DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Laser Additive Manufacturing of Grade 91 Steel for Affordable Nuclear Reactor Components

PI: Dr. Stuart Maloy-Los Alamos National Laboratory

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Collaborators: Dr. T. Lienert-Optomec, Inc.; Prof. T. DebRoy-The Pennsylvania State University; Prof. P. Hosemann-University of California Berkeley

ABSTRACT:

According to the Nuclear Energy R&D Roadmap Report submitted to Congress in 2010, two key challenges facing the nuclear energy industry involve: 1) making improvements in the affordability of new reactors, including accelerated deployment schedules; and 2) developing structural materials to withstand irradiation for long periods of time. Laser additive manufacturing (LAM) is particularly well suited for more rapid and economical fabrication of reactor components relative to current fabrication methods. In addition, samples with microstructures that are associated with improved radiation tolerance have been produced using LAM with alloys utilized for reactor applications during a feasibility study.

The proposed work directly addresses the two R&D objectives outlined above. The efforts: 1) provide a LAM solution for rapid and more affordable fabrication of nuclear reactor components; and 2) address fabrication of components with a-priori design for radiation tolerance. Samples for the proposed work will be fabricated using a modified 9Cr–1Mo–V–Nb steel (Grade 91). Grade 91 steel is referred to as a 2nd generation creep-resistant steel. It is now employed widely in fossil fuel power plants in both plate and piping forms for components operating at temperatures up to ~650°C, and is a candidate material for nuclear power plants as well. Grade 91 is the current “workhorse” alloy in these applications and was approved for use under the ASME Boiler and Pressure Vessel (B&PV) Code in 1983. Reactor components are often constructed by joining of components by manual arc welding. Welded components of Grade 91 achieve the microstructures and properties required for use via a heat-treatment referred to as tempering.

The primary goal of the proposed work is to determine the feasibility of laser additive manufacturing (LAM) for producing reactor components of a ferritic/martensitic steel (Grade 91) with an engineered microstructure. During AM of Grade 91, individual passes within each layer transform in the solid-state to form martensite on cooling. With careful selection of process parameters, the adjacent passes in the same layer and passes in the layer(s) above will provide partial or complete tempering of the martensite in-situ to achieve the desired properties. We propose to tailor the LAM process parameters to provide in-situ tempering of the martensite in previously deposited layers. Using this approach, the component will have the desired combination of properties and will require no further heat-treatment before service, at lower costs relative to current practices. A second objective is to fabricate a prototype of a grid spacer component (for a fast reactor) of the same steel using LAM.

Samples for the experiments will be produced using Grade 91 steel powder with a Laser-Directed Energy Deposition (L-DED) AM machine at Optomec. Micro-scale mechanical testing (at several temperatures) is also proposed to allow comparison with standard wrought Grade 91 to assess AM feasibility. Irradiation testing (H+ and Fe2+) will be undertaken at the LANL’s Ion Beam Materials Laboratory (IBML) at ambient and elevated temperatures with a few different dpa levels. Nano-hardness surveys will be conducted within and beyond the depth range of radiation to determine the change in hardness from radiation-induced damage. Microstructural characterization, both before and after irradiation testing, will involve optical microscopy, SEM including EBSD and TEM/STEM to determine the morphology, location, volume fraction, composition and crystal structure of the various phases, as well as the presence and density of radiation-induced defects such as dislocations, vacancies and clusters. Selection of AM process parameters will be guided by results generated by a well-tested, three-dimensional, numerical heat transfer model that combines the multiple thermal cycles with phase transformation kinetics to simulate the in-situ tempering effects to achieve the desired properties. Long-term stability of the microstructure will be evaluated up to and above the service temperature (~650°C) to develop a time-temperature-precipitation diagram to calibrate the tempering model.

The planned efforts are focused precisely on providing solutions to issues confronting the future of the nuclear energy sector. The proposed work has significant potential to transform fabrication methods for reactor components made from radiation tolerant materials with increased affordability, faster implementation schedules and improved radiation tolerance. The results of this work will likely shift the paradigm for future construction of these components.