-normal operation. To accomplish this task, a tiered program-structure was developed with focuses on accident testing, irradiation testing, safety/economic analysis, fabrication studies, integral testing, and commercialization efforts. This tiered approach has led to a vast materials database on three classes of FeCrAl alloys: Generation I, Generation II, and commercial FeCrAl alloys. Generation II FeCrAl alloys represent the alloys which closely resemble the expected chemistry and microstructure of a commercially deployable ATF FeCrAl cladding. Generation II alloys were developed based on the fundamental studies completed on Generation I and commercial FeCrAl alloys. A significant milestone lays ahead for FeCrAl alloys with the deployment of a LFA within a LTA in a commercial LWR and the established materials database for all three alloy classes is one of the primary enabling factors to meet this milestone.

Acknowledgements

This research was funded by the U.S. Department of Energy's Office of Nuclear Energy, Advanced Fuel Campaign of the Fuel Cycle R&D program and the U.S. Department of Energy, Office of Nuclear Energy, for the Nuclear Energy Enabling Technologies (NEET) program for the Reactor Materials effort.
This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for

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