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Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting

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ABSTRACT

Generative processes or additive layer manufacturing like selective laser melting (SLM) enable the fabrication of highly precise and complex component geometries that are otherwise difficult, costly, or even impossible to realize using conventional techniques. Titanium alloys and in particular TiAl6V4 are suited well for processing by SLM. However, a careful optimization procedure of the process parameters is necessary to obtain a high quality material: firstly, the optimization of the initial process parameters for the minimization of inherent defects, and secondly, the optimization of the further thermomechanical treatment to minimize internal stresses and adjust the microstructure. These two stages of optimization are represented here. For the initial program more than 40 small TiAl6V4 cuboids were produced with the variable scan parameters and two- and three dimensionally analyzed. The reducing of the porosity by 6–10 times is shown. The optimized process parameters were used for further manufacturing of the test specimen, some of them were then thermomechanically treated: annealed or hot-isostatically pressed. The hardness, tensile properties and high cycle fatigue resistance of all samples were tested and the similar tests were also conducted for the reference material: wrought TiAl6V4 alloy. The microstructure, porosity and the received mechanical properties were analyzed and compared, and the influence of thermomechanical treatment was evaluated. As a result of this double optimization, a significant improvement of ductility ($\varepsilon = 19.4\%$) and fatigue resistance compatible to the wrought TiAl6V4 for the SLM produced material was achieved. Furthermore, since some surfaces in complex components such as the channels in the turbine blade cannot be machined or polished, both treated ('machined') and untreated ('as built') surface conditions were considered and discussed.

1. Introduction

During the last decade, several additive manufacturing (AM) techniques for processing of complex metallic parts were developed and extensively investigated (e.g. Abe et al., 2001; Levy et al., 2003; Rehme and Emmelmann, 2007). AM offers a wide range of advantages, including a faster time-to-market, a near-net-shape production without the need of expensive molds and tools, a high efficiency in material utilization, the possibility to directly fabricate shapes based on CAD models, and a high level of flexibility as outlined by Levy (2010). Among AM techniques Brandl (2010) and Baufeld et al. (2011) investigated shaped metal deposition (SMD), which uses wires as initial material. Electron beam melting (EBM) is comprehensively developed among other by Murr et al. (2010). The usage of metallic powders in laser-based processes such as selective laser sintering (SLS) and selective laser melting (SLM) was intensively analyzed by Kruth et al. (2005). In the latter process, successive layers of metal powder are molten and consolidated on top of each other by a high intensity laser beam. The SLM process has already been described in several publications e.g. among other by Vrancken et al. (2012) and is a very powerful tool to generate geometrically complex structures of high performance materials. This renders it very interesting for aerospace industry, where enhanced-strength materials such as titanium alloys are being widely used. In particular, TiAl6V4 (Ti – 6 wt% Al – 4 wt%) has a great potential, since it shows a high specific strength, low density and high corrosion resistance at temperatures of up to 350 °C as outlined by Leyens and Peters (2003). Unfortunately, the SLM technology as a whole suffers commonly from several major problems.

Achieving the objective of SLM, i.e. obtaining high quality parts with a homogeneous, full material density, is very difficult to perform since no mechanical pressure is involved as it is, for example, in molding processes. Consolidation of the metal powder while processing is performed only by temperature effects, gravity and

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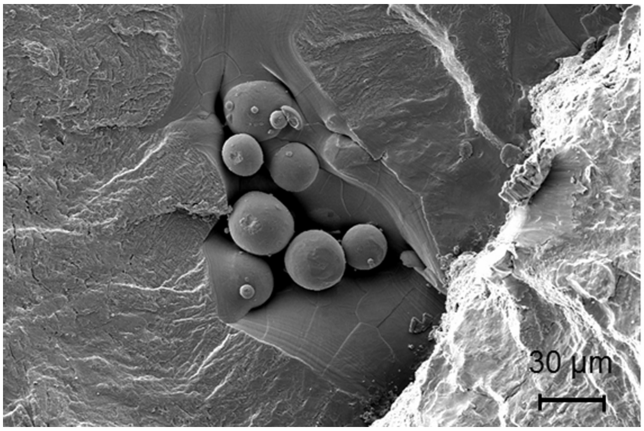

Fig. 1. Non-processed particles as nuclei for cracks: fracture surface of a sample with a colony of unmolten TiAl6V4 particles.

capillary forces. Non-optimal scan parameters may cause instabilities in the melt pool during the process, which lead to the formation of inner defects, such as unmolten particles, spherical entrapped gas bubbles, and lack of fusion as shown in Fig. 1.

Various types of defects inherent to the SLM have been well described by Vilaro et al. (2011) and are very important for the mechanical properties of the material. Presently, the pores and other defects cannot be avoided completely, but they should be kept to a minimum at the stage of the powder-layer consolidation, as was clearly confirmed among other by Kruth et al. (2007). Thijs et al. (2010) discussed the roles of scanning parameter (velocity, island size, scanning strategy etc.) for several standard steels and titanium alloys and investigate the qualitative states of porosity two-dimensionally (2D), however the optimum conditions are not represented and quantitative characteristics were not considered. Leuders et al. (2013) examined the SLM manufactured TiAl6V4 samples three-dimensionally (3D) using a computed tomography and measured their quantitative porosity. The authors received the high values of the relative density: from 99.77% up to 100%, but the tomographic measurement in this study provided a low resolution of 22 μm/voxel, which underestimated the real porosity values, since the pores smaller than 22 μm were not considered. Thus, the studies focusing on the need of minimization of inherent defects of TiAl6V4 fabricated by SLM parts are available quite numerously, but a systematic optimization of the technological process parameters are not sufficiently presented, especially in terms of the detailed quantitative analysis of porosity, which is still lacking.

Along with defects inherent to non-optimal laser scan parameters, there is a second important aspect strongly influencing the quality of the SLM material: internal stress resulting from a high temperature gradient and rapid solidification during the process.

The conventional microstructure of TiAl6V4 can be classified by the size and the arrangement of the two phases α (hcp) and β (bcc) [Leyens and Peters (2003)]. SLM promotes the formation of an acicular/lamellar α' hcp phase (martensitic), which has a finer microstructure and exhibits larger residual stresses, but it is inherently less ductile than the globular microstructure formed during conventional processing. The further thermomechanical treatment adjusts the microstructure and thus reduces internal stresses. By heat treating at intermediate temperatures below the β transus (so called "the low-temperature heat treatment strategy"), the initial fine martensitic structure is transformed to a mixture of α and β, in which the α phase is also present as fine needles as stated by Vrancken et al. (2012). When annealing above the β transus of 995 °C (so called "high-temperature strategy"), the martensitic material is restored into a structure similar to the conventional TiAl6V4, which are supported by the comparative study by Sercombe et al. (2008) as well as by the investigation of Vilaro et al. (2011).

The transformed structures are essential for the mechanical properties of the materials. Thus, as it was mentored among other works e.g. by Facchini et al. (2010), the high-temperature heat treatment strategy leads to slightly lower yield strength and ultimate tensile strength than the conventional microstructure. The low- temperature strategy, in contrast, increases the yield strength and ultimate tensile strength in comparison to 'as-cast' and wrought standards. However, the ductility and fatigue strengths are significantly inferior to standards for both temperature strategies. The completely satisfied ductility values can be explained, on the one hand, by the fact, that the effects of the thermomechanical treatment process for SLM samples were considered without prior optimization of their manufacturing in all there works; and on the other hand, that the applied post-treatment was not quite optimal.

As the post heat treatment for the SLM part can also be applied a hot isostatic pressing (so called HIP process), which is used in traditional powder metallurgy and foundry technology and was proposed among others by Agarwala et al. (1995). Despite the fact, that e.g. Thöne et al. (2012) indicated a relatively low ductility value for the SLM specimen after HIP treatment: 8.3%, (which can also be explained by the non-optimized manufacturing parameters), HIP seems to be very promising to restore TiAl6V4 properties due to the combined effect of high temperature and high pressure, and allows not only to adjust the microstructure, but also to fuse unmolten particles and "kissing bonds". This reduction of residual porosity is very important, since the pores within the sample can act as strong stress raisers and lead to failure, especially under fatigue loading. Leuders et al. (2013) investigated an effect on the high cycle fatigue (HCF) behavior of SLM-processed TiAl6V4 and revealed that minimization of porosity is much more important than the microstructure to avoid premature crack initiation under cyclic loading. The fatigue experiment in the HCF regime conducted by the aforesaid authors showed a multiple increase in durability of samples after HIP. Further research of HIP treatment on the SLM specimen but only with preliminary minimization of the porosity during the fabrication is certainly needed. To assure the reliability of ASLM parts, an effect of surface roughness on the fatigue behavior should to be considered. Fatigue tests should be therefore with surfaces in the 'as built' and 'machined' conditions performed.

Therefore, a careful double optimization procedure is necessary to obtain a high quality material: firstly, the optimization of the SLM parameters for the minimization of inherent defects, and secondly, the application of further thermomechanical treatment to minimize internal stresses and adjust the microstructure. These two stages of optimization are presented in this paper, which aims to comprehensively examine the factors influencing defects in TiAl6V4 processed by SLM.

For this reason more than 40 small TiAl6V4 cuboids were previously produced with the various scan parameters. The porosity of each test sample was quantitatively two- and three-dimensionally analyzed using laser optical and scanning electron microscopies and X-ray computed tomography. The optimized process parameters were afterwards used in the second part of the program to produce cylindrical specimen for the mechanical testing. Based on the fact that the initiator of cracks can be also a rough external surface and since some surfaces in complex components such as the channels in the turbine blade cannot be machined or polished, both treated ('machined') and untreated ('as built') surface conditions were considered. Various subsequent thermomechanical treatment techniques were tested: some samples were annealed with the various temperature strategies and some samples were hot-isostatically pressed. The hardness, tensile properties and high cycle fatigue resistance of all treated and non-treated samples were