Development and Evaluation of Cold spray Cr-coated Zr-alloy Cladding as Accident Tolerant Fuel (ATF) Design in LWRs

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1. Introduction

Since the Fukushima-Daiichi nuclear power plant accident in 2011, extensive research has been performed to improve accident tolerance of the nuclear fuel system (UO_2/Zr) in light water reactor (LWR).[1] The designs being considered by major fuel vendors, Westinghouse Electric Company (WEC), General Electric (GE), and Framatome include deposition of oxidation resistant coatings on the conventional Zr-alloy fuel cladding. More recently, the nuclear industries are also considering the use of these accident tolerant fuel (ATF) concepts for high enrichment fuel (up to 8%) to ahcieve higher burnup than the current regulatory burnup limit (62 GWD/MTU in PWR).[1] Thus, in addition to improved safety, the newly developed fuel cladding designs would allow for longer fuel life, less volume of spent nuclear fuel, and eventually safer and cheaper nuclear energy. WEC uses the cold spray technology (CST) to produce a thin Cr coating on Zr-alloy cladding, largely developed by the authors' group.

This paper presents overview of status of development and testing of ATF Cr-coated Zr-alloy cladding using CST, mainly driven by the Univ. Wisconsin, Madison. Fundamentals of CST is briefly introduced and details of the development of cold spray Cr-coated cladding are addressed. The performance testing of the coated cladding includes corrosion testing in prototypical normal operating conditions and high temperature steam oxiadtion tests. Fuel responses of the coated cladding under design-basis accidents such as reactivity-initiated accident (RIA) and loss-of-coolant accident (LOCA) have been actively evaluated.

2. Methods and Results

2.1 Cold spray deposition technology (CST)

Cold spray deposition technology (CST) is a solid-state, powder-based, material deposition process, where micron-sized feedstock powder particles are accelerated up to supersonic velocity by pressurized gas through a specially-designed converging-diversing nozzle system. The powder particles are impacted on a substrate and experienced severe plastic deformation to form a coating.[2] Strong adherent coatings are developed on the substrate above a certain particle velocity. Very high strain rate plastic deformation of particles and associated adiabtic shear instability at the particle-to-particle and particle-to-substrate are known as primary mechanisms of coating development. Fig. 1 shows the schematic diagram of cold spray process and material jetting and localized heating at the vicinity of the paricle/substrate interface, responsible for the coating formation.[2,3] The feedstock powder temperature is so much lower than the melting point that the deposition occurs in solid-state throughout the process.

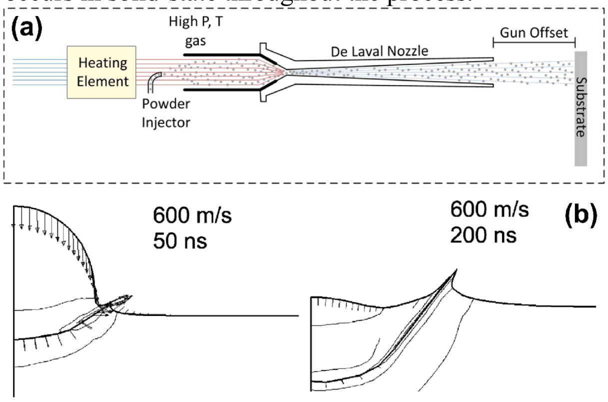

Fig. 1. (a) Schematic diagram of cold spray deposition technology and (b) FEM simulation result of Cu particle impact on Cu substrate.[2,3]

2.2 Cold spray Cr coating development

Zr-alloys have been used for LWR fuel cladding materials over five decades by virtue of their low thermal neutron absorption corss-section, corrosion resistance in normal operating condition, and good mechanical properties under neutron irradiation. However, Zr-alloy experiences significant oxidation and mechanical degradation under high temeprature steam environment in nuclear reactor accident conditions. In response to this performance, extensive collaborative research to develop cold spray Cr-coated Zr-alloy fuel cladding has been made between Univ. Wisconsin, Madison and Westinghouse Electric Company since 2014. For example, the team investigated the effect of Cr feedstock powder and cold spray parameters on the deposition efficiency and microstructure of Cr coatings on Optimized Zirlo™ tubes. The microstructure of the resultant coatings strongly depended on Cr powder microstructure and cold spray parameters.[4] In fact, powder manufacturing process determines the shape and microstructure (and associated mechanical properties) of the feedstock powder. Addition of helium to nitrogen propellant gas improved the deposition efficiency, adhesion strength, and density due to the increased particle impact velocity.

2.3 Corrosion/oxidation resistance

Corrosion performance of cold spray Cr-coated Zr-alloy samples was evaluated in the prototypical PWR condition (360 °C, 18.6 MPa with LiOH and boric acid) for 30 days. It showed negligible oxide layer (10 ~ 20 nm thick) formation on the coated surface while uncoated reference sample exhibited 1 ~ 2 μm thick oxide layer. EPMA analysis revealed most oxygen concentration was identified around Cr interparticle boundaries while no oxygen permeation through the coating was confirmed. The result emphasized the importance of quality and purity level of the feedstock Cr powder.

The cold spray Cr coatings provided ~ 50 times higher improvement in oxidation resistance compared to uncoated Zr-alloy in 1310 °C steam condition by formation of a protective Cr_2O_3 layer.[5] Fig. 2 shows the microstructure of oxidized Cr coated Zr-alloy at 1310 °C steam. The oxidation kinetics of cold spray Cr coatings was comparable to that of bulk Cr material. At elevated tempeatures, Cr/Zr chemical interaction was identified at the coating/substrate interface, which may influence mechanical integrity of the coated cladding after cooling down from high temperature accident scenarios.

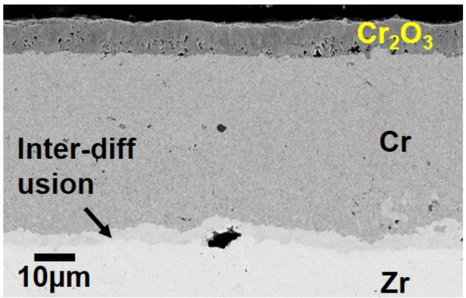

Fig. 2. Cross-sectional SEM image of cold spray Cr-coated Zr-alloy after exposure at steam environment at 1310 °C for 90 min.[5]

2.4 Reactivity-initiated Accident (RIA) Experiment

For accelerated deployment of the Cr-coated cladding in the current LWR fleet, it is necessary to demonstrate the response of Cr-coated cladding under power transient conditions such as reactivity-initiated accident (RIA) and loss-of-coolant accident (LOCA) events. A research project funded by the U.S. Department of Energy (DOE) has been investigating the thermal, mechanical, and irradiation response of Cr-coated Zr-alloy tubes under prototypical RIA conditions. The objective are being achieved by a pulse-type nuclear heat deposition on the Cr-coated cladding/UO_2 fuel system followed by comprehensive post-irradiation examination (PIE). The RIA tests has been performed at the Transient Reactor Test Facility (TREAT, Fig. 3) at Idaho National Laboratory (INL) to impose power excursions on two types of Cr-coated claddings (cold spray Cr coating, PVD Cr coating). The target peak cladding temperature (PCT), total energy deposition, and cladding internal pressure have been chosen to demonstrate potential late phase high temperature RIA such as cladding ballooning and burst, oxidation embrittlement, and cladding melting. All required samples were already fabricated. Reference testing with uncoated Zr-alloy cladding is being performed at TREAT facility. The project has been performed collaboratively by University of Wisconsin, Madison, University of Illinois Urbana-Champaign, U.S. Nuclear Regulartory Commission, and Pohang University of Science and Technology.

Fig. 3. A photograph of Transient Reactor Facility (TREAT) at Idaho National Laboratory (provided by INL).

2.5 LOCA Experiment

The Cr-coated Zr-alloy cladding designs can be a viable pathway to increased economic operation of current LWRs by improving fuel reliability and higher discharge burnup. Increasing the burnup limit reduces electricity cost and a total volume of spent nuclear fuel. However, burnup licensing extensions require sufficient information of the new fuel designs during design-basis transients like LOCA event. In particular, past transient experiments reported fuel fragmentation, relocation, and dispersal (FFRD) phenomena in high burnup fuels under LOCA. We have investigated the difference in thermal and mechanical behavior of ATF designs including Cr-coated cladding and FeCrAl alloys under blow-down and reflooding phases of a LOCA. A single-rod reflood facility has been constructred at Univ. Wisconsin, Madison to perform water reflooding test. Reproducibility and scoping tests have been completed using stainless steel cladding, Zr-alloy cladding, stainless steel pellets, and ceramic pellets under a variety of system conditions such as initial temperature, water subcooling, and reflooding velocity. The preliminary tests provide a credibility of the testing procedure and demonstrated behavioral differences depending on the testing condition. In addition, several thermocouples were installed inside the test section with different axial elevations to measure evolution of the temperature distribution of the cladding tube during quenching. The transition of boiling regimes were also visually examined using a high-speed camera.

3. Conclusions

Accident tolerant fuel (ATF) designs including Cr-coated Zr-alloy cladding are still being actively developed and qualified by nuclear fuel supplieres in U.S. under the DOE's leadership since 2012. The fuel suppliers has acquired out-of-pile testing data and simulation results from national laboratories and universities. For example, collaboratorive research activities between University of Wisconsin, Madison, Westinghouse Electric Company, and Pohang University of Science and Technology have been conducted to achieve accelerated licensing of cold spray Cr-coated cladding designs. It is noted that in-pile testing data are being collected from testing at commercial nuclear reactors for future licensing activities. The nuclear industries are also considering the use of these ATF concepts for high enrichment fuel (up to 8%) to achieve higher burnup level than the current regulargory burnup limit.

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