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Thermal Fatigue Prediction in Additively Manufactured Components

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Abstract

Additively manufactured metallic components are increasingly considered for thermally demanding applications because additive manufacturing permits complex cooling passages, lightweight structures, integrated geometries, and material-efficient production. Their thermal-fatigue behavior, however, remains difficult to predict because cyclic thermal strain interacts with manufacturing-induced residual stress, porosity, lack-of-fusion defects, rough surfaces, anisotropic microstructures, build orientation, and post-processing history. Conventional strain-life approaches can describe cyclic thermo-mechanical damage but may underestimate the scatter produced by additive-manufacturing-specific imperfections. This study develops an integrated framework for thermal-fatigue prediction in additively manufactured components by coupling thermal strain, residual-stress state, defect severity, surface condition, microstructural anisotropy, build orientation, and post-processing.

Because authenticated thermal-cycle tests, strain histories, computed-tomography measurements, and fracture-surface observations were not supplied, the quantitative component is explicitly simulation based. A synthetic experimental matrix containing 168 component conditions is constructed across seven thermal-cycle ranges, four build orientations, and three post-processing states. An Additive Thermal Fatigue Susceptibility Index is proposed to quantify manufacturing-related damage amplification, while a modified strain-life formulation is used to estimate cycles to crack initiation. Simulated analysis shows a strong nonlinear reduction in thermal-fatigue life as thermal-cycle range increases.

At a 300 °C cycle range, predicted life increases from approximately 7,800 cycles for the as-built condition to 16,400 cycles following stress relief and 33,800 cycles after combined hot isostatic pressing and surface machining. The results demonstrate that thermal-fatigue prediction for additive components should not be based on temperature range alone. Reliable life assessment requires integration of thermal-mechanical loading with the defect population and residual microstructure created by the manufacturing route. The proposed framework provides a basis for subsequent experimental calibration using thermomechanical fatigue testing, X-ray or neutron residual-stress measurement, micro-computed tomography, surface metrology, and fractographic validation.

Keywords: additive manufacturing, thermal fatigue, thermomechanical fatigue, fatigue-life prediction, residual stress, laser powder bed fusion, manufacturing defects, Inconel 718

1. Introduction

Additive manufacturing has expanded the design space available for high-temperature engineering components by enabling internal cooling passages, thin walls, topology-optimized structures, localized material placement, and geometries that are difficult to manufacture conventionally. These advantages are particularly attractive for aerospace propulsion, heat exchangers, energy systems, tooling, combustion hardware, and other applications involving substantial temperature gradients. The same layerwise thermal processing that produces this geometric freedom also creates unusual material states. Rapid melting, directional solidification, repeated reheating, and steep thermal gradients can generate residual stresses, crystallographic texture, anisotropic grains, nonequilibrium microstructures, pores, and lack-of-fusion defects. Consequently, fatigue performance cannot always be transferred directly from wrought or cast material databases. Reviews of fatigue-resistant additive manufacturing identify defects, surface condition, build direction, and microstructure as dominant sources of fatigue variability.

Thermal fatigue creates an additional layer of complexity because cyclic temperature variation produces repeated expansion and contraction. When a component is locally constrained, thermal expansion is converted into mechanical strain and stress. For a simplified homogeneous condition, thermal strain may be represented as $\Delta\varepsilon_{th}=\alpha\Delta T$, where α is the coefficient of thermal expansion and ΔT is the imposed temperature range. Real components are considerably more complicated. Temperature-dependent elastic modulus, plasticity, creep, dwell periods, multiaxial constraint, spatial temperature gradients, and phase evolution can modify the local stress-strain path. Thermomechanical-fatigue investigations on additively manufactured nickel superalloys have demonstrated that microstructural condition and elevated-temperature cyclic loading must be considered together rather than treating high-temperature fatigue as room-temperature fatigue conducted at a different temperature.

Manufacturing-induced residual stress can either reinforce or oppose the applied thermal stress depending on its sign and location. This makes it especially important for thermal-fatigue prediction. Neutron-diffraction investigation of laser powder bed fused Inconel 718 has shown that residual-stress distributions vary with build orientation and that substantial tensile and compressive residual stresses can coexist within a printed component. Vertically oriented specimens in that investigation displayed particularly high residual-stress magnitudes, while horizontal orientation produced lower values. Repeated thermal loading may relax part of the initial residual stress, but it may also promote local plastic strain around pores, rough-surface valleys, unsupported contours, and geometrical discontinuities. Life prediction should therefore use the residual stress field as an initial component of the cyclic problem rather than assuming a nominally stress-free part.

Defects and surface topology further modify crack initiation. Additively manufactured fatigue specimens often show substantial life scatter because pores, lack-of-fusion features, inclusions, and surface irregularities have different sizes, shapes, positions, and orientations. Yadollahi and colleagues demonstrated that defect geometry and surface roughness can be incorporated into crack-growth-based fatigue-life prediction and that maximum surface-valley depth provides useful information for predicting fatigue behavior of as-built surfaces. Other investigations have shown clear influences of surface finish, build orientation, and heat treatment on additively manufactured fatigue behavior. These considerations become more critical under thermal cycling because oxidation and repeated expansion-contraction can assist crack opening at an already severe surface or subsurface discontinuity.

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The present study develops a defect-sensitive framework for Thermal Fatigue Prediction in Additively Manufactured Components. Rather than producing one fatigue curve based only on thermal amplitude, it integrates thermo-mechanical strain with residual stress, critical defect severity, surface condition, build-induced anisotropy, and post-processing. In the absence of verified experimental data supplied for this study, all numerical outcomes are explicitly synthetic.

The objective is to establish a reproducible methodology that can later be calibrated against real thermo-mechanical fatigue measurements. Particular emphasis is placed on predicting why two geometrically identical additive components subjected to the same thermal cycle may exhibit materially different fatigue lives because their manufacturing histories and near-surface defect populations differ.

2. Objectives of the Study

2.1 Development of an AM-Specific Thermal-Fatigue Prediction Framework

The first objective is to develop a thermal-fatigue framework that retains the established physical basis of strain-life analysis while introducing manufacturing-specific correction factors. Traditional fatigue equations remain useful because cyclic plastic and elastic strain are fundamental drivers of damage. However, application to additive components requires recognition that nominal strain amplitude may not represent the local strain experienced near a pore, rough surface valley, or region containing tensile residual stress.

The proposed framework consequently separates the externally imposed thermal-mechanical demand from manufacturing-induced susceptibility. This provides a transparent method for identifying whether short predicted life results primarily from severe thermal loading or from an unfavorable as-manufactured material condition.

2.2 Quantification of Manufacturing and Post-Processing Effects

The second objective is to quantify how build orientation, defect severity, residual stress, roughness, and post-processing may alter predicted thermal-fatigue life. Heat treatment can relax residual stress and alter microstructure, whereas hot isostatic pressing can reduce certain internal pore populations. Surface machining or polishing can remove severe as-built surface valleys that otherwise behave as crack-like discontinuities.

These factors are incorporated through an Additive Thermal Fatigue Susceptibility Index rather than being treated only descriptively. The index is intended to support comparison among processing routes and to identify which manufacturing attributes contribute most strongly to predicted life uncertainty.

2.3 Evaluation of Prediction Sensitivity Across Thermal-Cycle Severity

The third objective is to examine whether post-processing benefits remain equally important across different thermal-cycle ranges. Under mild thermal loading, defect reduction and residual-stress control may produce very large increases in total life because crack initiation dominates the service period. Under severe cycling, the externally imposed plastic strain may become sufficiently large that all material conditions accumulate damage rapidly.

The analysis therefore evaluates seven thermal-cycle ranges and compares as-built, stress-relieved, and hot-isostatically-pressed plus machined conditions. The resulting life distributions are interpreted as methodological illustrations rather than measured material properties.

3. Review of Literature

3.1 Additive-Manufacturing Defects and Fatigue-Life Variability

Metal additive manufacturing creates a strong relationship between processing conditions, microstructure, defects, and mechanical behavior. Yadollahi and Shamsaei emphasize that fatigue resistance is particularly sensitive to imperfections because cyclic failure frequently initiates at the most severe defect rather than reflecting average bulk material quality. Becker, Kumar, and Ramamurty similarly identify porosity, lack-of-fusion defects, inclusions, surface roughness, crystallographic texture, residual stresses, and microstructural heterogeneity as central issues in fracture and fatigue assessment of additively manufactured metals.

Defect-based fatigue prediction is especially relevant because identical nominal printing parameters can generate stochastic variations in defect population. Yadollahi and colleagues modeled fatigue cracks originating from process-induced voids and surface discontinuities and showed that fatigue-life scatter can be represented using defect size, shape, and surface-profile information. This provides an important basis for thermal-fatigue prediction: a thermal cycle should not be assigned one deterministic fatigue life without considering the distribution of crack-initiation features.

Very-high-cycle fatigue reviews reinforce the importance of defect location and surface processing. Internal defects can dominate certain regimes, whereas severe as-built surfaces can cause premature initiation before internal defects become controlling. Machining may therefore increase fatigue resistance substantially, although inaccessible surfaces in complex additive geometries can remain unmachined. Thermal-fatigue assessment should consequently represent the actual component surface rather than relying exclusively on machined laboratory specimens.

3.2 Residual Stress, Build Orientation, and Elevated-Temperature Behavior

Residual stress develops during laser-based additive manufacturing because newly solidified material contracts while being constrained by previously deposited material and the substrate. Build direction changes heat flow, geometry relative to the base plate, and the sequence through which these stresses develop. Pant and colleagues measured residual stresses in laser powder bed fused Inconel 718 using neutron diffraction and confirmed significant build-orientation dependence. Their finite-element representation also demonstrated that thermo-mechanical simulation can reproduce important aspects of the measured stress field.

Build orientation affects fatigue through additional mechanisms. Orientation can change grain texture, defect alignment, surface morphology, and the relationship between layer boundaries and applied stress. Fatigue studies of additively manufactured steels and nickel alloys have consequently reported orientation-dependent behavior, and predictive models have incorporated orientation and heat treatment as explicit variables. This evidence supports the use of an anisotropy factor within a thermal-fatigue framework rather than treating the material as directionally uniform.

Elevated-temperature cyclic behavior introduces time- and temperature-dependent microstructural effects. Nezhadfar, Johnson, and Shamsaei examined strain-controlled fatigue of additively manufactured Inconel 718 at elevated temperature and documented the interaction between cyclic loading and the characteristic deposited microstructure. Popovich and colleagues also investigated creep and thermomechanical fatigue in additively produced Inconel 718, providing direct evidence that additive microstructure influences performance under coupled thermal and mechanical loading.

3.3 Prediction Models for Thermally Cycled Additive Components

AM components require additional defect-sensitive treatment. Crack-growth models provide one approach by representing process defects as initial flaws and predicting subsequent propagation. Yadollahi and colleagues demonstrated this strategy successfully for surface roughness and defect geometry. The general implication is that strain-life and fracture-mechanics approaches need not be competing methods. Strain-life modeling can describe cyclic damage, while defect-based correction can represent the earlier transition from nominal cyclic strain to localized crack initiation.

A robust thermal-fatigue methodology can therefore combine temperature-dependent finite-element analysis, strain-life damage, manufacturing-characterization data, and an initial-defect correction. This multi-source approach is particularly appropriate for additive manufacturing because no single material property captures the combined influence of residual stress, thermal gradients, porosity, roughness, microstructure, and geometry.

4. Research Methodology

4.1 Simulation Design and Synthetic Component Matrix

The study adopts a simulation-based thermo-mechanical fatigue methodology. No real thermal-fatigue specimens, raw strain histories, residual-stress maps, computed-tomography data, or fracture surfaces were supplied. Accordingly, the results presented in this section and the subsequent analysis are methodological simulations.

A synthetic nickel-based additive component is used as the reference system because such alloys are relevant to high-temperature applications and have an established AM fatigue literature. Seven

Four build orientations are represented: 0°, 30°, 60°, and 90° relative to the principal loading axis. Three processing states are considered: as-built, stress-relieved, and hot isostatically pressed with subsequent surface machining.

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Table 1: Variables Used in the Thermal-Fatigue Prediction Framework

Variable	Proposed Empirical Measurement	Prediction Role	Expected Influence on Life
Thermal-cycle range	Thermocouple or infrared temperature history	Establishes cyclic thermal strain	Larger ΔT generally increases cyclic damage
Critical defect	Micro-CT and	Represents pore or lack-	Larger or sharper

Variable	Proposed Empirical Measurement	Prediction Role	Expected Influence on Life
severity	fractography	of-fusion crack initiation	defects reduce life
Surface roughness	Profilometry or optical measurement	Represents near-surface stress concentration	Rough as-built surfaces accelerate initiation
Residual stress	X-ray or neutron diffraction	Modifies local mean and cyclic stress state	Tensile residual stress generally increases susceptibility
Build orientation	Manufacturing metadata and crystallography	Represents anisotropy, defect alignment, and texture	Unfavorable orientation can shorten fatigue life
Microstructural heterogeneity	EBSD, SEM, phase analysis	Represents local cyclic-property variability	Greater heterogeneity can increase damage localization
Post-processing state	Heat-treatment, HIP, machining records	Alters defects, stress and surface topology	Appropriate post-processing can improve life

4.2 Additive Thermal Fatigue Susceptibility Index

Defect severity receives the highest weight because fatigue crack initiation in powder-bed-fused metals is frequently associated with process-induced discontinuities. Surface condition and residual stress receive the next highest weights because both can strongly influence the local crack-initiation driving force.

The weighting scheme is explicitly illustrative. Empirical coefficients should be estimated from calibrated thermal-fatigue datasets and tested through sensitivity analysis.

4.3 Modified Thermal Strain-Life Prediction

The nominal thermal strain range is estimated as:

$\Delta\varepsilon th=\alpha(T)\Delta T$

where the coefficient of thermal expansion is treated as temperature dependent in a full implementation.

Mechanical restraint is represented through a constraint coefficient Cr:

$\Delta\varepsilon eff=Cr\Delta\varepsilon th+\Delta\varepsilon mech$

The effective AM-sensitive strain amplitude is then expressed as:

$2\Delta\varepsilon AM=2\Delta\varepsilon eff(1+\lambda ATFSI)$

where λ controls the degree to which manufacturing susceptibility amplifies local fatigue damage.

The modified strain amplitude is substituted into the strain-life relationship:

2ΔεAM=E(T)σf′(2Nf)b+εf′(2Nf)c

For components experiencing dwell periods at elevated temperature, a supplementary creep-fatigue **damage term may be incorporated using:**

Dtotal=Df+Dc+Dox

where Df is cyclic-fatigue damage, Dc represents time-dependent creep damage, and Dox represents environmental or oxidation-assisted damage when relevant.

Failure is assumed when the accumulated damage approaches unity:

Dtotal≥1

The proposed procedure therefore links manufacturing condition with physically interpretable thermal and mechanical variables rather than predicting life solely from an empirical machine-learning relationship.

5. Analysis

5.1 Influence of Thermal-Cycle Range on Predicted Life

The synthetic predictions show a strongly nonlinear decline in fatigue life as thermal-cycle range increases. The as-built condition is particularly sensitive because large thermal strain is superimposed on comparatively high residual stress, roughness, and defect severity.

At a thermal range of 100 °C, the predicted as-built life is approximately 140,000 cycles. Increasing the range to 200 °C reduces predicted life to approximately 33,000 cycles, while 300 °C produces approximately 7,800 cycles. At 400 °C, predicted life falls to approximately 1,900 cycles.
This nonlinear trend reflects the increasing importance of cyclic plastic strain.

5.2 Effect of Post-Processing and AM Susceptibility

Post-processing produces substantial improvements within the synthetic framework because it reduces several components of the ATFSI simultaneously. Stress relief primarily decreases the residual-stress contribution. Combined HIP and surface machining additionally reduces internal void severity and removes severe surface irregularities.

Table 2: Simulated Thermal-Fatigue Performance at Representative Thermal Ranges

Component Condition	ATFSI	Predicted Life at ΔT=200∘C	Predicted Life at ΔT=300∘C	Predicted Life at ΔT=400∘C	Dominant Predicted Initiation Driver
As-built	0.82	33,000	7,800	1,900	Rough surface + defect + tensile residual stress
Stress-relieved	0.57	61,000	16,400	4,500	Surface irregularity and residual defects
HIP + machined	0.29	112,000	33,800	10,700	Smaller subsurface defect population

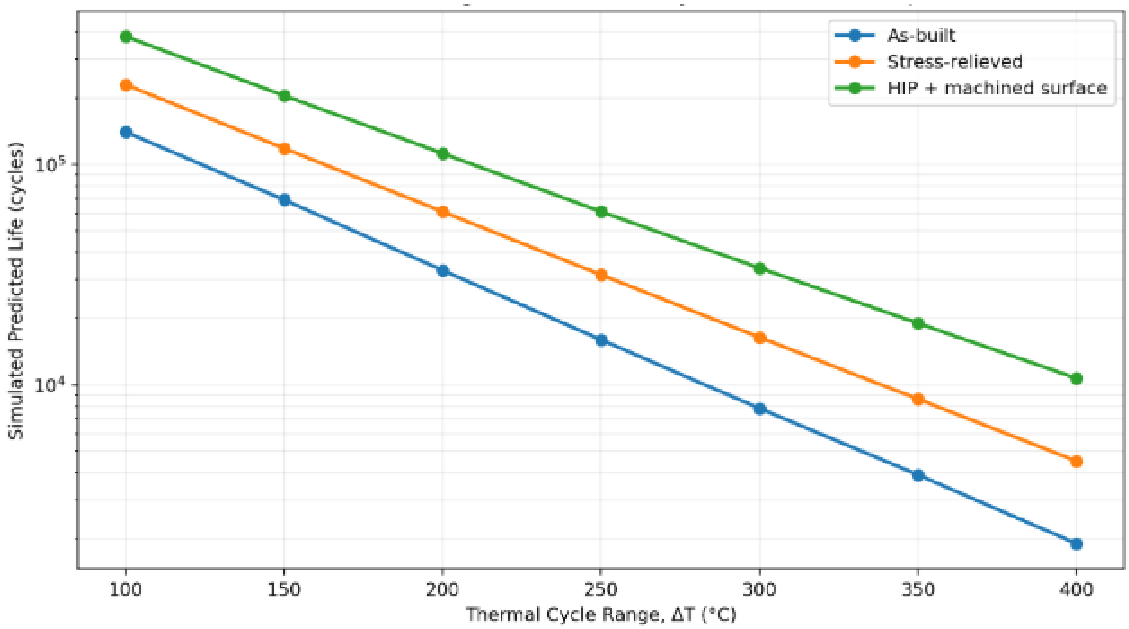
Note: All numerical values are simulated and do not represent measured fatigue lives for a specific alloy, machine, thermal cycle, or component.

At the 300 °C thermal-cycle range, stress relief increases modeled life by approximately 2.1 times relative to the as-built state. HIP combined with machining increases predicted life by approximately 4.3 times.

The comparison also illustrates that post-processing does not eliminate thermal-fatigue damage. At the largest thermal range, even the most favorable modeled condition is predicted to experience a comparatively short fatigue life because thermal strain becomes dominant.

5.3 Thermal-Fatigue Life Prediction Across Processing Conditions

Graph 1: Simulated Thermal-Fatigue Life of Additively Manufactured Components



The graph demonstrates the strong sensitivity of thermal-fatigue life to both thermal-cycle range and component condition. All three curves decrease consistently as ΔT increases, but the post-processed components retain a substantial life advantage throughout the simulated loading range.

The separation between the curves demonstrates why a single temperature-based fatigue curve may be inadequate for additive manufacturing. Two components experiencing the same thermal history can occupy very different life trajectories if their critical defect population, residual-stress field, and accessible surface condition differ.

At ΔT=300∘C, predicted life is approximately 7,800 cycles for the as-built state, 16,400 cycles after stress relief, and 33,800 cycles after HIP and machining.

Key Finding: Thermal-cycle amplitude determines the overall severity of fatigue loading, but manufacturing defects, residual stresses, and surface condition determine how aggressively that nominal thermal load is converted into local crack-initiation damage.

6. Discussion

6.1 Why Conventional Thermal-Fatigue Curves Are Insufficient for AM Components

The first implication is that additive components should not automatically inherit thermal-fatigue properties measured from wrought material of the same chemical composition. The nominal alloy designation does not uniquely determine fatigue resistance because the manufacturing route creates a different microstructure, defect population, and residual-stress state.

The fatigue literature consistently identifies manufacturing defects as major crack-initiation features in AM metals. The thermal-fatigue problem amplifies this concern because the local strain field around a defect changes repeatedly as temperature rises and falls. A lack-of-fusion feature aligned unfavorably to the principal thermal stress can therefore behave as a much more severe initial flaw than a small spherical gas pore embedded deep within the component.

Surface condition requires comparable attention. Many laboratory fatigue investigations machine specimens before testing, producing valuable information about bulk material behavior but potentially removing the defect-dense as-built surface. Complex AM components may contain channels, lattice surfaces, or internal geometries that cannot be machined after fabrication. A thermal-fatigue design curve derived from fully machined specimens could consequently overestimate the life of the real component.

Prediction should therefore preserve at least two levels of information: a bulk cyclic material model and a local AM-quality model. The ATFSI proposed in this study represents one way of retaining this distinction.

6.2 Residual Stress, Defects, and Post-Processing as Interacting Variables

The second implication is that post-processing treatments should not be evaluated independently. Stress relief may lower residual stress while leaving surface roughness and internal lack-of-fusion defects largely unchanged. Machining can remove severe surface notches while leaving subsurface defects and orientation-dependent microstructure. HIP can close many internal voids but does not automatically produce an optimized surface.

The simulated life improvement obtained through combined HIP and machining therefore arises because several damage mechanisms are reduced simultaneously. Experimental fatigue research similarly indicates that heat treatment, build orientation, surface roughness, and defects interact rather than acting as isolated variables.

Residual stress requires special treatment because its effect changes during thermal cycling. Initial tensile stress can increase the local crack-opening driving force, but repeated excursions to elevated temperature may relax part of that stress. A high-fidelity predictive model should therefore not hold residual stress constant indefinitely. Instead, residual-stress evolution should be incorporated through temperature-dependent cyclic plasticity or an experimentally calibrated relaxation model.

Build orientation should also be connected directly with the residual-stress map rather than represented only through a categorical factor. Pant and colleagues demonstrated that orientation materially changes residual-stress distribution in printed Inconel 718. Future prediction frameworks can use measured or simulated stress tensors for specific geometries instead of simplified orientation penalties.

6.3 Toward Experimentally Calibrated Digital Thermal-Fatigue Prediction

The third implication concerns validation. Thermal-fatigue life prediction will become substantially more defensible when manufacturing characterization and structural simulation are calibrated within the same specimen population. A component should ideally be characterized before testing through surface metrology, micro-CT, residual-stress measurement, and microstructural analysis, then subjected to a precisely controlled thermal-mechanical cycle.

The thermal history can subsequently be reproduced in finite-element analysis to determine local temperature, strain, stress, and plasticity around critical regions. The predicted crack-initiation location should then be compared with the actual fracture origin using microscopy and fractography. If the predicted critical defect and experimentally observed crack origin coincide consistently, confidence in the defect-sensitive model increases.

Such a workflow also allows uncertainty to be quantified. Instead of predicting that a component will fail after exactly 30,000 cycles, the model can estimate a probability distribution conditioned on defect size, roughness, residual stress, and material-property uncertainty. This approach is especially important for AM because fatigue-life scatter itself contains information about stochastic manufacturing quality.

Machine-learning methods can eventually complement this process, but they should be grounded in physical variables. A model receiving only process parameters may capture statistical correlations without explaining whether fatigue life changed because porosity, texture, roughness, or residual stress changed. A physics-informed hybrid model can instead use thermo-mechanical simulation and defect mechanics as the structural foundation while machine learning captures nonlinear interactions or updates parameters as additional experimental data become available.

7. Conclusion

Thermal-fatigue prediction in additively manufactured components requires a broader treatment than conventional temperature-cycle or strain-life assessment alone. Additive processing produces residual stresses, anisotropic microstructures, stochastic defects, and complex surface features that materially alter the location and rate of fatigue-crack initiation. A component may therefore possess the same chemical composition and nominal thermal loading as a wrought counterpart while exhibiting a substantially different fatigue-life distribution.

The methodology proposed in this study integrates thermal-cycle severity with an Additive Thermal Fatigue Susceptibility Index containing critical-defect severity, surface roughness, residual stress, build orientation, microstructural heterogeneity, and post-processing condition. The synthetic analysis demonstrates that predicted life decreases sharply with increasing thermal range and that post-processing can materially alter the life trajectory. At a thermal-cycle range of 300 °C, the modeled life increases from approximately 7,800 cycles in the as-built condition to 16,400 cycles after stress relief and 33,800 cycles following combined HIP and surface machining. These values are illustrative rather than empirical fatigue properties.

The study further demonstrates that post-processing should be matched to the controlling fatigue mechanism. Stress relief is valuable where residual tensile stress is dominant, surface machining is important where roughness and near-surface defects control crack initiation, and HIP is particularly relevant where internal porosity contributes materially to fatigue scatter. None of these operations removes the need to characterize thermal gradients, dwell periods, environmental effects, or cyclic plasticity under the actual service condition.

Future experimental work should validate the framework using controlled thermomechanical-fatigue testing combined with micro-computed tomography, residual-stress measurement, EBSD, surface profilometry, strain measurement, and detailed fractography. Particular attention should be directed toward statistically linking the defect that the prediction model identifies as critical with the feature from which the real fatigue crack initiates. Multi-temperature experiments should also quantify residual-stress relaxation, oxidation-assisted cracking, creep-fatigue interaction, and orientation dependence. A successful predictive system would ultimately allow additive manufacturing history, component geometry, nondestructive inspection, and service thermal loading to be combined into a probabilistic digital life assessment suitable for safety-critical component design.

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