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# On the effect of internal channels and surface roughness on the high-cycle fatigue performance of Ti-6Al-4V processed by SLM

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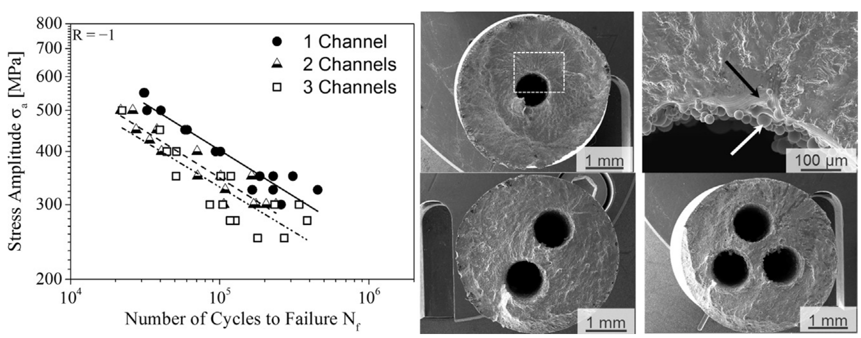
## HIGHLIGHTS

- For SLM processed samples containing internal channels crack initiation is observed at channel surfaces and bulk porosity
- Despite distinct crack initiation sites fatigue life data are characterized by a low degree of scatter for a given geometry
- Fatigue lives of the different geometries tested are clearly affected by the ligament size
- A fracture mechanics based approach is able to capture differences in fatigue lives of the sample geometries considered
- Based on the findings presented the superior impact of crack growth life on the overall fatigue life is deduced

## GRAPHICAL ABSTRACT

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## ABSTRACT

Selective laser melting (SLM) is an additive manufacturing process allowing for the production of metallic high performance materials and components with complex geometries. Therefore, possible applications are direct production of casting molds, tools or turbine blades with internal cooling channels for an optimized cooling efficiency. A disadvantage of the technology is the process-inherent surface roughness, which is critical especially under fatigue loading conditions. Since internal surfaces often cannot be smoothened due to limited accessibility, the objective of this study is to assess the fatigue properties of Ti-6Al-4V samples designed with internal axial channels featuring a rough as-built surface. Samples with various diameters and numbers of channels have been tested not always exhibiting a deterioration of the fatigue performance compared to solid samples. Subsequent fractography by scanning electron microscopy revealed distinct failure mechanisms. Besides the fatigue crack initiation on features of the unmodified internal surfaces, residual porosity in the bulk, *i.e.* lack-of-fusion defects, keyhole defects and gas pores, respectively, could be identified as crack origin. Relatively low scatter of fatigue lives found is attributed to rapid crack initiation and, thus, the dominant influence of the (micro-) crack growth regime.



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## 1. Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) technology employed for the layer-wise production of metallic parts. The energy of the laser source used point-wise melts powder within a powder-bed layer. Upon completion of a single layer, recoating of a next powder-layer and subsequent melting pursue the manufacturing process. Finally, three-dimensional objects can be built directly from a CAD model by this kind of progressive consolidation of powder-particles in a bed with the high-power laser beam. This free-form fabrication method enables flexible as well as cost- and material-efficient processing of high-performance materials and components with complex geometries, high densities and good mechanical properties [1,2]. One of the most commonly utilized and intensively studied materials in AM technologies is the titanium alloy Ti-6Al-4V [3,4]. This light-weight alloy is characterized by a good combination of strength and ductility and enables combining various advantages AM techniques offer [5,6]. Despite high prices of the precursor powder material, AM Ti-6Al-4V is a very attractive alloy for medical products and the aerospace industry due to its low density, good corrosion resistance and biocompatibility [7,8]. One potential application is a topologically optimized aerospace bracket, where the utilization of AM Ti-6Al-4V can contribute to a significant reduction of weight and, thus, fuel consumption over the whole life cycle of an airplane [9–12]. With respect to turbine blades, further enhanced efficiencies demand for an increase of combustion temperatures. Since this leads to a higher thermal exposure of the materials, components like blades have to be cooled. At this point the free-form fabrication within the SLM process offers an unprecedented freedom in design and allows the direct realization of complex internal cooling channels that are not manufacturable by conventional processing technologies, *e.g.* drilling and milling. Internal structures can be designed close to the outer surface effectively reducing maximum temperatures and wear of the blade [13]. These aspects are also beneficial in tool manufacturing, *e.g.* cutting tools, drill bits and tool inserts, where conformal cooling channels and concomitant enhanced cooling rates can reduce wear of the tools and increase the productivity through reduced cycle-times and higher process output [14–17]. On the opposite, powder-bed based metal additive manufacturing technologies, *i.e.* selective laser melting as well as electron beam melting (EBM), face various challenges that are detrimental with respect to current and future applications. Regarding static properties additively manufactured material can already fully compete with conventionally processed alloys [1]. However, residual porosity and the process-inherent rough surface set limitations to its utilization as fatigue load bearing parts. In previous studies on Ti-6Al-4V the detrimental influence of residual porosity in terms of fatigue life has been investigated, showing a significant reduction of the fatigue performance in the high-cycle fatigue (HCF) as well as the very high-cycle fatigue (VHCF) regime in as-built condition [18,19]. In machined samples initiation of fatigue cracks is facilitated by either keyhole defects and gas pores that are residue from the precursor powder, *i.e.* are already present in the particles of the gas atomized powder, or so-called lack-of-fusion defects that emerge from locally insufficient melting of the material [19–24]. Furthermore, it has been evidenced that the hot-isostatic pressing (HIP) treatment significantly increases the fatigue performance since compaction at high temperature (920 °C) combined with high pressure (1000 bar) effectively reduces the size of residual porosity [19,23,25].

Another factor that deteriorates the fatigue performance is the process-inherent, *i.e.* as-built, surface roughness [21,24,26]. The roughness of the surface emerges from two distinct mechanisms, the uneven solidification of the molten material due to turbulences of the melt-pool and the undesired melting of powder particles to the part contour due to the high local energy input. When inappropriate parameters are employed further effects can contribute to the overall surface roughness [11,21,27–30]. In terms of fatigue loading a rough surface is detrimental since the notch-like features act as stress raisers and, thus, as crack initiation sites resulting in a remarkable reduction of fatigue strength. The correlation of the surface roughness (on outer surfaces) and fatigue performance has been investigated by numerous authors [24,31]. Greitemeier et al. [26] showed for a stress ratio of $R = 0.1$ a fatigue limit of 200 MPa at $10^7$ cycles for laser-beam melted Ti-6Al-4V. Despite hot-isostatic pressing, an increase of fatigue strength was not achieved as fatigue cracks were initiated at the rough as-built surface. Consequently, the reduction of the size of inner defects was considered negligible in this condition. A surface modification by milling resulted in a significant improvement of the fatigue limit. Its value was enhanced to above 450 MPa and process-induced defects in the bulk were consequently identified as dominating crack initiation sites. Different results for SLM-manufactured Ti-6Al-4V were obtained by Edwards and Ramulu [21]. They performed fatigue tests at a stress ratio of $R = -0.2$ showing a poor fatigue limit of the SLM-processed material, *i.e.* about 75% lower than values for wrought material. Noticeably, they could not reveal a difference in fatigue strength between samples with as-built and machined surfaces. By removing the rough surface, internal defects were shifted to the sample surface and acted as fatigue crack initiation sites so that in terms of fatigue performance the impact of the process-inherent porosity in contact or close to the surface, respectively, was as detrimental as the as-built surface. Studies by Kasperovich et al. [20] revealed similar results. Accordingly, the authors suggested that only a combination of a HIP-treatment with an appropriate treatment of the as-built surface would result in viable fatigue behaviors. This suggestion is in line with the findings of a recent study by some of the current authors where a combination of HIP and shot peening was able to significantly improve fatigue performance [11].

Since a modification of the surface of complex internal structures of components is not easily feasible, *i.e.* conventional machining is not applicable, numerous alternative processes are in focus of research. Recently, technologies for an improvement of the surface quality of additively manufactured parts of complex shape such as shot-peening [32], laser-ablation, -remelting and -polishing [33–35], erosion by the use of abrasive fluids [36], chemical etching [37–40] and electrochemical polishing [41–44] have been investigated. For all processes significant improvements of the surface finish have been reported. Though, in terms of economic efficiency, post-processing steps are not desirable since they are time-consuming and cause additional expenses. Moreover, the effectiveness of the majority of the processes has solely been evidenced for relatively simple geometries. Only the chemical and electrochemical procedures have been deployed for highly complex structures, *e.g.* for smoothing of single struts of AM open porous structures [37–39]. However, the impact of defined removal of the rough surface of internal features like conformal cooling channels and its effect on the fatigue properties has not been reported in open literature so far. Local inhomogeneities additionally impede reliable and repeatable uniform material removal and sufficient surface finishes [44]. Clearly, all these issues have to be addressed to further increase the value of the powder-bed based AM technologies. Aerospace and medical industries enforce high standards and requirements regarding reliability and durability of components. For these applications, where AM parts often will be used under cyclic loading conditions, an in-depth understanding of the fatigue behavior is essential for fail-safe design, even if components with filigree internal structures are employed.

Since the surface finish is one of the key fatigue issues, the objective of the current study is to contribute to an enhanced knowledge of the extent of influence of the as-built surface on the cyclic mechanical response of selective laser melted Ti-6Al-4V. Due to its inherent characteristics, *i.e.* high strength and, thus, high notch sensitivity, Ti-6Al-4V is the material of choice as it represents a kind of worst case scenario. Tests employing cylindrical fatigue samples with internal channels built by SLM have been conducted and the results were compared to previous studies by Leuders et al. [18], who evaluated the fatigue performance of solid samples with similar geometry as well as Kasperovich et al. [20], who conducted several tests at the same stress ratio of $R = -1$.