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Advanced Surface Modification Strategies for Reliability Enhancement of Accident Tolerant Fuel Cladding in Nuclear Reactors

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ABSTRACT:

Metal additive manufacturing processes are currently used to fabricate complex metal part shapes while maintaining mechanical properties comparable to those fabricated via traditional means of cast and wrought processes. Increased deposition rates, repairing capability via cladding and the ability to produce near-net-shaped parts have significantly increased the adoption of directed energy deposition (DED) for fabricating and repairing parts; however, a significant challenge exists when planning to alter the deposited metals' microstructure and mechanical properties if they involve in-situ alloying during deposition because we are unable to achieve the required material properties based on the unavailability of pre-alloyed powders used for AM processes. In-situ alloying can also result in novel alloy development with enhanced mechanical properties. In the first approach, the in-situ alloying capability of a multi-feeder DED will be leveraged to explore the process-microstructure-property relationships of FeCrAl-based coatings deposited on wrought FeCrAl alloys. Next, custom developed hybrid DED system will be utilized to conduct ultrasonic impact peening treatment intermittently while laser metal deposition to fabricate functionally graded laser cladded coating with enhanced mechanical properties and wear resistance. Grain refinement, texture, residual stress, and phase transformation along the substrate to multi-layer coatings will be tracked via neutron diffraction technique at Spallation Neutron Source (SNS), ORNL then correlated to UIP process parameters. Sliding wear testing to measure wear resistance and frictional behavior will be observed using reciprocating tribometer and a state-of-the-art autoclave fretting rig (AFIR) at ORNL will be used to evaluate the developed cladding samples' fretting wear resistance against traditionally fabricated FeCrAl claddings under a simulated nuclear reactor operating environment. This project's primary research objective is to understand the competitions and correlations between complex thermal histories, alloy compositions, material states, and attending properties using multi-feeder powder-blown DED and UIP systems. The driving rationale for this fundamental problem is: if sufficient understanding exists to control the microstructure and materials states across the wrought-DED deposition interfaces, it will be possible to tailor any arbitrary and desired differences for future accident tolerant fuel (ATF) claddings with enhanced functionality.

Zirconium (Zr) alloys are widely used for ATF cladding in LWRs; however, increased corrosion may occur due to contact with specific metallic components, such as Pt, Hf, Inconel also known as 'shadow corrosion'. Zr alloy-based parts have multiple disadvantages, including hydrogen absorption in Zr during fuel operations, resulting in embrittlement and fuel rod failure. These observations have inclined us to select the FeCrAl as the primary material for the proposed research but the major findings from this research can be utilized to other alloy families and different application sectors outside nuclear energy. Tribology is the science of friction, wear, and lubrication, making it inherently inseparable from surface engineering. Additive manufacturing (AM) and materials processing offer unique capabilities that can be leveraged to enhance the reliability of various tribo-mechanical contacts. Such symbiotic relationship between AM, materials processing, surface engineering, and tribology with respect to sliding and fretting contact problem in particular for nuclear reactor components will be explored by this proposed effort.