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Developing LBM process parameters for Ti-6Al-4V thin wall structures and determining the corresponding mechanical characteristics

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Abstract

The Laser Beam Melting (LBM) process technology within the family of Additive Manufacturing technology is characterized by its ability to fabricate fully dense 3D structures directly from micro-sized metal powder. With the current state of the art, Ti-6Al-4V has been processed using LBM machine systems constituting a laser with a beam diameter of about 100 μm. In order to fabricate structures with smaller wall thicknesses, processing of Ti-6Al-4V is attempted on the LBM machine system, Realizer SLM 50 consisting of a laser with a beam diameter 10 μm. The proposed paper presents the development of process parameters for fabricating fully dense Ti-6Al-4V 3D structures using the LBM machine system, Realizer SLM 50. Further experiments are carried out to determine the wall thickness and mechanical properties achievable using the selected process parameters. Analysis and scientific arguments are presented to explain the influence of building direction and heat treatment on mechanical properties.

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1. Introduction

The presented research paper discusses processing of micro sized Ti-6Al-4V powder into a fully dense 3-dimensional structure using the Laser Beam Melting process. Characterized by its layer by layer manufacturing, Laser Beam Melting is one of the latest processes in the field of Additive Manufacturing technologies. With its characteristic free form fabrication concept and its ability to fabricate fully dense 3D geometry directly from digital data, Laser Beam Melting has become a very interesting topic for research and industry alike. Although highly appreciated by the industry, the Laser Beam Melting process still has some inherent limitations. One of which is its inability to fabricate thin structures. Some of the commercially available materials for Laser Beam Melting process include Titanium, Aluminum, Stainless Steel, etc. Although a commercial state of the art, Ti-6Al-4V has only been processed on Laser Beam Melting machine system with a relatively high power laser and a large beam diameter. The current research therefore focusses on processing Ti-6Al-4V on the Laser Beam Melting machine system Realizer SLM 50 which has the maximum laser power of 100 W and a beam diameter of 10 μm. The proposed initiative is above the current state of the art, which processes the material Ti-6Al-4V with machine systems with specifications of significantly high laser power and beam diameter. The minimum wall thicknesses associated with such systems are in the range of 200 μm – 300 μm. It is believed that the ability to process Ti-6Al-4V with a Laser Beam Melting machine system having a beam diameter in the range of 10 μm would significantly reduce the limitation on the smallest possible thickness of fabricated structures. One of the scientific risks foreseen is the limitation on the maximum laser power of 100 W possible on the Realizer SLM 50 machine system. Therefore significant parameter optimization and mechanical characterization is performed to derive the best possible processing specifications for the selected material. The following research presents various stages of process parameter optimization performed on Realizer SLM 50 and the resulting mechanical characteristics of the 3D structure.

2. Investigated material and LBM unit

Commercially available micro sized Ti-6Al-4V powder is used for the experiments. Ti-6Al-4V powder is produced by Inert gas atomization process using Argon as the atomizing gas. Argon atomization creates powder particles that are highly spherical in their morphology and the absence of any oxygen during the atomization process eliminates the possibility of oxidation of the powder particles. Spherical morphology of the particles is essential for a good flowability and therefore a suitable re-coating for the Laser Beam Melting process. Sieving of the powder between 20 μm and 50μm is performed to obtain a controlled particle size which is also essential for flowability as smaller size particles may form agglomerates and cause an unsuitable recoating. Limitation on the large size particles is to control the surface roughness of the formed structure. Fig. 1 shows the SEM image the sieved Ti-6Al-4V powder used for performing experiments.

![SEM image of Argon Atomized Ti-6Al-4V powder sieved for particle size between 20 μm and 50 μm.](image)

Laser Beam Melting machine system used for conducting the experiments is the Realizer SLM 50. The machine uses a circular platform of 70 mm diameter and has been modified to have a build height of 80 mm from the standard build height to 40 mm. This modification was necessary for fabricating the tensile bars vertically and with
an inclination of 45° to the horizontal. During the phase of mechanical characterization, tensile bars in 3 orientations would be fabricated to understand the anisotropic behavior of the fabricated structure associated with the Laser Beam Melting process. As the Laser Beam Melting process is a layer by layer process, it is essential to understand the anisotropic characteristics of the fabricated structure. The key components of SLM 50 machine system include a high intensity Fiber laser which is deflected using an X-Y scanner and focused using an F-Theta lens. Realizer SLM 50 uses a Ytterbium fiber laser with a maximum power of 100 W and a beam diameter of 10 μm. The process of material deposition on the build platform is performed using a re-coater having 2 wipers blades and a material feeder mechanism. The laser-powder interaction takes place in an inert atmosphere created by a continuous laminar flow of Argon which performs the dual function of preventing oxidation of Titanium during the Laser Beam Melting process and of blowing away the fumes created during the melting of Ti-6Al-4V powder.

3. Development of Laser Beam Melting process parameters

The parameters that can be varied during the Laser Beam Melting process include layer thickness, laser power, scan strategy and scan speed which is indirectly controlled by manipulating the exposure time and point to point distance values. Variation in each of these parameters can have an effect on the relative density and mechanical characteristics of the resulting structure.

Layer thickness for the process is influenced by the particle size of the powder being used. In order to achieve better quality, a smaller layer thickness is preferred. For the current Laser Beam Melting experiments, a 30 μm layer thickness is used as the average particle size is between 40 – 50 μm, based on analysis from SEM image.

The Realizer SLM 50 machine provides a choice of two scanning strategies. Firstly a single exposure performed in x and y direction alternatively with every consecutive layer. The second choice is a double exposure in both x and y direction in each layer. The choice of scanning strategy is essential in controlling the melting and solidification behavior in the formed structure and therefore its resulting microstructure. Fig. 2 shows an illustration to explain the difference between the two scanning strategies. Initially a single exposure strategy is applied for the experiments.

The scientific approach for process parameter development is a highly iterative one. Due to the extreme number of combinations possible by varying laser power, exposure time and point to point distance, an elimination based step by step approach is taken and the unqualified combination of parameters are eliminated at each stage. The first step in this approach involves fabrication of single weld track to perform a qualitative analysis by determining the continuity and structure of the formed weld track.
The fabricated weld tracks are analyzed with a laser scan microscope in order to qualify or disqualify the process parameter combination. Fig. 3 shows an example of the resulting weld track from a qualified and a disqualified process parameter. The qualified process parameters are further analyzed during fabrication of thin walls resulting from the consecutive buildup of single weld tracks layer by layer.

Microscopic images of combinations from various process parameters are analyzed to determine the connection of the structure to substrate plate, continuity of the formed structure and its approximate thickness. An important factor analyzed is the ability of the process parameter to form a strong bond with consecutive layers in the powder bed. This is essential for the formation of a mechanically strong, homogeneous structure.
Fig. 5. 3D samples of Ti-6Al-4V using Laser Beam Melting for relative density analysis a) 5 mm cubes with different parameter combinations b) microscopic cross section of an analyzed sample.

The next stage of process parameter development involves fabrication of 3D structures. Process parameter combinations that enable formation of a continuous wall and a good bonding between the layers are qualified for this stage. Wall thickness analysis on single walls is performed to estimate the appropriate hatch distance which would be a new parameter input at this stage of the analysis. The hatch distance is selected so as to have a sufficient overlap between the adjacent weld tracks during irradiation of the complete surface at a particular layer. For the analyzed single walls, the qualified process parameter combinations resulted in approximate wall thicknesses between 100 μm and 300μm. Wall thickness of 100 μm as indicated in Fig. 4 (b), is significantly smaller than the current state of the art. Thus based on the combination qualified process parameters with various hatch distances, 3D structures were fabricated and analyzed. Fig. 5 (a), shows a completed build with 5 mm cubes formed by Laser Beam Melting of Ti-6Al-4V. In part b) of Fig. 5, the cross section of a fully dense cube is shown. The analyzed relative density using image analyses tools is found out to be above 99.5%. In order to achieve the indicated result, the scanning strategy of double exposure in direction perpendicular to each other for every layer is performed. In addition, the build platform is heated to a temperature of 200°C. Based on wall thickness analysis, for the qualified parameter in 3D cubes, the selected hatch distance would approximately result in a 50% overlap with the adjacent weld track. The power values used for each exposure are approximately the same and a volumetric energy density of about 100 J/mm3 is calculated for the qualified process parameter. Laser Beam Melting of Ti-6Al-4V is performed in an argon atmosphere to eliminate the possibility of oxidation. Moreover, it has been investigated [1] that residual oxygen is absorbed within initial stages of the layer wise melting process. As for samples fabricated within this work a support structure with a height of 4 mm is manufactured between platform and part. It is therefore assumed that residual oxygen is consumed within the support structure and the testing geometry is not influenced.

4. Mechanical testing geometry and set up

In order to evaluate the process parameters for the production of real parts, a comprehensive material characterization was performed. The most important values for qualifying additive manufactures components are the yield strength YS, the ultimate tensile strength UTS and the elongation at break E. All three parameters can be identified by standardized uniaxial tensile testing according to DIN EN ISO 6892-1 [2]. Thereby, cylindrical bars are manufactured with a height of 70.0 mm and a diameter of Ø 8.0 mm applying process parameters described within chapter 3. Afterwards the finale tensile testing geometry is produced with a grinding process. According to DIN 50125 [3] the testing geometry is manufactured as scheduled in Fig. 6 (b), while a picture of the actual geometry is given in Fig. 6 (a). For testing an evaluation length of 8.0 mm with a diameter of Ø 4.0 mm is utilized. With a clamp length of 28.0 mm in combination with hydraulic clamping equipment slipping of the high strength material is avoided. Comparable testing geometries have been used for mechanical characterization of LBM aluminum specimens within different research projects [4].
As described in chapter 2 the LBM is a layer by layer process. Consequently, different elastic-plastic and failure behavior can be expected for different testing orientations. In order to determine the highly anisotropic material properties, three different sets of specimens, parallel, 45° and 90° to the building direction, are manufactured and tested. Furthermore, it is known that an additional heat treatment can improve the ductility of the produced parts. Therefore, one set of specimens is additionally heat treated after the LBM process to enable a comparison of mechanical properties with just as built parts. Heat treatment is performed according to Vrancken [5] for a period of 2 hours at 850°C and followed by furnace cooling. Argon atmosphere is used during the heat treatment process to reduce the possibility of oxidation of samples.

Fig. 6. (a) machined tensile testing geometry; (b) schedule of machined tensile testing geometry; (c) tensile testing geometry at different building directions with support structure after LBM.

5. Results and discussion

The influence of the testing orientation and the heat treatment on the yield strength is presented in Fig. 7 (a). Comparing heat treated specimens depending on the building direction, the ones built in 0° and 45° have YS of about 1200 MPa ± 40 MPa, while for 90°-specimens YS of about 1000 MPa ± 30 MPa can be identified. This decrease for 90°-specimens can be explained due to the fact that for the perpendicular specimen’s unmelted layer areas are more decisive for lowering the strength. The effective stress bearing cross section for the 90°-specimens is located perpendicular to the initiated stress and thereby lowered more dominant than for 0°-specimens and 45°-specimens. Furthermore, it can be pointed out that without heat treatment YS of 1309 MPa ± 64 MPa is representative for 45°-specimens.

Results of testing for UTS presented in Figure 8 (b) confirm the above identified effects. On the one hand, a decrease of the UTS from about 1400 MPa for not heat treated to about 1200 MPa for heat treated part occurs. On the other hand, both, 0°-specimens and 45°-specimens, have UTS of about 1200 MPa, while 90°-specimen achieve reduced UTS with about 1100 MPa. In agreement with the results of the YS, the effects can be explained by lack of connection between layers which is most dominant for 90°-specimens.
Finally, the failure behavior of the specimens characterized by elongation at break, $E$, is investigated. Thereby a high standard deviation is characteristic which can be caused by a wide range of reasons. To investigate those two methods are utilized. On the one hand cross sections are analyzed to detect porosity and on the other hand the fracture surface is analyzed by SEM. As a result no significant porosity or un-melted areas can be proved within the fracture zone, which would give an explanation to the highly varying results for elongation at break. The effect of building direction on $E$ cannot be identified as significant for 45° and 90° direction, taking into account standard deviation.

Within the tested parameters heat treatment of 45°-specimens leads to an increase of elongation at break from $1.26\% \pm 0.32\%$ to $5.71\% \pm 1.12\%$. Vrancken [5] explains tendency for a decreasing YS and UTS in combination with an increasing $E$ with microstructural change of material during heat treatment. Very high cooling rates during SLM process lead to a fully acicular α′martensitic microstructure of Ti-6Al-4V. These fine α′ needles cause lattice distortion and reduce the possibility for dislocations to slip. During heat treatment, residual stresses are reduced [5]. Thereby the slipping ability for dislocations is improved which leads to reduction of strength and increase in ductility.

The mechanical behavior can be described more precisely by analyzing the fracture zone as well as the fracture development of specimens built in different orientation. The fracture zone (a) and fracture development (b) of 0°-specimen is shown in Fig. 8. The fracture zone is formed as a rough surface without any predominant direction to the induced stress. As layers, which are not melted during additive manufacturing, are positioned parallel to the load direction, the effective stress bearing cross-section is not reduced dominantly. In contrast, one exemplary fracture zone and development of 90°-specimen are shown in Fig. 8 (e) and (f). The fracture zone is formed as plane perpendicular to the uniaxial induced stress. In this case, an unmelted layer reduces the stress bearing cross-section significantly, as it is located within the same plane. Furthermore, the fracture zone and development of a 45°-specimen is presented within Fig. 8 (c) and (d). As all layers are melted with 45° to the length axis of the specimen this influences the fracture development. As a result, fracture is favored within these layers.
The mechanical strength properties for SLM Ti-6Al-4V presented within this work, show very good agreement with SLM Ti-6Al-4V manufactured with different machines and various producers [6,7]. All presented strength parameters fulfill within DIN 17865 standardized characteristics for Ti-6Al-4V castings. Thereby the lower border for YS is 785 MPa and for UTS 880 MPa [8].

Furthermore, an elongations at break is standardized with a minimum of 5 % within DIN 17865 [8]. This value can not be reached for not heat treated specimens. Although it is lower than standardized it is comparable with published elongation at break values for SLM Ti-6Al-4V [9]. Heat treatment enables to increase E for 45°-specimens by 4.5 times to 5.71 %, fulfilling the standard. Still within literature higher values are reported for comparable heat treatment strategies [5]. Wirtz [9] reports of oxid segregation within SLM Ti-6Al-4V specimens which cause notch effects and reduce ductility. The effect is dependent on the cooling rate of the melted powder and it is more dominant for increasing cooling rates [9]. As within this work very high cooling rates are utilized this significantly influence the investigated mechanical properties. With heat treatment oxides are soluted and balance between areas with high and low concentrations enabled. As heat treatment parameters strongly influence the oxid solution progress and thereby the notch effect as well as the mechanical characteristics, it can be assumed that elongation at break can further be increased by improved heat treatment strategy.

Summarizing the comprehensive material characterization, two important findings can be derived. On the one hand, additive manufactured parts with the LBM-process have a very strong anisotropic behavior, and on the other hand the mechanical properties can be significantly be changed by heat treatment operations. Consequently, a tailoring of the material according to the final application is possible. This is for example interesting for improving the crash behavior within the automotive industry.

6. Conclusion

Additive manufacturing of Ti-6Al-4V parts by Laser Beam Melting with high power is state of art for commercial production. Based on the presented research, Laser Beam Melting of highly dense Ti-6Al-4V has been proven to be possible using a low power and a small beam diameter laser beam melting machine system such as
Realizer SLM 50. Fabrication with small beam diameter has the impact of achieving thinner wall structures than currently obtainable with Ti-6Al-4V using the process of Laser Beam Melting in metal powder bed.

In order to further verify the achieved results, mechanical characterization of the fabricated samples is performed by analyzing yield strength, ultimate tensile strength and elongation at break. The obtained results verify compliance with published mechanical characteristics of LBM Ti-6Al-4V and fulfill DIN 17865 where characteristics for Ti-6Al-4V castings are standardized. Taking into account the anisotropic behavior inherent to additive manufacturing, three different building directions, parallel, 45° and 90° to building direction, are considered. It is pointed out that 90°-specimens have the lowest strength within the investigated parameters. This can be explained due to the fact that for 90°-specimens unmelted layer areas are more decisive than for 45° and 0° building direction. The effective stress bearing cross section for the 90°-specimens is located perpendicular to the initiated stress and thereby lowered more than for the others. Furthermore, the effect of heat treatment after LBM is pointed out. While, on the one hand, YS and UTS is decreased, on the other hand, E is increased by heat treatment.

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