

MECHANICAL PROPERTIES AND MICROSTRUCTURAL CHARACTERIZATION OF Ti-6Al-4V FABRICATED BY SELECTIVE LASER MELTING: EFFECT OF BUILD ORIENTATION AND POST-PROCESS HEAT TREATMENT

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Abstract

Selective laser melting (SLM) of Ti-6Al-4V produces components with complex geometry unachievable by conventional subtractive methods, yet strong anisotropy in mechanical properties arising from columnar prior- β grain growth and non-equilibrium α' martensite formation remains a fundamental concern for load-bearing aerospace structures. This dissertation systematically investigates the effects of build orientation (0° , 45° , 90° relative to the build platform) and two post-process heat treatments (stress relief at $650^\circ\text{C}/3$ h and HIP at $920^\circ\text{C}/100$ MPa/2 h) on quasi-static tensile, high-cycle fatigue ($R = 0.1$, 10^7 -cycle runout), and fracture toughness (K^{Ic}) of SLM Ti-6Al-4V. As-built vertical specimens exhibited lowest UTS (1020 MPa) and highest anisotropy ratio (vertical/horizontal UTS = 0.88) due to inter-layer fusion defects. HIP treatment transformed acicular α' to a coarser ($\alpha+\beta$) lamellar microstructure, eliminated sub-surface lack-of-fusion pores, and raised K^{Ic} from 44 to 71 $\text{MPa}\cdot\text{m}^{1/2}$ ($\pm 61\%$), approaching wrought-annealed values. Fatigue strength at 10^7 cycles improved from 390 MPa (as-built) to 580 MPa (HIP), attributed to pore closure eliminating crack initiation sites. These results provide a processing–property roadmap for qualification of SLM Ti-6Al-4V in aerospace certification pathways.

Keywords: selective laser melting; Ti-6Al-4V; anisotropy; HIP; fatigue; fracture toughness; additive manufacturing; microstructure

1. Introduction

Additive manufacturing (AM) via selective laser melting (SLM) has transitioned from rapid prototyping to serial production of flight-critical components, with engine brackets, fuel nozzles, and cabin partition inserts now certified under EASA CS-25 and FAA AC 33.70-2 frameworks [1]. Ti-6Al-4V ($\alpha+\beta$ titanium alloy) is the most widely processed AM metal in aerospace owing to its high specific strength (~ 200 kN·m/kg), excellent corrosion resistance, and biocompatibility. However, the inherently rapid solidification of SLM ($\dot{\epsilon} \sim 10^6$ K/s) suppresses equilibrium β decomposition, producing a fully martensitic α' matrix with elevated hardness but limited ductility and inferior fatigue performance relative to wrought counterparts [2].

2. Literature Review

Extensive literature exists on SLM Ti-6Al-4V mechanical properties, yet direct comparisons are complicated by differences in machine parameters, powder characteristics, and specimen extraction strategy. Lewandowski & Seifi [3] reviewed AM metal properties and noted fatigue scatter one to two orders of magnitude wider than wrought alloys, primarily attributed to residual porosity and surface roughness. Simonelli et al. [4] demonstrated that crystallographic texture established during SLM produces a 10–15% difference in elastic modulus between vertical and horizontal builds. The role of HIP in closing internal pores and homogenising microstructure has

been well documented [5], but its interaction with build orientation anisotropy has received limited systematic study—the gap addressed in this thesis.

3. Experimental Programme

3.1 SLM Processing

Specimens were fabricated on an EOS M280 system using EOS Ti64 powder ($d_{50} = 36 \mu\text{m}$, sphericity > 0.90). Optimised parameters: laser power $P = 280 \text{ W}$, scan speed $v = 1200 \text{ mm/s}$, hatch spacing $h = 120 \mu\text{m}$, layer thickness $t = 30 \mu\text{m}$, yielding volumetric energy density $E_v = P/(v \cdot h \cdot t) = 64.8 \text{ J/mm}^3$. Relative density measured by Archimedes method: $99.6 \pm 0.1\%$.

3.2 Heat Treatment

Stress relief (SR): 650°C , 3 h, argon atmosphere, furnace cool. Hot Isostatic Pressing (HIP): 920°C , 100 MPa Ar, 2 h, followed by furnace cool at 5°C/min to 300°C then air cool.

3.3 Mechanical Testing

Quasi-static tensile tests per ASTM E8; fatigue per ASTM E466 (rotating bending, $R = 0.1$); fracture toughness per ASTM E399 (CT specimens, $B = 12.5 \text{ mm}$, $W = 25 \text{ mm}$). Microstructure characterised by EBSD on a Zeiss Sigma 500 FEG-SEM.

4. Results

Condition	UTS (MPa)	El. (%)	K_{Ic} (MPa·m ^{1/2})
As-built 0°	1158	7.4	44
As-built 90°	1020	5.9	38
SR 0°	1095	9.1	55
HIP 0°	980	14.2	71
Wrought ann.	950	16.0	75

HIP narrows the UTS anisotropy ratio from 0.88 to 0.97, effectively eliminating orientation dependence—a key finding for multi-axis loaded structural components.

5. Conclusions

- As-built SLM Ti-6Al-4V exhibits strong build-orientation anisotropy (UTS ratio 0.88) driven by inter-layer fusion defects and columnar β texture.
- HIP at $920^\circ\text{C}/100 \text{ MPa}$ closes sub-surface pores, transforms α' to $(\alpha+\beta)$ lamellar microstructure, and raises K_{Ic} by 61%.
- Fatigue strength at 10^7 cycles improves from 390 MPa (as-built) to 580 MPa (HIP), approaching wrought-annealed performance.
- Post-HIP properties are nearly isotropic, enabling design engineers to treat HIP'd SLM Ti-6Al-4V as orientation-independent in structural analyses.

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