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Low- and high-cycle fatigue resistance of Ti-6Al-4V ELI additively manufactured via selective laser melting: Mean stress and defect sensitivity

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ABSTRACT

Selective laser melting (SLM) is a net-shape AM technology to produce metal parts also for load-carrying applications. The present work is aimed at investigating the fatigue performance of the biomedical titanium Grade 23 (aka Ti-6Al-4V ELI) AMed via SLM. Low and high cycle fatigue tests are carried out on samples that received a low temperature stress-relief treatment. In addition, the effect of selected post processing treatments on the high cycle fatigue response is assessed. Material characterization is complemented with residual stress and microhardness measurements, computed tomography scans, metallographic and fractographic inspections. These experimental analyses served to elaborate an interpretative model accounting for the modifications produced by the post-processing treatments. The results denote the important role exerted by mean and residual stresses as well as defects on the fatigue performance. The relatively low fatigue strength of SLM manufactured parts indicates that further developments in this fabrication route are still necessary to make their mechanical properties competitive with those of traditionally processed components.

1. Introduction

Additive Manufacturing (AM), sometimes colloquially termed 3D-printing, comprises net-shape production technologies that build a solid object from the sequential superposition of layers representing the cross-sections obtained by virtually slicing the 3D model of the component. Nowadays, AM is becoming a key enabling technology for direct fabrication of functional or structural end-use products and is already revolutionising not only the way we produce, but also the design guidelines. Advantages offered by AM over conventional subtractive or formative techniques stem from broader design freedoms that allow geometries of virtually any complexity to be manufactured with minimal tooling, rapid delivery times, and low material waste [1,2].

Since 1990, several AM technologies have been developed to sinter metallic powders. They can be distinguished regarding the way the layers of material are deposited and consolidated [3,4]. In powder bed fusion processes, the powder is spread to a controlled thickness (typically on the order of 0.1 mm) over the build platform or the previously built layers. After powder consolidation, the build platform is lowered and a new layer is spread. The process repeats until the entire model is created. Different heat sources are used to sinter or fuse the powder. For instance, a laser or an electron beam is adopted in Selective Laser Melting (SLM)/Selective Laser Sintering (SLS)/Direct Metal Laser Sintering (DMLS) or Electron Beam Melting (EBM), respectively [5,6]. The former operate in an inert environment, the latter in vacuum. In all cases, the heat input is intense and highly localized so that the process parameters must be carefully tuned, especially in terms of scan speed, pattern and energy density [7].

SLM is well suited to additively manufacture small-to-medium amounts of parts with moderate-to-high surface finish [2]. Titanium and its alloys are frequently manufactured via SLM, mainly in the biomedical, aerospace and energy context, to obtain components of high-added value that justifies the high production costs of this fabrication route. Meaningful examples thereof are turbine blades with internal conformal cooling channels [8] and customized medical implants even with cellular or porous structure for improved osseointegration [9,10]. The geometrical complexity of these components, often inaccessible to conventional subtractive/formative manufacturing techniques, and the poor machinability of Ti alloys, linked to the high energy required to remove/deform the material, make AM in general and SLM in particular the only viable solution from a technical or economical standpoint.

Among Ti alloys, Ti-6Al-4V, hereinafter abbreviated in Ti64, is the most important, covering about 60% of the entire world market [11].

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Nomenclature

Symbols

AM	additive manufacturing
area	area obtained by projecting a defect or a crack onto the plane x-y perpendicular to the maximum tensile stress
b	fatigue strength exponent (Eq. (1a))
c	fatigue ductility exponent (Eq. (1b))
c_1, c_2, m	parameters of Eq. (4) used to fit high cycle fatigue data
CT	computed tomography
E	Young's modulus
F	cumulative probability
H'	Ramberg-Osgood coefficient (Eq. (3))
HCF	high cycle fatigue
HIP	hot isostatic pressing
HV	Vickers hardness
LEVD	largest extreme value distribution
LCF	low cycle fatigue
LOF	lack of fusion
n'	Ramberg-Osgood exponent (Eq. (3))
N_f	number of cycles to failure
R	load (stress) ratio
S^2	estimated regression variance (Eq. (5))
SEM	scanning electron microscope
SLM	selective laser melting
SWT	Smith-Watson-Topper model [44]
y	reduced variate of LEVD
V	defect volume
α, β, γ	material parameters of Eq. (7)
ε	axial strain
ε'_f	fatigue ductility coefficient (Eq. (1b))
σ	axial stress
σ'_f	fatigue strength coefficient (Eq. (1a))
σ_Y	yield stress
σ_U	tensile strength
ϕ	non-dimensional defect shape factor (Eq. (6))

Subscripts

a	amplitude
el	elastic
m	mean
pl	plastic

This two-phase α + β Ti alloy combines superior fatigue strength-to-weight ratio, high operating temperatures, excellent corrosion resistance and biocompatibility [12]. A specific advantage resides in the wide range of microstructural options that can be obtained by thermo-mechanical processing and heat treatment, allowing one to balance the fatigue properties with other design limiting properties (strength, stiffness, fracture toughness, etc.). Unlike other metallic materials for structural applications, such as steels and Al alloys, wrought Ti alloys display clean microstructures without the presence of hard inclusions, which impact detrimentally on ductility and fatigue resistance. The most important microstructural parameter determining the mechanical properties of α + β Ti alloys is the α colony size, which controls the maximum dislocation slip length and, as a consequence, its mechanical properties [13]. Basically, α + β-processed fine-grained (equiaxed or bimodal) compared to β-annealed fully lamellar microstructures show superior fatigue resistance as a consequence of the smaller α colony size, in general at the cost of a lower crack growth resistance, which is instead a peculiar characteristic of the latter coarse microstructures conferred by extrinsic crack-tip shielding mechanisms [14].

When Ti-64 is additively manufactured (AMed) via SLM, the mechanical properties are less dictated by the aforementioned relationships. In fact, the microstructure resulting from the very high cooling rate from the β-field is in general composed of an acicular α' hcp phase, a metastable martensitic phase displayed by the α + β Ti-alloys [15–17]. It is characterized by low ductility, hence not adequate for most structural applications, especially because the mechanical properties are further degraded by the presence of defects and internal stresses produced by the high thermal gradients affecting the SLM process [18]. Typical flaws are pores produced by initial powder contamination, evaporation or local voids after powder-layer deposition [16,19] and lack of fusion (LOF) defects. These latter are caused by insufficient energy density resulting in incomplete powder bed consolidation and generally assume the form of irregularly shaped cavities that may entrap unmelted powder particles [20,21].

The combination of low ductility, defectiveness and residual stresses can be very critical to the fatigue strength of SLM products. Therefore, the fatigue characterization of SLM manufactured Ti-64 has attracted in recent times the attention of the research community [20–27]. Kasperovich and Hausmann [22] carried out a systematic investigation of the effect of SLM process parameters on the fatigue resistance of Ti-64, observing that the detrimental presence of porosity can be minimized adopting moderate laser scanning velocity and large spot size. A further decrease in porosity was achieved via hot isostatic pressing (HIP). Liu et al. [20] investigated the onset and morphology of LOF defects in SLM manufactured Ti-64, noting that their effect on the fatigue resistance is more detrimental in the vertically than the horizontally built samples. Nicoletto [23] made similar observations for DMLS fabricated Ti-64. The pioneering works of Leuders et al. [24,25] were among the first to study post-process treatments with the aim of improving the fatigue resistance of SLM manufactured Ti-64. They found that heat treatments conducted either below or above the β-transus improve ductility and hence the fatigue strength and that HIP brings porosity below the minimum level detectable by X-ray computed tomography (CT), increasing the fatigue strength to values comparable to conventionally processed Ti-64. Edwards and Ramulu [26] carried out fatigue tests on SLM fabricated Ti-64 in the as-built condition, observing that the fatigue strength is 75% lower than the corresponding wrought material due to poor surface finish, porosity and surface tensile residual stresses. Greitemeier et al. [27] found that the fatigue strength of Ti-64 produced by DMLS is mainly controlled by surface roughness and internal defects. The role of microstructure becomes important only if the latter effects are eliminated. In this case, fine microstructures are preferable to the coarse lamellar ones typically obtained after HIP. Günther et al. [28] explored the very-high-cycle-fatigue resistance of additively manufactured Ti-64 using an ultrasonic testing machine. They distinguished two failure modes, i.e. surface fatigue crack initiation, typical of HIPed samples and localized at α-phase clusters, and internal fatigue crack initiation, occurring in as-built and heat-treated samples near pores and LOF defects. HIP greatly improves fatigue resistance; further increments are possible only by decreasing the α-colony size, as for wrought components. A systematic analysis of the fracture surfaces was undertaken with the aim of interpreting the fatigue results by the light of the $\sqrt{area}$ model originally developed by Murakami [29] for steels and cast irons, whose fatigue behaviour is mainly dictated by inclusions [30] and shrinkage porosity [31], respectively. The same approach was adopted by Beretta and Romano [32], who were able to rationalize the large variety in fatigue data published in the open literature by correlating the data to the defect characteristic size $\sqrt{area}$, thus confirming the applicability of this method to AMed Ti components. Li et al. [33] presented a comprehensive review of published fatigue data of AMed Ti-64 outlining the lower fatigue performance with respect to conventionally processed components and the necessity for post-processing