Micromechanical Integrity Evaluation of Advanced Manufactured SA508 Steels for Spent Fuel Verification Probe Housings

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1. Introduction

Verification probes deployed in spent fuel storage pools are subjected to extremely harsh environments, including high-level gamma/neutron radiation, accidental physical impacts, and underwater corrosion. These conditions threaten the structural integrity of the probe housing, which serves as a critical containment boundary for sensitive safeguards detection assemblies [1]. To enhance the durability and design flexibility of next-generation verification systems, advanced manufacturing technologies such as Powder Metallurgy-Hot Isostatic Pressing (PM-HIP) [2] and Directed Energy Deposition (DED) [3] are actively being considered. Unlike conventional forging, these techniques can deliberately engineer unique hierarchical microstructures that potentially offer an unprecedented balance of strength and impact toughness. Because conventional bulk testing averages out these fine-scale heterogeneities, localized micromechanical evaluation is essential to precisely decouple the individual phase contributions governing the overall structural resilience. This study investigates the micromechanical baseline of conventionally made, PM-HIPed, and DED SA508 steels to evaluate these advanced microstructural benefits and assess their suitability for high-performance probe housing components.

2. Methods

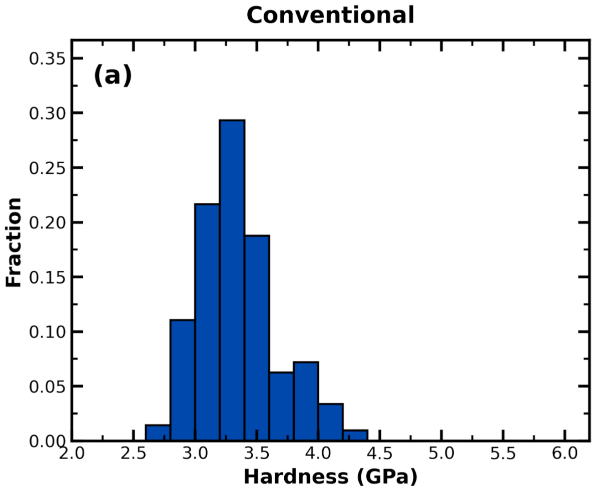
To simulate the localized mechanical response of probe housing materials fabricated via different routes, three SA508 Grade 3 Class 1 variants were systematically evaluated.

Three material variants—Conventional forging, PM-HIP, and laser-based DED—were prepared. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were utilized to determine the macro-phase constitution and estimate inherent manufacturing-induced residual stress states.

High-speed nanoindentation mapping employing the continuous stiffness measurement (CSM) technique was executed to resolve phase-specific mechanical responses. Over 100 indentation arrays per sample were performed. To properly capture near-surface properties relevant to housing surface degradation, the indentation parameters were carefully optimized for the shallow sub-micron regime. Maximum penetration depths were strictly confined below ~300 nm across all variants, aiming to facilitate the evaluation of highly localized phase heterogeneities while minimizing bulk-averaging artifacts. The mechanical properties were calculated using the Oliver-Pharr method [4], and the resulting nano-hardness datasets were compiled to construct probability density functions for statistical comparison. All specimens were mechanically polished with a final step using 0.05 μm colloidal silica suspension for 20 min. The resulting surface roughness is estimated to be Ra < 30 nm. Although this Ra value is not negligible relative to the maximum indentation depth (~200 nm), the consistent polishing protocol applied across all three variants ensures that any roughness-related systematic effect is uniform, and thus does not affect the comparative analysis between specimens [5].

3. Results & Discussion

The analysis of the nano-hardness probability density functions revealed distinct, manufacturing route-dependent mechanical signatures. As shown in the individual hardness distribution profiles, the conventionally forged SA508 (Fig. 1a) exhibited a narrow, unimodal hardness distribution, reflecting a homogenized, heavily tempered bainitic matrix, with an average nano-hardness of 3.35 ± 0.31 GPa (n = 208).



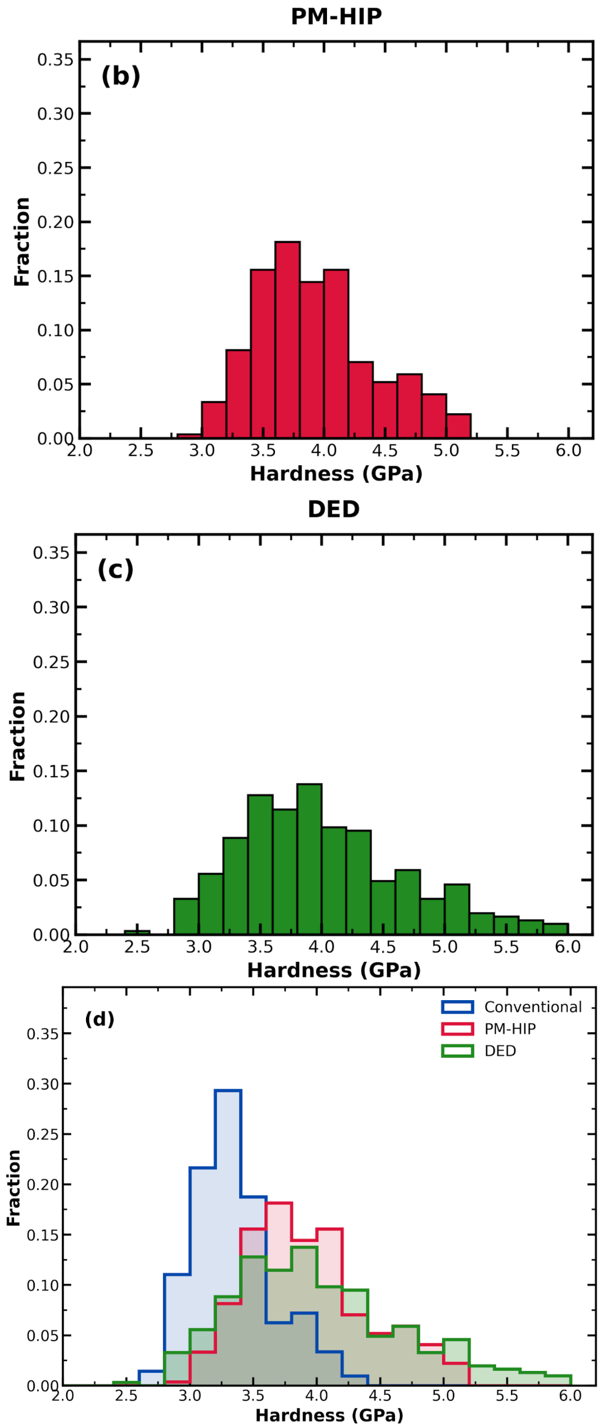


Fig. 1. Nano-hardness distribution profiles of SA508 steels manufactured via different routes: (a) Conventional forging, (b) PM-HIP, and (c) DED, showing distinct individual histograms. (d) Overlaid step-plot comparison highlighting the contrast between the unimodal distributions of Conventional/PM-HIP and the bimodal, hierarchical distribution of DED.

Similarly, the PM-HIP variant (Fig. 1b) displayed a narrow unimodal distribution, confirming exceptional macro-scale consolidation, with an average nano-hardness of 3.94 ± 0.48 GPa (n = 270). However, its baseline hardness was shifted higher than the forged variant by approximately 18%, which is attributable to solid-solution strengthening and oxide nanoparticle pinning.

Conversely, the individual profile (Fig. 1c) and the overlaid comparison (Fig. 1d) clearly illustrate that the as-built DED SA508 exhibits a distinctly broad and bimodal hardness distribution, with a median nano-hardness of 4.01 ± 0.67 GPa (n = 305). Furthermore, the overall hardness of the DED variant is significantly elevated compared to the conventional forging by approximately 20%, which is primarily driven by the rapid cooling rates and subsequent microstructural refinement inherent to the laser-based process. This micromechanical heterogeneity strongly suggests the presence of a hierarchical dual-phase-like microstructure rather than a manufacturing defect. The high-hardness peaks are likely attributed to fine martensite or Martensite/austenite (M/A) rich regions with high dislocation density, whereas the moderate-hardness peaks appear to correspond to auto-tempered zones composed mainly of tempered martensite and bainite. This composite-like behavior is expected to improve overall yield strength without sacrificing ductility.

4. Conclusion

The findings of this study indicate that advanced manufacturing introduces unique micromechanical signatures tailored by their specific thermal histories. While PM-HIP offers superior homogeneity (3.94 GPa ± 0.48 GPa), the bimodal micromechanical signature of the DED material (4.01 ± 0.67 GPa) indicates a highly advantageous hierarchical heterogeneity. This composite-like microstructural feature is expected to provide an optimal balance of strength and ductility, making it exceptionally resilient against external impacts. By characterizing the localized micromechanical behavior driven by these advanced manufacturing processes, this study establishes that both PM-HIP and DED are highly promising fabrication routes for ensuring the long-term structural integrity of next-generation spent fuel verification equipment.

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