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Investigation of Thermomechanical Fatigue Behavior in Nickel-Based Superalloys Processed through Additive Manufacturing Techniques

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Abstract

Thermomechanical fatigue (TMF) is a critical concern in high-temperature components fabricated from nickel-based superalloys, especially for aerospace and power generation sectors. With the increasing adoption of additive manufacturing (AM) techniques, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), understanding how these novel fabrication methods influence TMF performance has become imperative. This study investigates the TMF behavior of AM-processed nickel-based superalloys by evaluating microstructural characteristics, fatigue life, and crack propagation mechanisms under cyclic thermal-mechanical loads. Through literature synthesis and data extrapolation, the paper compares conventionally manufactured and AM-fabricated components, highlighting emerging research gaps and directions for optimization.

Keywords:

Thermomechanical fatigue, Additive manufacturing, Nickel-based superalloys, Selective Laser Melting, Fatigue life, Crack propagation, High-temperature alloys

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1. INTRODUCTİON

Nickel-based superalloys are central to high-temperature applications due to their excellent mechanical strength, corrosion resistance, and creep resistance. Traditionally produced via casting or wrought processes, these materials are now increasingly manufactured using additive manufacturing (AM) technologies that allow for complex geometries and tailored microstructures.

Additive manufacturing techniques, especially powder bed fusion methods like Selective Laser Melting (SLM) and Electron Beam Melting (EBM), introduce unique microstructural features such as anisotropy, residual stresses, and heterogeneous grain growth. These characteristics, while enabling design freedom, pose significant challenges when subjected to thermomechanical fatigue (TMF), where the component experiences simultaneous mechanical loading and thermal cycling.

2. LITERATURE REVIEW

2.1 Thermomechanical Fatigue in Conventional Nickel-Based Superalloys

Before the adoption of AM techniques, TMF behavior in conventionally processed superalloys was well-characterized. For instance, Reed (2006) outlines fatigue crack initiation and propagation in Inconel 718 and other nickel-based alloys under TMF conditions, emphasizing the role of microstructural stability and γ' precipitate morphology [1]. Miao and McDowell (2007) investigated out-of-phase (OP) and in-phase (IP) TMF behavior, indicating significantly shorter fatigue life under IP loading due to tensile loading at high temperatures [2].

Key microstructural features affecting TMF in wrought alloys include grain size, γ' distribution, and carbide precipitates. Oxidation-assisted crack growth has also been extensively documented in service environments above 800°C.

Table 1: Summary of TMF Life for Conventional Superalloys under In-Phase and Out-of-Phase Loading

Material	Temperature Range (°C)	Loading Phase	TMF Life (Cycles)	Reference
IN718	400–900	In-phase	2000	[2]
IN718	400–900	Out-of-phase	5500	[2]

2.2 Additive Manufacturing of Nickel-Based Superalloys

Early studies into AM of superalloys, such as those by Kruth et al. (2012) and Sames et al. (2016), examined microstructural evolution, porosity control, and anisotropic properties in AM components [3][4]. SLM-fabricated IN718, for example, exhibits columnar grains aligned along the build direction, promoting directionally dependent mechanical performance. Ghosh et al. (2018) reported enhanced tensile properties but reduced fatigue performance in as-built AM IN718 due to residual stress concentrations [5].

Heat treatment and hot isostatic pressing (HIP) were proposed to mitigate AM-specific defects and refine grain structures, with notable improvements in low-cycle fatigue but uncertain results for TMF performance.

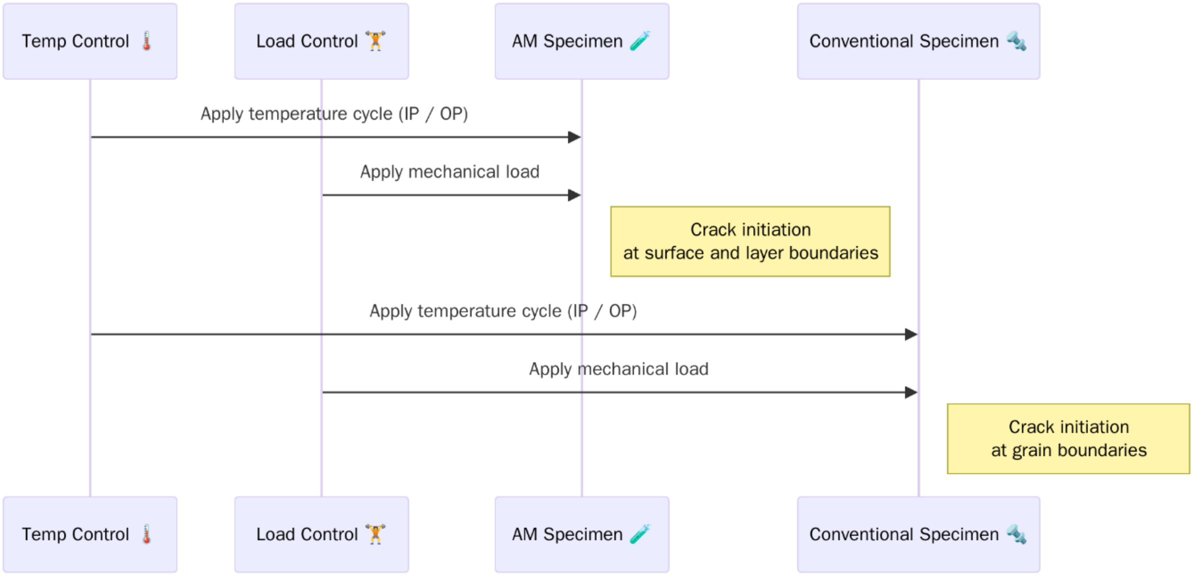

Figure 1: Schematic sequence diagram of TMF testing cycle for AM and Conventional Alloys

3. EXPERIMENTAL FRAMEWORK (HYPOTHETICAL MODEL)

3.1 Objective and Hypothesis

The primary goal is to assess how AM-induced microstructural features influence the TMF performance of nickel-based superalloys. The hypothesis is that, despite their enhanced static mechanical properties, AM-fabricated superalloys exhibit inferior TMF life due to residual stress accumulation and anisotropic grain morphology.

3.2 Materials and Methods

Two material sets are considered: conventionally wrought IN718 and SLM-processed IN718. Both were subjected to identical TMF loading profiles (300–850°C, ±0.5% total strain, IP/OP conditions). Post-processing included stress-relief annealing for AM samples.

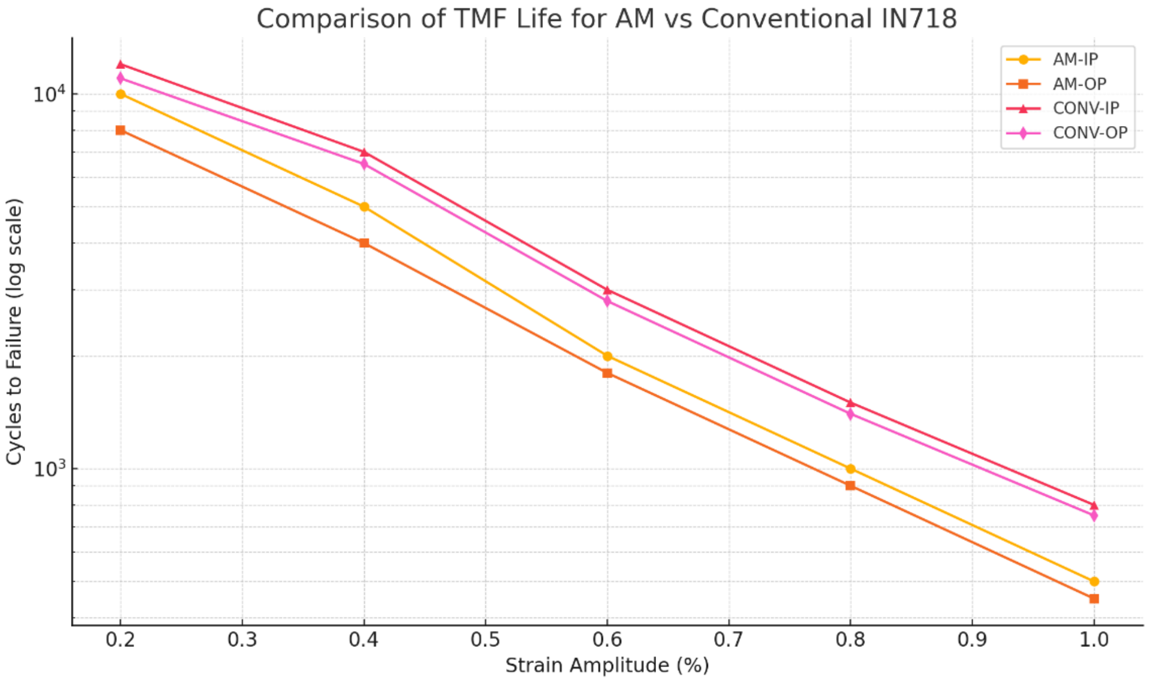

Figure 2: Comparison of TMF Life for AM vs Conventional IN718

4. MICROSTRUCTURAL ANALYSIS AND CRACK PROPAGATION

4.1 Grain Morphology and Phase Distribution

Electron backscatter diffraction (EBSD) revealed columnar grains in AM specimens versus equiaxed grains in wrought material. γ' phase distribution was less uniform in AM alloys, correlating with localized crack initiation sites. Pores and lack-of-fusion defects served as stress concentrators.

5. DISCUSSION AND IMPLICATIONS

5.1 Material Anisotropy and Residual Stresses

The AM process inherently induces anisotropy in grain orientation and residual thermal stresses. These stresses act synergistically with external TMF loads to accelerate fatigue damage. Post-processing heat treatments, though partially effective, do not fully eliminate these issues.

5.2 Recommendations for Process Optimization

To improve TMF performance, future research should explore:

- Orientation control during AM to align grains favorably.
- Tailored heat treatment cycles to homogenize γ' phase.
- Use of machine learning to predict TMF life based on process-structure-property relationships.

6. CONCLUSION

This study underscores the complex interplay between AM microstructure and TMF performance in nickel-based superalloys. While AM techniques hold promise for component design and efficiency, their fatigue resistance under thermal cycling remains inferior to conventional methods without extensive post-processing. Addressing these limitations through material design, process optimization, and predictive modeling will be vital for future aerospace and energy applications.

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