MECHANICAL PROPERTIES AND POROSITY OF Ti-6Al-4V ALLOY PREPARED BY AM TECHNOLOGY

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DOI: 10.17973/MMSJ.2017_02_2016190

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The specimens manufactured using principle LS (Laser sintering) by the additive manufacturing technologies from the Ti-6Al-4V (Grade 5) titanium alloy are investigated. The powder Ti-6Al-4V is well-known for its slightness and high strength. Metal additive manufacturing processes produce parts with porosity. The possibility of changes in a porosity during an additive manufacturing build may also be an indication of problematic points during the process. This paper is investigated our work to monitoring of part porosity during an additive build, including characterization of mechanical properties such as the average yield strength (YS) and ultimate tensile strength (UTS) , and elongation. Also, the development and detailed characterization of microstructures were carried out.

KEYWORDS

porosity, LS, tensile test, Ti-alloy, mechanical properties, microstructure

1 INTRODUCTION

Selective Laser Melting is an additive manufacturing technique that can print metal parts in 3D. A laser is used to melt metallic powder in specific places [Warnke 2009; Safka 2015].

With the LS method, the workpiece is constructed in a three-dimensional layer structure. To accomplish this, the metal is applied in thin layers of very fine powder and, using a laser beam, melted onto those areas where the workpiece will be developed. Depending on the surface quality and production speed requirements, the powder is automatically applied with layer thicknesses of 20 to 100 µm [Bandyopadhyay 2010]. In the following step, a powerful fibre laser selectively melts the designated areas. Sharp focusing provides the laser beam with a very high power density by which the material is melted in a very precise manner. Thus, workpieces with an absolute density can be produced with wall thicknesses from 40 µm on up.The layer structure facilitates the production of highly complex lattice or honeycomb structures, which cannot be produced using other methods [Leuders 2013]. With the SLM process, the material is therefore only built up where required by the intended use and future strain requirements. One of the benefits here is, for example, the minimization of weight due to the optimized material usage.

Objects printed with LS are made with powder materials, most commonly plastics, such as nylon, which are dispersed in a thin layer on top of the build platform inside an LS machine. A laser, which is controlled by a computer that tells it what object to "print" pulses down on the platform, tracing a cross-section of the object onto the powder. The laser heats the powder either to just below its boiling point (sintering) or above its boiling point (melting), which fuses the particles in the powder together into a solid form [Bidulska 2010]. Once the initial layer is formed, the platform of the LS machine drops — usually by less than 0.1mm — exposing a new layer of powder for the laser to trace and fuse together. This process continues again and again until the entire object has been printed [Vrancken 2012].

However, the complexity of the processing/microstructure and properties relationships makes LS a manufacturing technology that has to be fully yet understood [Baufeld 2011].

Ti6Al4V alloy is one of the most widely used titanium alloys. Owing to its excellent properties, it has been widely used in aerospace, marine, power generation and offshore industries. However, its high yield ratio and large spring back make it difficult to occur plastic deformation. It is easy for Ti6Al4V to generate hard and brittle compounds with oxygen, hydrogen, nitrogen and other elements in the air in the process of cutting. Thus it is difficult to be machined. The above factors restrict the extensive application range [Parthasarathy 2010].

Most of the properties of PM materials are strongly related to porosity. Porosity can be used as an indicative to evaluate and control the processes which the components underwent [Bidulska 2012]. Pores act as crack initiators and due to their presence distribution of stress is inhomogeneous across the cross section and leads to the reduction of the effective load bearing area [Bidulska 2014]. Both the morphology and distribution of pores have a significant effect on the mechanical behavior of PM materials as well as microstructure [Bidulsky 2014]. The effect of porosity on the mechanical properties depends on the following factors: the volumetric fraction of pores, their connectivity, size, morphology, chemical composition; a lubricant; die design and regarding sintering: atmosphere, temperature and time [Maccarini 2014].

In connection with the porosity evaluation, formability should also be evaluated. The relation between mechanical properties and formability is close and significant [Petrousek 2015].

2 EXPERIMENTAL CONDITIONS

A commercial titanium based powders (Ti6Al4V) was used as material to be investigated. The chemical composition is shown in Tab. 1.

Component	Ti	Al	V
	90	6	4
Other elements <1 %: N, C, H, Fe, O			

Table 1. Chemical composition of the studied material [mass.%]

The specimens were prepared by LS technology. Workspace for sample preparation is 90 x 90 x 80 mm3 (x,y,z). The laser system in this machine is Fibre laser 100 W (cw).

The static tensile test was conducted in accordance with standard STN EN ISO 6892-1 on tensile machine TINIUS OLSE H300KU. In the static tensile test were used static conditions and strain rate was 0,002 s^{-1}.

By LS technology were created specimens for the static tensile test with a relatively simple shape according to MPIF Standard 10. The specimen with principal dimensions is shown in the

Fig. 1. The thickness of the sample was 2,75 mm. This technology guarantees accuracy about 0.01 mm.

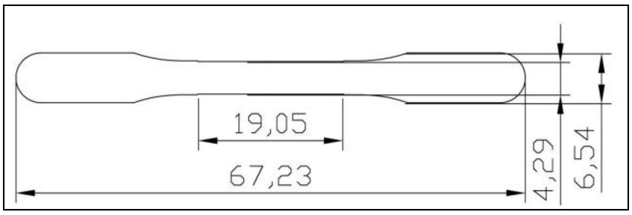


Figure 1. Dimension of sample for static tensile test prepared by LS technology

Allocating sample for measurement porosity, f_{circle}, f_{shape} (the morphological characteristics that show the shape of the pores with a major impact on the mechanical properties, such as presented in the Fig. 2), Aspect (representing the ratio between major axis and minor axis of ellipse equivalent to pore) and D_{circle} (average length of diameters measured at 2 degree intervals and passing through object´s centroid) shown in the Fig. 3. These parameters were measured on the surface of the sample (area 2), in thickness (area 1) and the cross section of the sample (area 3) [Bidulska 2010; Bidulska 2014; Bidulsky 2014].

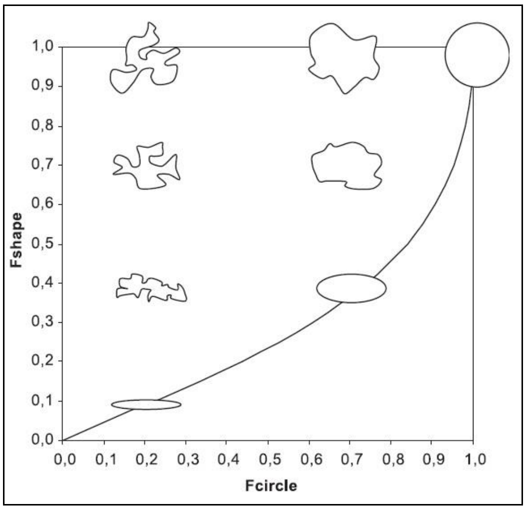


Figure 2. The pores shapes in depending on f_{shape} and f_{circle}.

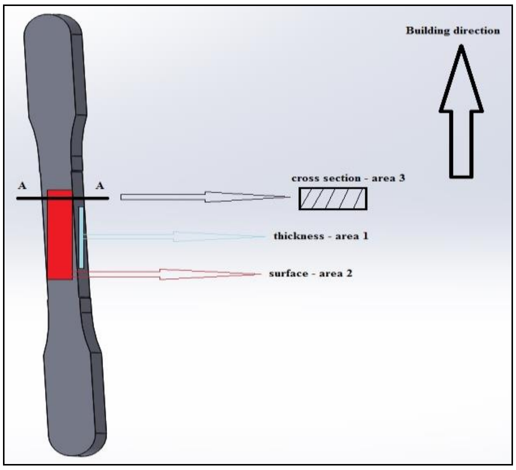


Figure 3. The schematically divided sample into three areas.

Methodology for evaluating the total porosity was described in work [Bidulska 2011]. Microstructures were obtained by OM Zeiss and software AxioVision.

3 RESULT AND DISCUSSION

The Fig. 4 shows a diagram of the static tensile tests of samples prepared by LS technology and without heat treatment. The tensile test was conducted on 15 samples. The course of uniform deformation is the same in all samples. After reaching the yield strength the brittle fracture occurred, which is characteristic of the powder materials. The ultimate tensile strength for all samples was the same, namely 1080 MPa.
Yield strength was in the range <600; 745 MPa>. Ductility measured by the videoextensometric system was in the range <10; 12%>.

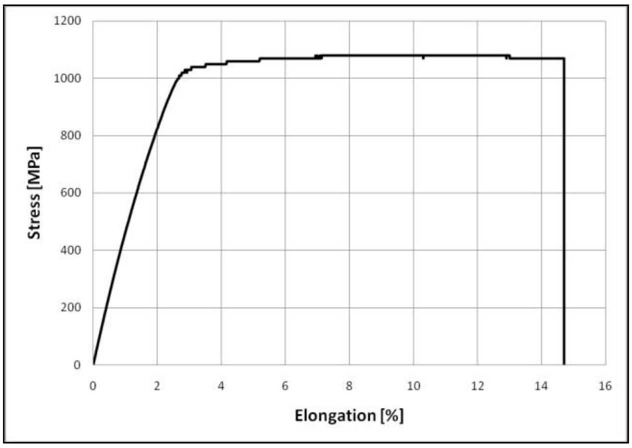
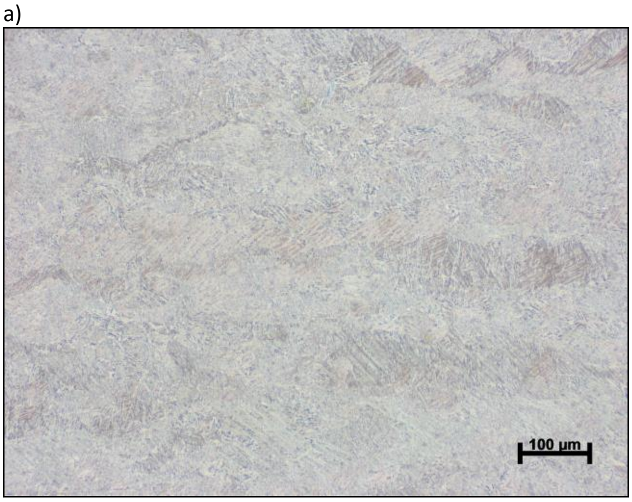


Figure 4. Diagram from the static tensile test

The result of the LS process is a completely martensitic structure (α). Martensitic plates originated from the prior β grain boundaries and fill the columnar grains (Fig. 5a). Consequently, in the picture pores are not visible, and it is necessary to change the contrast by DIC filter. In the Fig. 5b is thus possible to see individual pores and continuous pores.

a)



b)

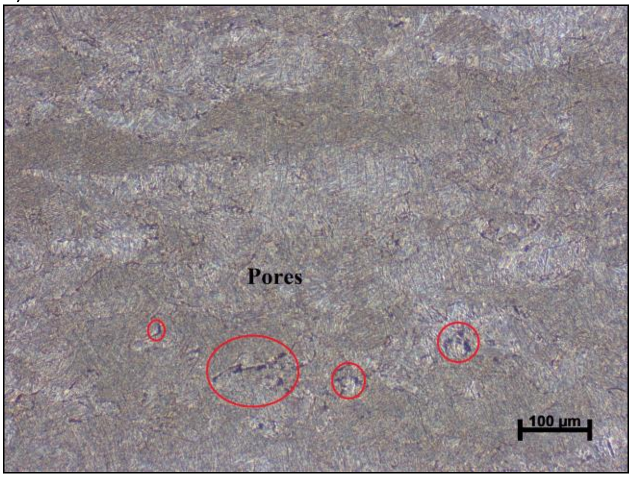
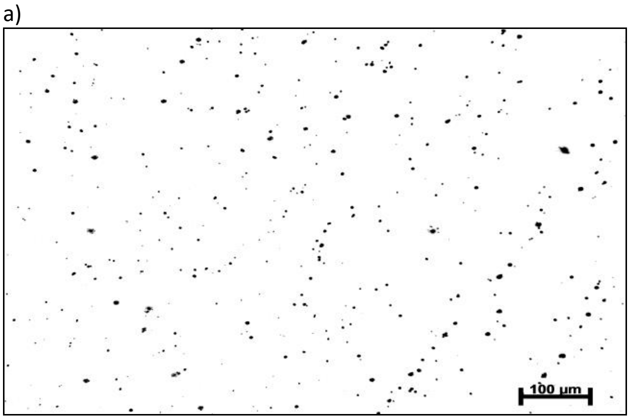


Figure 5 a) Microstructure of Ti6Al4V from OM b) Microstructure of Ti6Al4V from OM with DIC filter outlining the pores

Evaluation of the porosity of the etched samples is difficult because the contrast between the grain and pores is small. Therefore, it is appropriate to assess the porosity of the only polished samples, not etched. Etching causes incorrectly indicating pore. The Fig. 6a is an example of non-etched microstructure in which porosity was evaluated. The program ImageJ these pores marked (Fig. 6b). This program works with the contrast of white - black and recognizes each pixel from created picture. The data are evaluated in the coordinate system <x, y>.

a)



b)

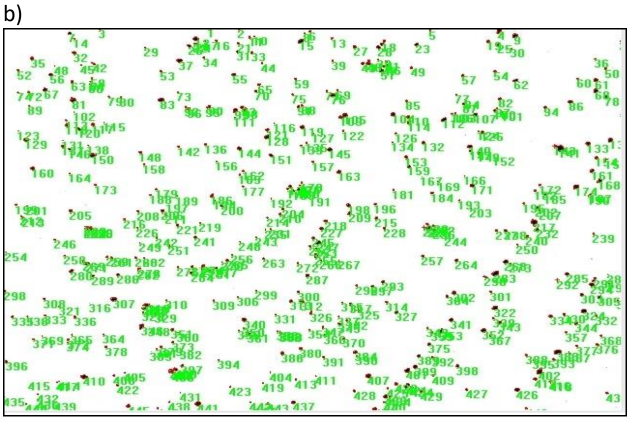


Figure 6 a) Microstructure of Ti6Al4V from OM, not etched b) Microstructure of Ti6Al4V from OM with grid in ImageJ <x, y>

The dependence between f_{circle} and f_{shape} expresses the shape of pores, as shown in the Fig. 2. If the ratio is „1", then the pores have ideal circular shape. In this case, an ideal shape of the pores were more than 94% (Fig. 7). The shape of the pore is important for initiation cracking in the static tensile test but also in further mechanical processing. Pores with sharp edges are more prone to cracking. This factor is multiplied with the pore size.

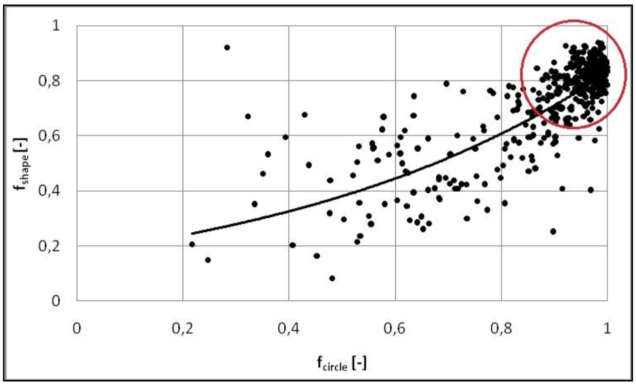


Figure 7. Dependence f_{circle} vs. f_{shape}. In red circle are ideal shape pores

In the Fig. 8 is shown dependence between f_{circle} and D_{circle}. Regarding pore dimension, small pores evolve easily to a circular form, while large pores are very irregular and have a significant internal notch effect on mechanical properties. The average pore size was 15 µm. The pores more than 20 µm are potential initiators of cracks (gray ellipse). These pores are below 0.1%, and therefore it can be said that the pore size, in this case, does not affect on the mechanical properties. The higher amount of large pores causing a risk that it can be created associated pore to complexes.

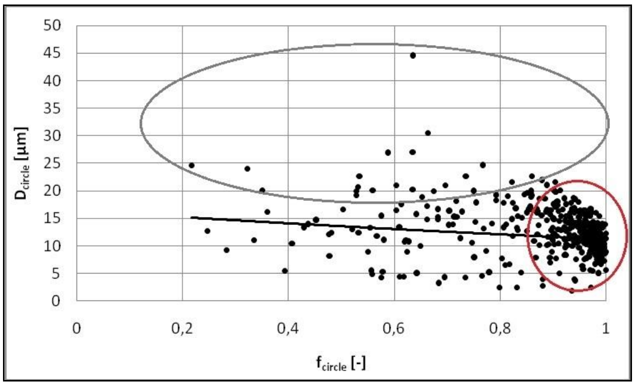


Figure 8. Dependence f_{circle} vs. D_{circle}. In red circle is the average pore size. In gray circle are pores with a higher diameter

The Fig. 9 shows dependence between f_{circle} and aspect. Aspect value is important regarding the technology used. This value is used to evaluate of the smallest and largest pore size which is described by an ellipse. If the ratio is „1" it points out that technology is appropriate in the fact that there will be no merging of pores.

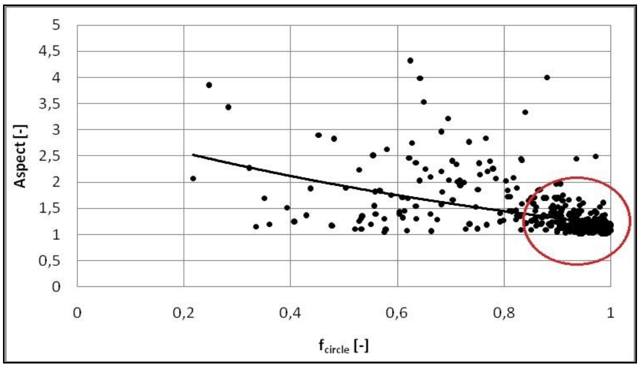


Figure 9. Dependence f_{circle} vs. Aspect. In red circle are pores that are close to the ratio of 1

The Tab. 2 shows the average values D_{circle}, f_{shape}, f_{circle}, Aspect, P_{dig} and P. P_{dig} is a porosity value obtained using by software ImageJ. The p-value is calculated porosity by Archimedes. The difference between these values is small what indicates the accuracy of the measurement.

Ti6Al4V						
	D_{circle} [μm]	f_{shape} [-]	f_{circle} [-]	Asp. [-]	P_{dig} [%]	P [%]
Area 1	12,68	0,87	0,71	1,40	5,3	5,0
Area 2	15,54	0,80	0,76	1,29	5,1	
Area 3	14,78	0,79	0,70	1,40	5,1	

Table 2. Porosity evaluation of the studied material

The results show that LS technology which was used is suitable for the material Ti6Al4V. The total porosity is higher, but the pore distribution is homogenous. This fact has the most significant effect on the mechanical properties what is documented by results from static tensile test. Pore size about 15 μm in conjunction with the pore distribution is ideal and has no significant effect on mechanical properties. In view of the fact that 15 μm is the large amount of porosity for this form of production it will be need the optimization of the setting machine. Greater concentration of pores was on the edge of samples. This technology uses recycled powder. Thus may develop clusters with larger particles of the powder. Evaluation of porosity in different directions <x, y, z> didn't show any deviations.

4 CONCLUSIONS

Based on realized experiments and measurements, achieved results can be summarized as follows:

- The LS technology is suitable for the preparation of products made from Ti6Al4V from the standpoint of porosity evaluation and mechanical properties.
- Up to 94% of pores have an ideal shape.
- Porosity distribution is homogenous, and it does not affect on the mechanical properties.
- The value of the porosity was 5%, and it is relatively high. It can be caused by the powder was recycled.

ACKNOWLEDGEMENTS

Authors are grateful for the support of experimental works by project VEGA 1/0732/16.

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