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Fatigue life of additively manufactured Ti–6Al–4V in the very high cycle fatigue regime

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ABSTRACT

The present study reports on the impact of two different additive manufacturing routes, i.e. selective electron beam melting (EBM) and selective laser melting (SLM) on the fatigue life of the titanium alloy Ti–6Al–4V in the high cycle fatigue (HCF) and in the very high cycle fatigue (VHCF) regime. Cylindrical fatigue specimens were manufactured by EBM and SLM and tested in differently post-treated conditions. The EBM specimens were tested in the as-built condition, SLM manufactured specimens were heat treated at 800 °C and hot isostatically pressed, respectively. The type, size and location of every crack initiating discontinuity was determined and thoroughly investigated by scanning electron microscopy. Three main findings were derived from the present investigation. Fatigue properties of as-built EBM and stress relieved SLM specimens in the HCF and VHCF regimes are very similar. Defect types and defect sizes of similar nature were observed in both conditions. In consequence, stress relieving heat treatment has not to be conducted in EBM processed Ti–6Al–4V. The shape of the discontinuities, however, currently is not considered by traditional approaches for estimation of fatigue strength. The fatigue performance of the SLM processed and subsequently hot isostatically pressed condition is superior to its two additively manufactured counterparts and similar to conventionally processed material. Duplex S–N behavior with a clear transition area was observed in case of the Ti–6Al–4V specimens tested.

1. Introduction

During the last decades, an increased interest in additive manufacturing (AM) emerged due to unprecedented design freedom arising from the related novel production technologies [1–6]. The powder based AM processes selective laser melting (SLM) and selective electron beam melting (EBM) are mature technologies, enabling manufacturing of near net-shape and light-weight components in a time efficient and resource saving manner. AM requires no molds or tools and enables the fabrication of very complex and customized parts [7,8]. Additive manufacturing was developed from rapid prototyping techniques [1]. All techniques allow for layerwise processing of three-dimensional components, e.g. using powder layers in case of SLM and EBM. Clearly, EBM and SLM are basically very similar AM technologies [1,7,9,10]. Part information is provided by files edited by computer aided design (CAD) and subsequently sliced according to the requirements of the system employed. However, contrary to the SLM manufacturing route, EBM processing is performed at elevated temperatures >700 °C. High scan speeds related to the electron beam technology enable for preheating of every layer prior to melting [11,12]. Heating of the entire build chamber of the EBM machine reduces the temperature gradients and local cooling rates and, thus, the process-induced residual stresses [8,12–18]. In case of SLM processing, the build platform only is heated up to 200 °C [17]. Another factor is the different environmental influence during processing. Application of an electron beam requires high vacuum conditions. Therefore, pick-up of elements like oxygen during EBM processing can be avoided. The laser beam is working in a protective inert gas atmosphere [19–21]. Numerous alloys were processed by SLM and EBM, respectively, in recent years. Data reporting on mechanical properties as well as microstructure evolution in steels [22], aluminum alloys [23], copper [24], cobalt-chromium alloys [25], nickel-base superalloys [26,27] and mainly

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titanium based alloys with an emphasis on Ti–6Al–4V [2] have been published so far.

Due to their superior strength-to-density ratio, titanium alloys are used in the aerospace industry for components like blades and disks in the front stages of the engine [6]. Moreover, titanium alloys are well suited for applications in medical industry due to their good corrosion resistance and biocompatibility [5,28]. Both industries demand high reproducibility and reliability of components processed by any manufacturing process, i.e. by novel routes such as SLM and EBM as well. In order to evaluate loading scenarios for components in application the following calculation can be considered: Compressor and turbine blades of aircraft engines are subjected to high frequency cyclic loadings at frequencies >1 kHz during in-service time [29,30]. The operating time of turbine blades before rejection is given with $>1.5 \times 10^4$ h [29]. Thus, in-service time of a turbine blade covers approximately 5.4×10^9 loading cycles. Numerous studies reported on a transition of the failure mechanism for the very high cycle fatigue (VHCF) regime. Atrens et al. [31] reported on a change of fatigue crack initiation mechanisms in titanium alloy Ti–6Al–4V in the high cycle fatigue (HCF) regime. Gilbert and Piehler [32] found an increasing number of internal fatigue cracks in case of increasing number of cycles. Moreover, short fatigue lives were solely attributed to surface fatigue crack initiation, whereas internal fatigue crack initiation was observed only at high fatigue lives [31,32]. The formation mechanism of internal fatigue cracks in the HCF regime in case of forged titanium alloy Ti–6Al–4V used for hip prostheses was thoroughly studied [32]. It was reported, that identification of the internal fatigue crack initiation points in case of forged material is a challenging task and internal fatigue crack initiation is attributed to "a number of flat, smooth features or facets at the point of crack initiation", cf. [32]. It was proposed that internal fatigue failure occurs due to the fracture of the hexagonal α phase on particular crystallographic planes. Heinz et al. [33] performed ultrasonic fatigue tests on conventionally processed titanium alloy Ti–6Al–4V and described a transition of the failure mechanism and significantly decreasing fatigue strength after exceeding 10^7 cycles. According to results available, no fatigue limit exists in the region ranging from 10^5 to 10^9 cycles for Ti–6Al–4V in the conditions investigated [34]. Moreover, Zuo et al. [34] found a transition of the failure mechanisms with increasing number of cycles to failure. Internal fatigue cracks initiate at the primary α-grain boundary or inside the α-grain in case of a bimodal microstructure whereas in case of basketweave microstructures the fatigue crack is initiated at the $\alpha + \beta$ interfaces [34]. Furuya et al. [35] reported on failure-relevant clusters of facetted structures at the crack initiation point. These facets are formed in the α-phase in an inclined direction with respect to the loading axis and show a major impact on fatigue life [35,36].

Fatigue properties of materials processed by additive manufacturing have been focal point of numerous recent publications [8,14,17,18,37–42]. However, comprehensive data allowing for evaluating process–microstructure–property relationships in the VHCF regime are very limited in literature [38]. Most studies conducted so far characterized single issues of the fatigue performance of Ti–6Al–4V. Mainly fatigue properties in the HCF regime and crack advance in fracture mechanics tests have been characterized [8,17,18,37,39–43]. Besides the impact of process-induced porosity the detrimental effects of residual stresses have been revealed [17,18]. Leuders et al. [17] demonstrated that post-processing heat treatments leading to stress relieve had to be conducted in order to improve damage resistance. As mentioned before, preheating of every layer during EBM processing can significantly decrease process-induced residual stresses and, thus, substitute subsequent heat treatments of EBM manufactured components [18]. However, data reporting on fatigue properties of EBM and post-treated SLM materials in a comparative manner with an emphasis on the high and the very high cycle fatigue regimes were not available in literature.

Therefore, the present study investigates the fatigue behavior of additively manufactured Ti–6Al–4V specimens processed by EBM and SLM, respectively, in the HCF and VHCF regimes. Post treatments were performed in case of the SLM processed batches according to data available in literature. Microstructural analyses and fractography investigations were performed focusing on crack initiation mechanisms. Data obtained clearly reveal the role of process-induced defects and the superior performance of specimen conditions post treated by hot isostatic pressing. The latter treatment allows for meeting the fatigue performance of conventionally processed Ti–6Al–4V even in the VHCF regime.

2. Experimental details

2.1. Materials and manufacturing

Specimens made of pre-alloyed powder of Ti–6Al–4V were processed using SLM and EBM. The investigated batches are summarized in Table 1.

Specimens of batches *SLM-1a*, *SLM-1b* and *SLM-2* were manufactured by selective laser melting using the SLM 250^{HL} system (SLM Solutions GmbH, Lübeck, Germany) equipped with a single 400 W fiber laser. The Ti–6Al–4V powder supplied by the machine manufacturer (SLM Solutions GmbH, Lübeck, Germany) featured a particle size ranging from 20 to 63 μm. The chemical composition as determined by glow discharge optical emission spectroscopy (GDOES) was 7.1% Al, 4.3% V and balance titanium (in wt.%). Standard processing parameters supplied by the system manufacturer were applied, i.e. a laser power of 175 W, scan speed of 710 mm s^{-1} and a line offset of 0.12 mm. Specimens were built with a layer thickness of 30 μm in Argon atmosphere. Specimens for mechanical testing were machined from raw cylinders by turning. The build direction corresponded to the loading direction during mechanical testing. The build platform was heated to 200 °C during fabrication. Batches *SLM-1a* and *SLM-1b* were heat treated at 800 °C for 2 h in Argon atmosphere in order to reduce residual stresses within the specimens [17]. Batch *SLM-2* was post treated by HIP at 920 °C for 2 h at 1000 bar in an Argon atmosphere.

The specimens of batch *EBM* were produced by EBM in vacuum atmosphere using the Arcam A2X system (Arcam AB, Mölndal, Sweden). The powder used for manufacturing is characterized by a chemical composition of 7.3% Al, 4.5% V and balance titanium (in wt.%), a size distribution from 45 to 100 μm and was supplied by the machine manufacturer. The layer thickness was 50 μm. Again, specimens for mechanical testing were machined by turning from raw cylinders. The loading direction during fatigue testing was parallel to the building direction. Batch *EBM* was investigated in the "as-built" condition, i.e. without any post treatment. For manufacturing the standard parameters provided by the machine manufacturer were used, i.e. the machine was operated at an acceleration voltage of 60 kV, the maximum beam current was set to 21 mA with a scan speed of 4530 mm s^{-1} and a line offset of 0.1 mm.

Table 1
Definition of the investigated batches of Ti–6Al–4V (Data for batch *SLM-1a* partly recompiled from [17]).

Manufacturing route	Heat treatment	Hot-isostatic pressing (HIP)	Testing frequency
SLM-1a	800 °C	–	10 Hz
SLM-1b	800 °C	–	19 kHz
SLM-2	920 °C	HIP, 1000 bar, Ar	19 kHz
EBM	–	–	19 kHz