

Effect of Build Parameters on Mechanical Properties and Residual Stresses of LP-DED Inconel 718 Overhanging Structures

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Abstract

Additive manufacturing of Inconel 718 via laser powder direct energy deposition (LP-DED) offers design flexibility for repair and fabrication of large components. However, mechanical properties remain sensitive to process parameters and geometric constraints, which impact the consistency of material properties. This study investigates the effect of different build angles (0°, 20°, 30°, and 35°) at different laser powers (1070W and 2000W) on the mechanical properties and residual stresses. Eight overhanging structures were fabricated using Inconel 718 and subjected to various heat treatments (SR+HIP+SOL+Aging). Numerical simulations were developed to predict residual stresses in the samples, and models were validated through X-ray diffraction residual stress measurements. Specimens were machined from the samples for tensile and high-cycle fatigue (HCF) testing. The paper concludes with a comparison and remarks about the repeatability and reproducibility of material properties between build angles and different power approaches.

Keywords: Inconel 718, LP-DED, Overhangs, Finite-element analysis, High Cycle Fatigue

1 Introduction

Nickel-base superalloy Inconel 718 is extensively used in high-temperature, high-stress applications, such as turbine discs, compressor blades, and structural connectors in aerospace and power-generation systems, due to its excellent combination of strength and corrosion resistance and fatigue life [1]. Achieving reliable fatigue performance is critical for safety and service life in these demanding environments, yet conventional casting and forging routes impose limitations on part complexity and lead times [2].

Additive manufacturing (AM) techniques, particularly laser-power directed energy deposition (LP-DED), can fabricate near-net-shape Inconel 718 components with tailored geometries and localized property control. However, the rapid thermal cycling intrinsic to LP-DED induces heterogeneous microstructures, sizable residual stresses, and geometric distortions, all of which can markedly influence fatigue crack initiation and propagation [2].

Most fatigue studies on additive-manufactured Inconel 718 have focused on laser-power bed fusion (L-PBF) processes, revealing correlations between processing parameters, porosity distribution, and endurance limits [3]. Few investigations have systematically examined LP-DED variants under consistent post-processing protocols (solution treatment, hot isostatic pressing, and ageing) [4]. Moreover, the interplay between experimentally measured fatigue life and finite

element predictions of residual stress and distortion remains unexplored for LP-DED geometries [5].

In this work, we combine high-cycle fatigue testing with microstructural analyses, alongside thermomechanical simulations of slanted “box” specimens, to quantify the influence of LP-DED build parameters on the fatigue endurance of Inconel 718. Specimens were produced at varying laser powers and build angles, subjected to a standardized heat-treatment sequence, and tested at stress levels based on tensile properties. Thermomechanical finite-element models provided insight into residual stress fields and deformation patterns. Results establish process-structure-property relationships critical for qualifying LP-DED Inconel 718 in fatigue-sensitive applications.

2. Materials and Methodology

2.1 Specimen Fabrication

Inconel 718 feedstock powder was deposited utilizing a proprietary laser powder-directed energy deposition (LP-DED) system (RPMI 222XR chamber) within an argon atmosphere. Four build angles (0°, 20°, 30°, and 35°) and two laser power settings (1070 W and 2000 W) were examined. All additional parameters are provided in Table 1.

Table 1. LP-DED Process Parameters by Laser Power

Laser Output	End Part Thickness	STL Thickness	Spot Size	Hatch Width	Layer Thickness	Powder Flow Rate	Contour Speed	Hatch Speed
1,070 W	0.250"	0.180"	0.070"	0.045"	0.015"	11 g/min	32 IPM	40 IPM
2,000 W	0.325"	0.220"	0.105"	0.070"	0.025"	13 g/min	28 IPM	40 IPM

The block geometry consisted of slanted “box” coupons with dimensions of 4x4x3.25 in, with rounded edges for simulation fidelity.

2.2 Thermomechanical Simulation

Finite-element analyses were performed in ANSYS 2023 R2 using the Additive DED Workbench to predict residual stresses and deformations in each slanted box:

- **Geometry and Meshing:** Imported CAD with rounded edges; hexahedral Cartesian mesh, 2.5 mm cell, cluster volume = 250 mm³
- **Thermal Run:** Moving Gaussian heat source (matching 1070 W/2000 W), element birth/death to simulate layer deposition, convective boundary $h = 10 \text{ W/m}^3 \cdot \text{K}$, base held at 300 K, dwell time = 10 s
- **Structural Run:** One-way coupling: map transient thermal fields into the stationary structural solver to compute von Mises and out-of-plane deflection
- **Validation:** Compared simulation profiles to CMM-measured deformations and X-ray diffraction residual stress (Lambda Inc. and NASA MSFC)

2.3 Post-Processing Heat Treatment

All as-deposited boxes underwent a four-step sequence to homogenize microstructure and close residual porosity:

1. **Stress Relief (SR):** $1950 \pm 25^{\circ}\text{F}$ (1163°C) for 1.5 h under vacuum, followed by furnace cooling.
2. **Hot Isostatic Pressing (HIP):** 2125°F (1163°C) for 3-4 h at 15 ksi (103 MPa), slow cool in the HIP vessel
3. **Solution Treatment (SOL):** $1950 \pm 25^{\circ}\text{F}$ ($1065 \pm 14^{\circ}\text{C}$) for 1 h, followed by air cooling or faster.
4. **Ageing (Age):** $1400 \pm 15^{\circ}\text{F}$ ($760 \pm 8^{\circ}\text{C}$) for 10 ± 0.5 h, furnace cool to $1200 \pm 15^{\circ}\text{F}$ ($650 \pm 8^{\circ}\text{C}$), hold at $1200 \pm 15^{\circ}\text{F}$ until a total ageing time of 20 h is reached, then air cool.

2.4 Mechanical Testing

- **Tensile Testing:** Instron 5982, room temperature, strain rate $1 \times 10^{-3} \text{ s}^{-1}$, 0.2%-offset yield and ultimate strength per ASTM E8.
- **Fatigue Testing:** MTS Landmark, load-control, $R = 0.1$, 40 Hz. Initial stress amplitude = 90% YS; survivors at 5×10^6 cycles increase 20% for the next specimen; failures before runout decrease 20% in amplitude.

2.5 Microstructural and Fractographic Characterization

- **Sectioning and Mounting:** Cut both XY and Z orientations, hot mount in powder BAKELIT black (phenolic resin for general purpose), grind to 1200-grit, polish with 0.1 μm silica, electro-etching using a solution of 70% phosphoric acid and 30% DI water, applied voltage of 7 volts for a duration of 30 s per sample.
- **Optical microscopy:** Keyence VHX 5000 for dendrite spacing, grain morphology, and porosity.
- **SEM and EDS:** JEOL JSM-IT500 for fracture-origin imaging and phase identification.
- **Fractography:** SEM examination of crack initiation and propagation striations.

3. Results

3.1 Deformation Patterns

The deformation trends for DED-built Inconel 718 slanted boxes indicate a clear relationship between increasing overhang angles and resulting deformation. Numerical simulations conducted at two laser power levels (1070 W and 2000W) revealed that deformation increases significantly with steeper build angles (30° and 35°), attributed primarily to reduced structural support and larger overhang regions.

For example, directional deformation measurements at a laser power of 1070 W for the 20° and 30° inclination angles showed discrepancies of approximately 10-15% when compared to experimental results, indicating good model reliability. At the 20° and 30° overhang angles, directional deformation along the Y-axis was closely matched by experimental validation, with discrepancies below 10%. Similarly, simulations at 2000 W further emphasized larger deformation magnitudes compared to the lower laser power.

3.2 Residual Stress Behavior

Residual stresses significantly varied based on the inclination angle and applied laser power. Generally, residual stresses were higher in vertically built walls (0°) and progressively reduced as the wall angle increased to 35°. Simulation data for stresses (S_{xx} , S_{yy} , S_{zz}) indicated pronounced tensile stress regions, primarily due to steep thermal gradients.

Experimental X-ray diffraction measurements validated the simulation results effectively, particularly for vertical walls at 1070 W laser power, where the discrepancy between predicted and experimental residual stress values remained minimal. Residual stress simulations and experimental validations along specific measurement paths for 0°, 20°, 30°, and 35° slant angles revealed strong overall agreement, despite minor deviations at particular points.

3.3 Influence of Base Removal

Removing the base of the fabricated boxes significantly influenced the residual stress and deformation outcomes. Simulations showed residual stresses reduced substantially (by approximately 40-70%) upon removal of the base plate. However, this action resulted in an approximate 30% increase in total deformation, highlighting the trade-off between residual stress mitigation and dimensional stability.

3.4 Additional Experimental Testing

Mechanical testing and microstructural analyses, including tensile and fatigue testing, as well as detailed micrographs of as-built and heat-treated conditions, are currently in progress. These forthcoming results will further validate and expand upon the simulation findings.

4. Discussion

The observed deformation patterns confirm that the build angle and laser power significantly impact structural stability during the DED process. Higher deformation at increased inclination angles, particularly at 30° **and** 35°, aligns with reduced inherent structural support. The reliability of simulation data, validated by experimental results with discrepancies below 15%, underscores the computational model's robustness.

Residual stress analysis further reinforced the influence of laser power and geometric configuration. The high tensile residual stress in vertically oriented structures reflect pronounced thermal gradients, highlighting the importance of optimizing heat management strategies during fabrication. Agreement between experimental and simulated residual stresses, particularly in vertical and moderately inclined walls (20° and 30°), suggests the simulations effectively predict stress distribution and magnitudes.

The trade-off identified between residual stress reduction and deformation upon baseplate removal presents critical consideration for post-processing strategies. While reducing residual stresses is beneficial for mechanical properties and structural integrity, the accompanying increase in deformation must be carefully managed through optimized process parameters and structural support strategies.

Future experimental outcomes, particularly from mechanical testing and detailed microstructural analyses, are expected to provide deeper insights into the microstructural mechanisms behind deformation and residual stress development. These findings will contribute significantly to validating and further refining the predictive models, ultimately guiding improved manufacturing practices for DED-processed Inconel 718 components.

Conclusion

This study demonstrates that numerical simulations effectively predict deformation and residual stress behaviors in Inconel 718 components fabricated by the DED process. Increasing overhang angles substantially affect deformation, while the residual stress distribution strongly depends on inclination angle and laser power. Simulations show high predictive accuracy, validated by experimental measurements, affirming the potential of numerical modeling for optimizing DED process parameters. Further experimental analyses will enhance understanding and enable more precise refinement of manufacturing techniques for high-performance Inconel 718 components.

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