ABSTRACT

This dissertation titled "Microstructure evolution and mechanical behavior of PBF-LB manufactured IN939 superalloy" presents a comprehensive investigation of the microstructural evolution and mechanical behavior of powder bed fusion-laser beam *(PBF-LB) IN939* superalloy. The study places particular emphasis on overcoming key challenges associated with process-induced heterogeneity, heat treatment optimization, and high temperature performance relevant to turbine and aerospace applications. Microstructural investigation confirms occurrence of heterogeneous grain morphology and the absence of γ' precipitates in the as-built *(AB) IN939* superalloy due to rapid solidification associated with the *PBF-LB* process. Detailed characterization through electron backscatter diffraction *(EBSD)*, and scanning electron microscopy *(SEM)* reveals a strong location dependence of grain structure, and associated properties such as residual stress and hardness along the build height, driven by variations in cooling rate and thermal gradients inherent to the *PBF-LB* process. The top section exhibits shorter columnar grains together with larger cellular structures and existence of tensile residual stresses. On the other hand, the bottom section consists of finer cellular grains and longer columnar grains with occurrence of compressive residual stresses. *X-ray* diffraction *(XRD)* analyses reveal accumulation of higher strain in the bottom section. All these microstructural variations directly influences the mechanical behavior, as evidenced by multi-scale hardness measurements as well as tensile and compressive tests. These tests are performed at room temperature and elevated temperatures that are carefully chosen considering the service requirement of the superalloy. The *AB* superalloy demonstrates consistently higher hardness at the top section, thereby revealing the non-uniformity in hardness throughout the build height. Furthermore, occurrence of a clear indentation size effect is noted for this superalloy, signifying the influence of applied load levels at small scales. Upon assessing the mechanical performance of *PBF-LB IN939* superalloy at the bulk scale through conventional tensile testing, distinct yield strength anomaly *(YSA)* is noted. This is also accompanied by temperature-dependent reductions in ultimate tensile strength, ductility, toughness, and strain-hardening capacity. Digital image correlation (*DIC)* strain mapping exposed significant strain localization that could not be captured by conventional extensometers. Fractographic analysis reveals a transition in fracture behavior, with dimples at room temperature, evolving toward quasi-cleavage and brittle fracture at 750 °C and 850 °C. Considering the heterogeneity along with absence of the precipitate phase in the as-built *PBF-LB IN939* superalloy, thermal treatments are designed to evolve the microstructure further. Heat treatment studies demonstrated that solution treatment *(ST)* is the most critical step in homogenizing the microstructure, dissolving melt-pool features, promoting γ' precipitation, and stabilizing carbides. The specimen solution treated at 1190 °C *(1190_ST)* produced refined γ' precipitates and a partially recrystallized microstructure, leading to the best balance of strength, hardness, ductility, and strain uniformity, while the specimen solution treated at 1240 °C *(1240_ST)* result in full recrystallization and coarser γ' precipitates with comparatively lower strength. Subsequent multi-step aging treatments further coarsened γ' but resulting to limited mechanical improvement relative to *ST* alone. Evaluation of high temperature mechanical performance at 850 °C shows substantial reductions in tensile and compressive strength for both *1190_ST* and *1240_ST* specimens w.r.t the as-built specimen, due to γ' coarsening, loss of coherency, and γ matrix softening. However, compressive strength retention was relatively higher than tensile strength, highlighting tension-driven embrittlement as the critical limitation at service temperatures. High temperature nanoindentation performed on the *1190_ST* specimen confirmed localized softening, reduced hardness/modulus, and strong sensitivity to γ/γ' interfacial strength, aligning well with macroscopic observations. Collectively, this work establishes clear correlations between process-induced microstructural features, heat treatment-driven phase evolution, and high temperature mechanical response. These insights provide a scientific basis for optimizing *PBF-LB IN939* superalloy for reliable use in demanding high temperature turbine and aerospace environments.

Keywords: Powder bed fusion-laser beam, Microstructural evolution, High temperature mechanical behavior, Solution treatment optimization, γ/γ' phase stability, Strain localization, Nanoindentation