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Characterization and Optimization of Additive Manufacturing Processes for Aerospace Titanium Alloys

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Abstract

Selective Laser melting (SLM) is an additive manufacturing technology that uses laser as a power source to sinter powdered metals to produce solid structures. The application of SLM permits engineers to develop and implement components with topologically optimized designs and resultant material properties in comparison to conventionally produced casting parts. Current aviation programs as ACARE 2020 (Advisory Council for Aviation Research and Innovation in the EU) and Flightpath 2050 request a reduction of fuel consumption as well as CO2 and NOx emissions in the next years. To meet these requirements there is a clear trend to produce light-weight components for engines and structural parts of aircrafts through SLM. Since SLM process is a key technology for aeronautical application, this paper focusses on the qualification of a high performance titanium alloy as well as on the investigation of optimized process parameters and positioning strategies of the structures produced in the SLM machine.

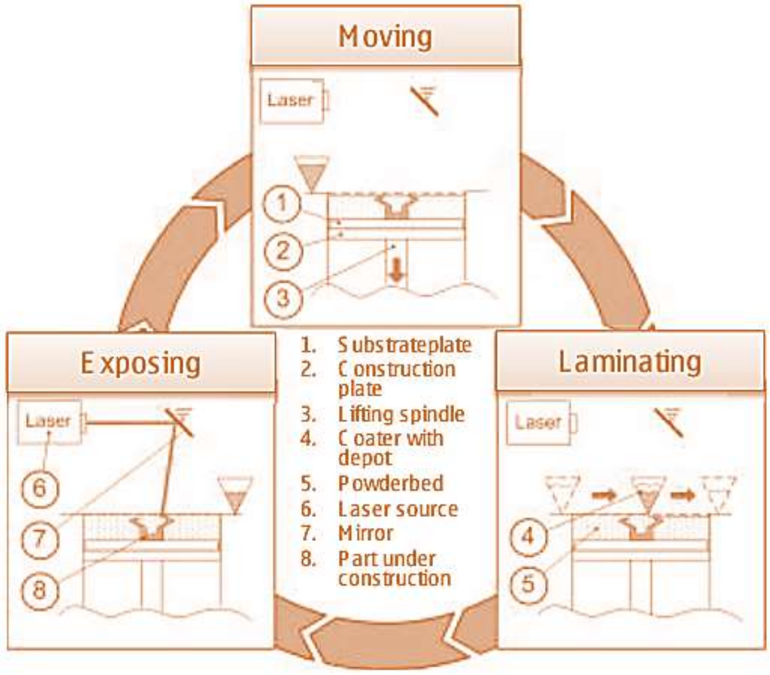
1. Introduction

In the field of commercial aviation, a demand for more than 28,000 new large commercial aircraft on the global market is expected for the period of 2012-2031. Approximately 10,000 of the old aircraft will have to be replaced. A global growth of 4.7 % per year in air traffic, measured in passenger kilometers (RPK), is also estimated [1]. Embraer forecasts a requirement for more than 5,000 new jets in the 30 to 120-seat capacity segment over the next 15 years, with a total market value estimated up to US$ 200 billion [2]. In addition, aviation programs ACARE 2020 (Advisory Council for Aviation Research and Innovation in the EU) and Flightpath 2050 request a reduction of fuel consumption as well as CO2 and NOx emissions over the course of the next years for aircrafts [3,4]. These framework conditions represent a challenge for the producers of structural parts and engines for aircrafts. In order to fulfill current and future requirement, the aircraft industry must undergo considerable technological developments concerning innovative materials and design techniques as well as new fabrication processes.

An interesting additive manufacturing technology for the fabrication of components with innovative designs and also topological optimized geometries is the selective Laser melting (SLM). SLM allows a layer by layer production of complex components directly out of metal powder based on CAD-Data. An exceptional advantage of SLM is the possibility to manufacture complex lightweight structures that cannot be produced using conventional processes. Lightweight structures can contribute to the increase of efficiency and also to reduce the fuel consumption and the emission levels of gases by aircrafts. Embraer is working in cooperation with Fraunhofer IPK to investigate the characteristics and mechanical properties of a titanium parts made by Selective Laser Melting for a structural aerospace application. In order to achieve advancedknowledge regarding these produced parts it is essential to analyze the process and the resultant parts. To attain this target, test geometries of Titanium alloys were built and different properties such as density, micro hardness, surface roughness, tensile and fatigue properties were examined. As the final result structural metal parts were produced by the SLM process to evaluate the achieved results.

2. Selective Laser Melting (SLM) of titanium alloy

Selective Laser Melting (SLM) allows the processing of several metal materials and is especially appealing for individual parts with complex geometries. Using SLM, designers can integrate functions as cooling channels, rear slices and build lightweight structures directly into the component and manufacture this component in one single process step. The iterative process flow is shown in Figure 1.

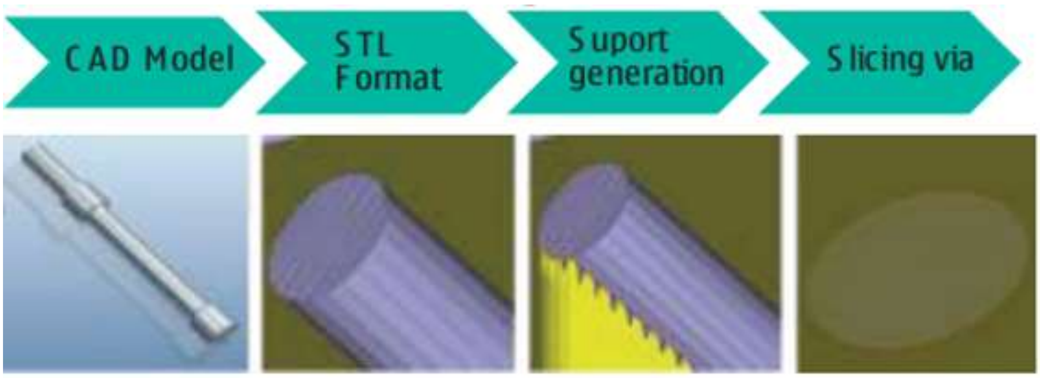


The substrate plate is lowered to one layer thickness and the powder is evenly distributed by the coater over the platform. Then the material is selectively melted. These three steps repeat until a whole part is built up, layer by layer. During the process the whole process chamber is flooded with an inert gas such as Argon to avoid oxidation of the metal powder. The powder that has not been used in the process is sieved and reused for the next process. The features that concern the selection of the layer thickness are shown in Table 1. In order to achieve high process stability, velocity and low material costs, and still being able to build a part with an acceptable resolution and surface quality, a layer thickness of 50 µm is used in this paper.

TiAl6V4 is counted among the (α+β)-alloys and it is today's most common used titanium alloy. It covers 50 % of the whole production of titanium alloys. It is also the most explored and tested titanium alloy with very balanced properties, such as low density, ductility, good corrosion and oxidation resistance. It is used in high operating temperatures and high stresses, for example in the building of gas turbines. The properties of the titanium-alloy depend on the microstructure, the size and arrangement of the α- and βphase. The microstructure is depending on the cooling process. The both extreme forms are the lamellar and the globular microstructure. Simple cooling from the β-phase leads to a lamellar microstructure, the lamellas are coarsed with decreasing temperature. Fast quenching leads to a martensitic transformation of the ß-phase with a fine-spitted structure. Globular microstructure is the result of recrystallization. Both forms of microstructures can exist in fine and coarse distribution [7]. Several researches on the field of titanium alloy manufacturing by SLM are been carried out and are showing a high potential for its application [8,9,10].

3. SLM testing geometries

The workflow of the pre-processing for the production of TiAl6V4 testing geometries is shown in Figure 5. The CADmodel is converted into a stereolithography format (STL). After that follows the support generation and the slicing of the part.



The production of TiAl6V4 specimens was carried out using a SLM 250HL machine by the company SLM SolutionsGmbH, Lübeck, Germany. The significant parameters used for the manufacturing of testing geometries are the laser power PL, the scanning velocity vs and the focus diameter ds, which depend on the focus position. The used SLM parameters for the production of testing geometries. The layer thickness of 50 µm remains constant during the whole manufacturing process.Round specimens in 0°, 45° and 90° orientation are generated according to VDI 3405-2 [15]. The last steps before the SLM-process begging are as follows: cleaning of the process chamber and the coater, adjust of the substrate plate and application of the first layer.

After the additive manufacturing, the specimens have to cool down, be removed from the machine and get cleaned from the powder used during the process. Moreover a thermal post-processing is used before the hot isostatic pressing (HIP)in order to increase the surface quality, close micro cracks and reduce very high residual stresses in the component. According to DIN 17869 stress relief heat treatment is recommended for internal welding stresses of multilayered weld seams in a component. The process parameters are based on indications of DIN 65083 for thermal treatment of casted components made of titanium and titanium alloys for aerospace [16,17]. The following process parameters were used Hot Isostatic Pressing according to DIN 65083 "causes the healing up of internal structural defects such as micro blowholes and pores in castings, through annealing at high temperatures and pressures". So the HIP-process reduces the porosity and increases the density of the part. Thus fatigue properties get improved. The static and dynamic strength, the breaking elongation and durability are increased and more uniform mechanical properties are achieved [17,18].

4. Analysis of the processed material

The relative density gives information about the deviation of the determined density from the literature density. The deviations arise through blemishes in the microstructure which are either blowholes or air pockets. Also the porosity of the surface leads to a decreased density. Particularly additive manufactured parts have a high porosity. To determine the density of the solid parts, the

Archimedes' principle was applied. Therefore the specimens are cleaned of adhering impurities. Then the cube is weighed on air and afterwards moistened with distilled water to reduce measurement errors caused by adherent air bubbles. A beakerfilled with water is placed on the electric balance. To determine the density of the water, the temperature is measured by a high precision thermometer and taken from a table out of DIN ISO 3369. The specimen is attached to a 0.2 mm line, fixed on a tripod and slowly dipped into the liquid. The weight shown on the balance is equal to the weight of the displaced fluid, caused by the solid body [19,20]. As reference, the literature density of the casted material without porosity, the value of 4.43 g/cm³ is used [16]. The detected density of the SLM-specimen is around 4.35 g/cm³ which correspond to 98.19 % relative density.

he Vickers micro hardness is used for the hardness analysis as the process can be used for almost every material and small specimens. The measurable Vickers Hardness range is 10 HV to 2000 HV. DIN 6507-1 describes the implementtation of the process [21]. The measurement is made in the xy- and xz-direction. The determined hardness in xy-direction is 316 HV30 and in xz-direction 320 HV30. Hence the hardness of the specimens are approximately 88 % and 89 % in reference to the average literature value of 360 HV30, as the literature hardness lies between 330 to 390 HV30 [22].For measurement of the surface roughness, the profile method based on DIN EN 4288 is used. In this stepwise process, a rod with a diamond top is driven over the surface. The 45° and 90° specimens were measured at the side surfaces (Rz1 and Rz2) and on top of the specimens (Rz3). As seen in Table 5 the cover surface Rz3 show higher roughness Rz. The increased roughness of the 45° specimens is a result of the layer-by-layer construction where a stage effect occurs due to the high inclination. The 90° specimens have a higher roughness on top, due to the layers becoming gradually smaller towards the top.

5. Conclusion

Industry, innovative material and manufacturing technologies are needed. Additive Manufacturing opens new opportunities for engineers to design light weight and topological optimized parts for aircrafts. However, more knowledge regarding the SLM process and the resultant material properties of the produced parts are essential. In this paper crucial information concerning the necessary analysis of the powder material as well as SLM-parameters for the production of additive manufacture components of TiAl6V4 are given. Results of post-processing, applied on TiAl6V4 components, produced by SLM, show enormous potential in improvement of surface quality. Microstructure and computed tomography analyses show that HIP-process leads to a homogenous microstructure and can reduce the porosity of the titanium alloy parts. The mechanical properties of the produced SLM components, finishing technologies for the machining of these as well as the definition and development of quality control processes are important topics to be investigate in following research activities. Only with the help of continuous process improvements it will be possible to produce parts, that ensure the quality and safety required by aeronautical industry.

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