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Understanding PM-HIP Interparticle Evolution and its Influence on Fracture Toughness in Alumina-Forming Steels

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ABSTRACT:

The objective of this project is to understand how interparticle (i.e., powder particle surfaces) evolution during hot isostatic pressing (HIP) influences fracture toughness of Al-bearing steels. Powder metallurgy with HIP (PM-HIP) manufacturing is attractive for nuclear applications because components can be several orders of magnitude larger than those fabricated by additive methods, exhibit homogeneous fine-grained microstructures, and offer exceptional mechanical properties. There is growing interest in PM-HIP manufacturing of Al-bearing steels, specifically alumina-forming austenitic (AFA) stainless steel and FeCrAl for high temperature oxidation-resistant structural, cladding, and fuel assembly components, owing to the improved creep strength and reduced embrittlement of the PM-HIP products. However, the high Al concentration of AFA and FeCrAl could lead to a significant population of residual oxides and porosity along prior powder particle boundaries (PPBs), thus compromising fracture toughness. PPB oxides and porosity are coupled artifacts associated with the high oxidation potential of Al. Hence, Al-bearing steels are especially susceptible to interparticle artifacts and consequent degradation of fracture performance, underscoring the critical need to understand the origin of these degradation mechanisms.

Tailoring PM-HIP processing parameters can control evolution of oxide and PPB microstructure, and consequently control fracture performance in Al-bearing steels. We will take an iterative loop approach in which we will vary HIP process parameters. Within each loop iteration, we will conduct a set of quasi-*in situ* experiments with closely coupled phase field models, to understand oxide and PPB formation mechanisms. These quasi-*in situ* experiments will interrupt the HIP process at specified percent densifications to characterize microstructure and fracture properties; phase field simulations of pressure-assisted sintering will provide insight into fundamental scientific drivers for the oxide and PPB evolution. This project leverages a new HIP at Purdue supported by an FY23 CINR Infrastructure award.

The scientific outcome of this project will be a fundamental understanding of interparticle evolution during HIP, specifically the development of powder cohesion, pore retention, and phase formation. The broader engineering impact will be process-structure-property maps directly linking HIP process parameters, microstructure, and fracture properties; these maps will enable original equipment manufacturers (OEMs) to design HIP components that will conform to nuclear code specifications and operate within desired safety margins. This project is relevant to DOE-NE because one of the greatest hurdles facing PM-HIP deployment in nuclear is how to limit the formation of residual oxides and porosity during HIP, and whether their effects on fracture behavior are acceptable. Educationally, we will stand up the Manufacturing Innovation in Nuclear with Data Science (MINDS) Research Experience for Undergraduates (REU) partnership with three undergraduate-serving institutions.