USAGE OF MINIATURE SPECIMENS TO INVESTIGATE TENSILE PROPERTIES OF 3D-PRINTED Ti-6Al-4V

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Abstract

In the scope of this paper, the usage of the miniature samples and investigating using small samples is discussed. The miniature samples were used for determination of mechanical properties for titanium alloy deposited by additive manufacturing. The tensile tests on the standard and the miniature samples were provided for commonly used Ti-6-Al-4V alloy. These titanium alloy samples were produced by electron beam melting and by selective laser melting method that belongs to powder bed fusion processes of 3D printing. The purpose of this work was to demonstrate that local material characteristic can be obtain using the miniature specimen. The usage of small samples could provide many advantages for testing of mechanical properties. In our investigation it is shown that the results are in good agreement for standard and miniature specimens. The strength characteristics reached identical values. However, the plastic characteristic, such as elongation and reduction of area, are not comparable duo to the presence of internal defects. The small defects, such as lack of fusion or pores, have major impact on the miniature samples in comparison to the negligible influence on the larger specimens. The fractography included in this research reveals the differences for the small and standard size specimens.

Keywords: 3D printing, miniature specimens, titanium alloy, tensile properties

1. INTRODUCTION

Great attention is payed to the rapid production and development of titanium alloy and their usage. Titanium can be assessed to group of future material; higher product fabrication of this material is expected. This metal has many advantages, such as lightweight, high fracture toughness, excellent corrosion resistance and biocompatibility for medical application [1-3]. The latest research showed that the additive manufacturing (AM) belongs to the most promising techniques how to prepare titanium alloys with complex structures and in cost-effective way. The AM provide a product without need of additional work or processes. The product produced by AM is in the final base thanks to usage of the computer-aided-design (CAD) model. Electron beam melting (EBM) and selective laser melting (SLM) techniques are widely used methods of metal 3D printing. EBM and SLM method are described as bed fusion processes. The major difference between EBM and SLM method is the source of energy: a laser or an electron beam. [1,4,5].

In this paper, the titanium alloy Ti6Al4V deposited by both the SLM and the EBM technique is discussed. The mechanical properties (tensile yield strength, ultimate tensile strength) were compared on small and large specimens. The aim of this work is to demonstrate that local material characteristics can be obtained using the miniature specimen. The usage of small samples could provide many advantages for testing of mechanical properties, such as material-, time- and cost-saving. In the future, the miniature samples can be used for inspection of local properties in the building chamber and for continual control of the printing process and to ensure the validity of the building process of AM.

2. MATERIAL AND METHOD

The tensile properties of SLM- and EBM- produced titanium alloy using small and large specimens are discussed here.

2.1. Material

The first half of the specimen was deposited by EBM using the Arcam Q10 machine under helium atmosphere. The pressure of about 4×10^{-3} mbar was used in the chamber. The powder ELI Ti-6Al-4Vgrade 23 was batched in the machine. The chamber pre-heating was set to 1013 K. The second half of the specimen was printed by SLM technology under protective atmosphere of argon using M2 Concept Laser machine. The preheating of the building chamber was not provided. The same powder as for EBM deposition was used in the case of SLM process. After deposition, the specimens were heat-treated under vacuum to minimize residual stressed after the printing process. The specimens were slowly heated to 1093 K and held on that temperature for one and half hour. The cooling to 773 K followed and afterwards to room temperature. The deposited parameters of both processes were summarized in **Table 1**. Using these two techniques the round tensile test specimen was produced in ZXY direction [6]. The round specimen had diameter of six millimetres and follow the standard [6].

Table 1 Summary of AM parameter

Process parameter	Current, Voltage	Scan speed	Layer thickness	Hatch spacing
EBM	15 mA, 60 kV	4530 mm/s	50 µm	200 µm
Process parameter	**Laser power**	**Scan speed**	**Layer thickness**	**Hatch spacing**
SLM	200 W	800 mm/s	30 µm	112 µm

2.2. Tensile testing

The tensile testing was performed on samples with diameter of 6 mm (gauge length of 30 mm) and on miniature tensile test samples M-TT [7-10], the specimen geometry is depicted in **Figure 1**. The miniature samples were cut out from as deposited round specimens. The sampling schema is depicted in **Figure 2**. The tensile tests of standard and M-TT specimens were performed under the quasi-static loading conditions at room temperature. Specially designed testing machine with load capacity of 5 kN and linear drive for testing of mini-specimens was used. Specimens were tested with the strain rate of 0.001 s^{-1} at room temperature. Digital Image Correlation based optical extensometer was used for strain measurement. Tests were following the ASTM E8 standard. The dimensions of the specimen were measured by digital micrometre before the testing, after the fracture by a stereomicroscope. These important values were evaluated: yield stress at 0.2 % deformation (OYS), ultimate stress (UTS), uniform elongation (UE), elongation (El) and reduction of area (CR). The averaged values with corresponding standard deviation

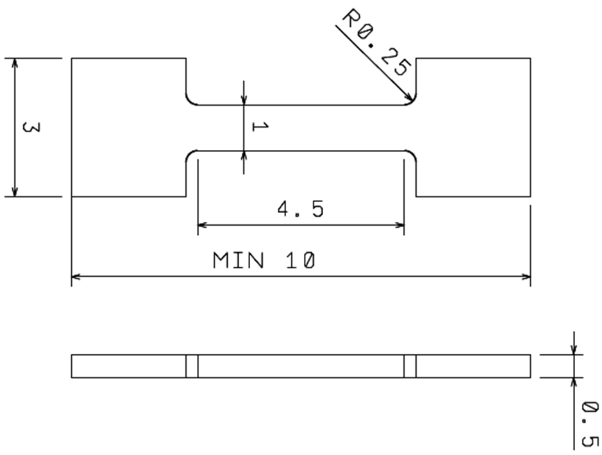

Figure 1 Specimen geometry of M-TT sample

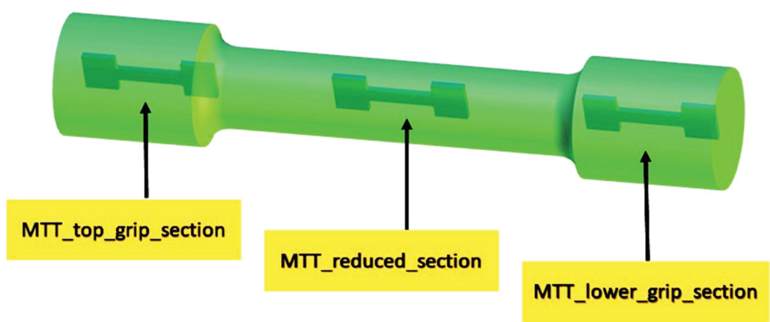

Figure 2 Schematic drawing of sampling

values were calculated from at least three valid measurements per batch.

2.3. Fracture analysis

The analysis of fracture surfaces on broken tensile tests specimens was performed by the scanning electron microscope (SEM) JEOL 6380.

3. RESULTS

The tensile test results, such as the sample type and evaluated values (OYS, UTS, UE, El and CR) are summarized in **Table 2**.

Table 2 Tensile test results

Method	Data set	diameter (mm)	thickness (mm)	Value	OYS (MPa)	UTS (MPa)	UE (%)	El (%)	CR (%)
EBM	MTT_top_grip_section		0.5	Average	1063.2	1155.8	7.5	10.2	17.7
				St. Dev.	18.3	20.3	0.3	0.6	3.5
	MTT_reduced_section		0.5	Average	1034.2	1104.3	4.2	6.0	17.8
				St. Dev.	19.8	35.5	1.8	3.5	13.1
	MTT_lower_grip_section		0.5	Average	1022.0	1103.1	4.6	6.8	21.4
				St. Dev.	25.3	25.2	1.4	2.9	11.2
	round specimen	6.0		Average	1052.9	1093.8	1.3	22.4	7.5
				St.Dev.	2.6	4.7	0.3	0.6	1.5
SLM	MTT_top_grip_section		0.5	Average	999.6	1059.3	6.2	11.2	31.3
				St. Dev.	14.8	5.7	0.7	3.6	5.1
	MTT_reduced_section		0.5	Average	988.0	1038.7	5.1	8.7	23.6
				St. Dev.	10.4	9.9	1.3	4.8	2.6
	MTT_lower_grip_section		0.5	Average	890.2	958.3	1.7	2.8	18.3
				St. Dev.	8.7	11.5	0.3	0.7	1.7
	round specimen	6.0		Average	976.3	1025.0	3.8	4.5	9.7
				St.Dev.	12.0	3.8	0.3	1.6	0.5

The fractures of EBM- and SLM- printed specimens are depicted in **Figure 3**. The comparison of standard and the M-TT specimen fracture area can be observed in **Figure 4** for EBM-produced specimen or in **Figure 5** for SLM-produced specimens. The detail image of fracture areas of EBM-produced samples is presented in **Figure 6**.

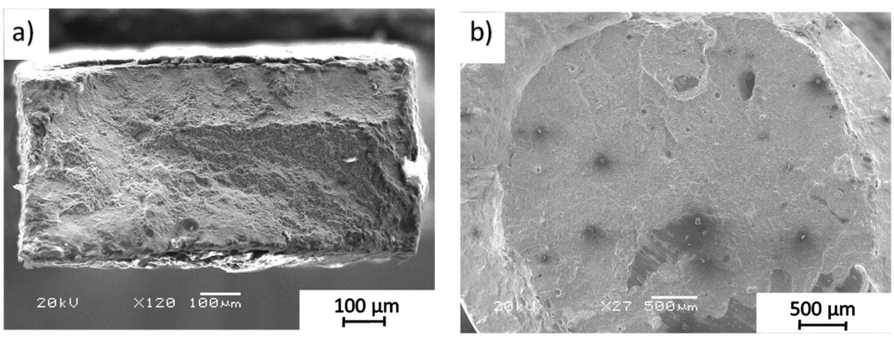

Figure 3 Fracture surface of a) M-TT from reduced section and b) round specimen produced by EBM

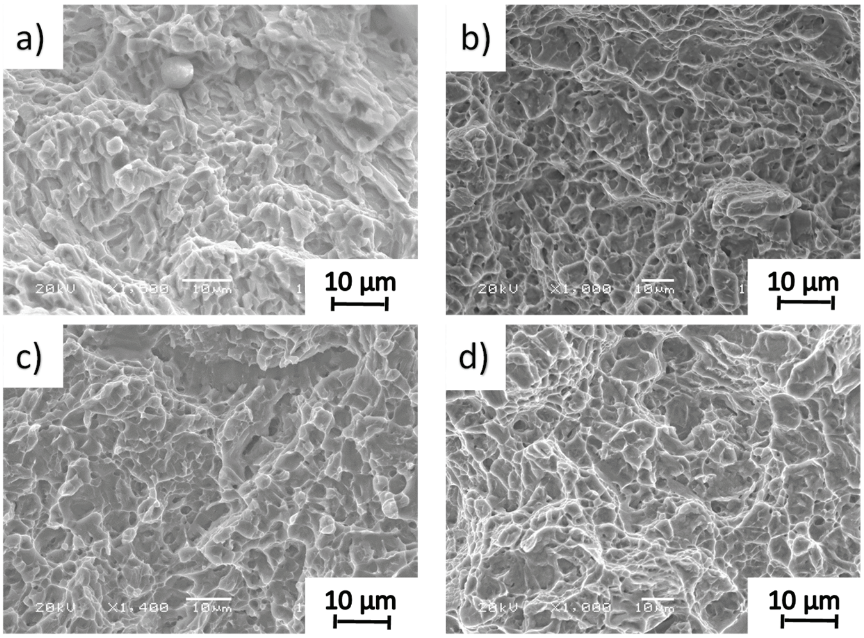

Figure 4 Fractures of a) M-TT specimen produced by EBM, b) M-TT specimen produced by SLM, c) EBM round specimen, d) SLM round specimen

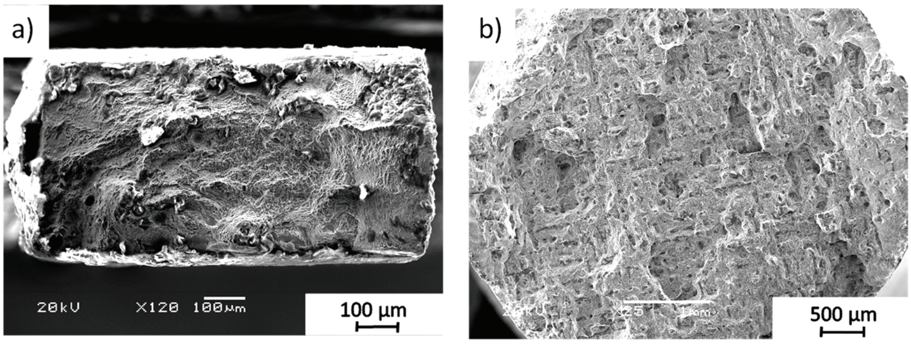

Figure 5 Fracture surface of a) M-TT from lower grip section and b) round specimen produced by SLM

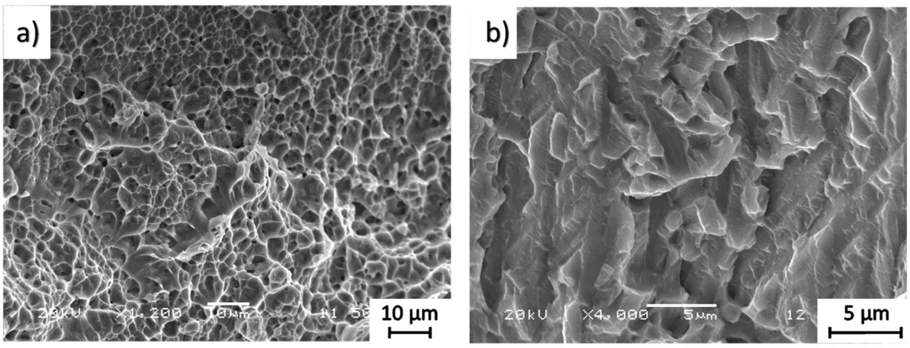

Figure 6 Detail fracture area of specimen deposited by EBM a) round specimen and b) M-TT specimen

4. DISCUSSION

The production of the M-TT specimens from various locations had been chosen thanks to dissimilarities in difference samples height. This can be related to the fact that the round samples were built in ZXY direction. In the case of EBM specimens, very similar values of strength characteristics were obtained. More precisely the yield strength reaches around 1030 - 1060 MPa and the ultimate strength was around 1100 - 1150 MPa for both type of testing specimens, see **Table 2**. However, significant difference is observed in elongation results of EBM. In **Figure 6** is depicted fractures of EBM specimens and it is possible to see a mixture of ductile and brittle fracture on the M-TT specimens. This fact may explain the lower value of elongation for M-TT specimens. In the case of SLM samples, negligible difference in results of strength parameter (OYS reaches round 980 - 1000 MPa and UTS reaches around 1030 - 1060 MPa) and substantial difference in elongation was observed, summary in **Table 7**. Nevertheless, the SLM specimen from lower grip section had also lower values of OYS and UTS that the others. These samples contained added amount of defects. The reason may come from in the SLM techniques itself. The SLM-printed samples had limited heating flow possibilities of the powder bed. In the future, it is necessary to carry out the investigation with more specimens to estimate the results. Generally, great amount of defects was discovered on the surface fracture of both AM techniques, see **Figure 5**. Mostly lack of fusion was present. All of the fractures can be assessed as ductile trans-crystal fractures, see **Figure 3**. Faster heat flow rate can lead to formation of lack of fusion defect on the surface of larger specimens. The large quantity of lack of fusion affect mainly the surface of smaller specimens and that is the reason why values of elongation are lower.

5. CONCLUSION

The comparison of the M-TT and the round specimens suggests a good reliability of using M-TT specimen for investigation of strength characteristics of the material using AM techniques. However, the plastic characteristic, such as elongation and reduction of area, are not comparable duo the presence of defects in AM prepared samples. The small defects, such as lack of fusion or pores, have major impact on the miniature samples in comparison to the negligible influence on the standard specimens with larger area. This observation was similar for both investigated AM processes. In summary, the M-TT specimens could provide inspection of local properties for EBM and SLM methods with respecting all of the aspects that specimen miniaturization brings.

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