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A comprehensive analysis of residual stress formation in the selective laser melting process through numerical simulation and experimental validation for Inconel-625

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ABSTRACT

In this study, a multiscale finite element model is developed to simulate the Laser Powder Bed Fusion (LPBF) process using the Modified Inherent Strain (MIS) approach. This method represents an advancement over the traditional Inherent Strain (IS) technique, which was originally designed for welding process simulations. The IS method, while effective for simpler thermal-mechanical problems, lacks the ability to fully capture the complex interactions present in metal Additive Manufacturing (AM). In contrast, the MIS approach has been specifically adapted to address these complexities by considering the mechanical constraints imposed by sequentially deposited layers. These constraints significantly influence the evolution of residual stresses and strains throughout the fabrication process. The adoption of a multiscale modeling strategy enables accurate prediction of residual stress formation during LPBF, which is a critical factor in determining the structural integrity, quality, and mechanical performance of the final manufactured component. Nevertheless, a key research gap remains in the literature including very limited comparison between experimental data and MIS-based numerical predictions, particularly in terms of residual stress distribution below the top surface of components. Existing studies indicate that residual stress typically decreases from the top layer to the bottom when using the MIS approach. Therefore, the primary focus of this research is to evaluate the effectiveness of the MIS method in predicting residual stress below the top surface, which is crucial for ensuring accurate predictions in complex parts with non-uniform geometries. In this work, key process parameters, such as laser power and scan velocity, were systematically varied to evaluate their effects on residual stress distributions along both longitudinal and transverse directions. To validate the numerical simulations, experimental X-ray diffraction (XRD) measurements were conducted on fabricated Inconel-625 test coupons. The results demonstrated that while the MIS model provides accurate residual stress predictions at the surface level with an error of 12%, some discrepancies emerge in deeper subsurface regions, where the model tends to underestimate tensile residual stresses. This suggests that further refinements, such as incorporating real-time thermal feedback in macroscale analysis or machine learning-based corrections may be necessary to enhance the predictive accuracy of stress distributions in multi-layer AM processes. Ultimately, this study highlights the strengths and limitations of the MIS method and offers valuable insights for future research aimed at improving residual stress predictions in LPBF-manufactured components.