Mechanical properties comparison of Ti6Al4V produced by different technologies under static load conditions

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Abstract. The most commonly used technology among the additive manufacturing is Direct Metal Laser Sintering (DMLS). This process is based on selective laser sintering (SLS). The method gained its popularity due to the possibility of producing metal parts of any geometry, which would be difficult or impossible to obtain by the use of conventional manufacturing techniques. Materials used in the elements manufacturing process are: titanium alloys (e.g. Ti6Al4V), aluminium alloy AlSi10Mg, etc. Elements printed from Ti6Al4V titanium alloy find their application in many industries. Details produced by additive technology are often used in medicine as skeletal, and dental implants. Another example of the DMLS elements use is the aerospace industry. In this area, the additive manufacturing technology produces, i.a. parts of turbines. In addition to the aerospace and medical industries, DMLS technology is also used in motorsport for exhaust pipes or the gearbox parts. The research objects are samples for static tests. These samples were made of Ti6Al4V alloy by the DMLS method and the rolling method from a drawn rod. The aim of the paper is the mechanical properties comparative analysis of the Ti6Al4V alloy produced by the DMLS method under static loading conditions and microstructure analysis of this material.

1 Introduction

Metal elements manufactured abusing additive technologies are nowadays increasingly used. There are many additive manufacturing methods (i.e. SLS, SLM, LMD, EBM), which apply the metal powders to form construction elements, that are developed by different companies. However, all these solutions common goal is the possibility to obtain parts of complex geometry, which would be difficult or impossible to obtain by means of classic manufacturing techniques (e.g. machining, casting) [4]. In each additive technology, the component manufacturing process precedes the creation of a three-dimensional computer model. This allows to make rapid changes and better matching of the element without the need to produce a detail, translating into costs and time savings [10]. For this reason, metal parts manufactured by additive methods are used in medicine, aerospace and motorsports.

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One of the most popular and the most used metals for three-dimensional printing is Ti6Al4V titanium alloy. This material is characterized by high mechanical properties, resistance to corrosion and high temperatures [5]. Due to the biocompatibility with the human body, this material is often used to produce implants applied in medicine. Titanium elements are able to replace bone defects in the human skeleton. Implants made of titanium alloy take over loads and relieve damaged bones. For this reason, it is important that the material used for that type of element has a higher stiffness and a higher Young's modulus as compared to the bone [1]. The implant grafted in the human body is required to carry and withstand loads for the patient lifetime [9]. The character of loads during the implant operation is variable. For this reason, it is reasonable to try to predict the fatigue life of components produced in the three-dimensional printing process [7]. Creating a 3D computer model of the structural element enable making rapid changes before production, which allow for savings in time and costs, make additive technologies more popular in machine construction. Their special advantage is the ability to manufacture parts of any geometry, which would be impossible or very difficult to obtain using classical manufacturing techniques. In addition to medical applications, additive technologies are also widely used in motorsports. The examples of printed elements, which are applied in industry include exhaust pipes, gearbox elements made of Ti6Al4V titanium alloy. Prevalent printing technologies in the area of motorsports are methods: SLA (among liquid materials) and SLS (for the production of metal components). In the aerospace industry, additive technology is increasingly being made of titanium elements [6]. Titanium is used for hull stiffening, chassis or turbines. The Ti6Al4V alloy is a frequently chosen material due to: lower weight compared to structural steels, resistance to temperatures occurring in flight, resistance to corrosion, as well as the possibility of joining titanium with composite materials.

The aim of the paper is a comparative analysis of the Ti6Al4V alloy mechanical properties under static loading conditions produced by the DMLS method and microstructure analysis of this material.

The scope of work includes test results presentation of Ti6Al4V material samples made using the DMLS method as well as those made of a rod drawn under static loading conditions and the assessment of the alloy microstructure.

2 Conditions and test results

In order to determine the mechanical properties of the Ti6Al4V material produced in the rolling process from a drawn bar and using the DMLS additive technology, a static tensile test was carried out in accordance with the recommendations of PN-EN ISO 6892-1: 2016 standard. The tests were carried out using an extensometer. The control parameter during the tests was the displacement of the machine piston of 0.05 mm / s.

2.1 Research stand

The tests were carried out on the test stand shown in Figure 1. The stand for strength tests was the INSTRON 8502 hydraulic testing machine.

Fig. 1. Test stand for static tests - Instron 8502.

2.2 Research material

The test object in the conditions of static and variable loads were samples made according to PN-74 / H-043227 standard with geometrical dimensions shown in figure 2. Samples for testing were made of Ti6Al4V material by two methods. The first of them was pulled from a drawn rod. The second series of samples was made using additive technology.

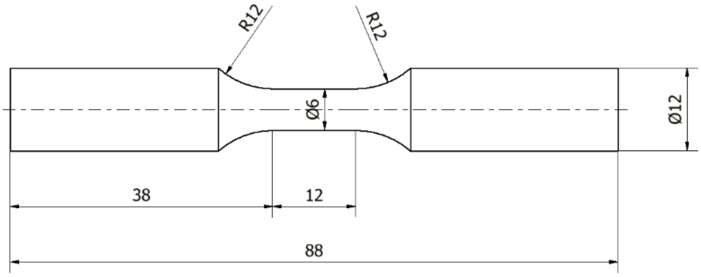

Fig. 2. Geometric features of the test specimen under static load conditions according to PN-74 / H-043227.

The first series of test sample was made of Ti6Al4V rod in a turning process with a diameter of 12 mm. The physical form of the sample is shown in Figure 3.

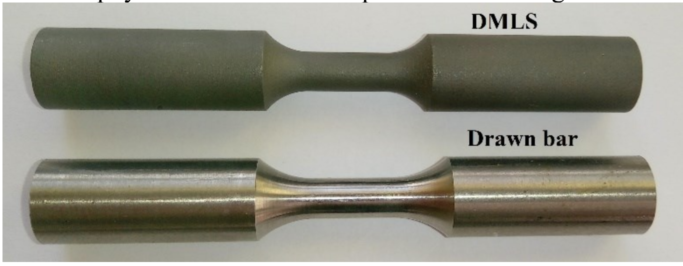

Fig. 3. Sample form for static tests made from a DMLS technology and a drawn rod.

Table 1 presents the mechanical properties of the material according to PN-EN 4267 standard.

Table 1. Mechanical properties of TI6Al4V produced according to PN-EN 4267 standard.

Mechanical properties of Ti6Al4V alloy		
S_u	MPa	1013
$S_{y0.2}$	MPa	927
A	%	19.5
Z	%	52

The second series of samples was made using the DMLS method from the Ti6Al4V alloy. The physical form of the test object is shown in Figure 3.

The properties of the printing powder are given in the manufacturer's data sheet. They are included in table 2. The elements were made on an EOS M280 printer with the print parameters presented in table 3.

Table 2. Mechanical properties of TI6Al4V powder according to EOS.

Mechanical properties of Ti6Al4V alloy		
S_u	MPa	1150
$S_{y0.2}$	MPa	1030
E	MPa	110000
A	%	11

Table 3. Printing parameters of Ti6Al4V samples.

Printing parameters of the sample production using the additive method				
1	2	3	4	5
Building direction	Work platform dimension	Laser power	Scanning speed	Minimal layer thickness
Z - direction	250x250x325 mm	200 W	to 7 m/s	30 µm

2.3 Research results

The results of experimental tests are presented in tabular form for two types of samples and summarized in table 4.

Table 4. Average values of static strength parameters under tensile loads.

Material production method	Static parameters of Ti6Al4V material				
	$S_{y0.2}$	S_u	E	A	Z
	MPa	MPa	MPa	%	%
1	2	3	4	5	6
Additive technology DMLS	1052	1127	114510	15.5	17.3
Drawn rod	947	1010	113060	29.7	38.1

3 Test results analysis

3.1 Comparison of own research results with the results of other authors

Table 5 presents an exemplary comparison, based on the literature data, of the test results obtained under static loading conditions. The experimental results and the results published in the publications show that the Ti6Al4V material produced with the DMLS additive technology is characterized by higher value of the strength S_u and the yield point $S_{y0.2}$ than the material produced by the traditional (metallurgical) method.

Table 5. Mechanical properties of Ti6Al4V alloy produced by additive technologies.

Author	Ti6Al4V alloy properties under static load conditions			
	S_u	$S_{y0.2}$	E	A
	MPa	MPa	MPa	%
1	2	3	4	5
Benedetti [1]	1092	1022	112700	16.5
Benedetti [2,3]	1090	1015	113000	10
Edwards [4]	1035	910	-	3.3
Konečná [5]	1195	952	-	7.4
Kumar [6]	1237	1161	-	7.6
Kumar [6]	1222	1151	-	9.8
Quintana [7]	1360	1225	-	3.1
Rafi [8]	1219	1143	-	4.9
Zhang [10]	1262	1084	-	6.1

3.2 Determining the work needed to create a damage

On the basis of the results obtained, the work required to create damage in a static tensile test was determined. To determine the work, strength and displacement parameters are needed. The work determined is the area below the line representing the stretching plot for the Ti6Al4V alloy (Figure 4). Table 6 presents the results of the work needed to create damage for samples made with DMLS technology and turned samples.

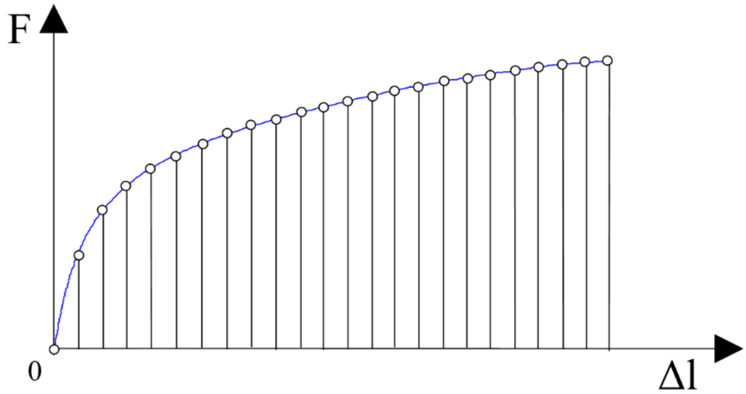

Fig. 4. Scheme of defining surface areas to determine the work needed to create damage.

Table 5. Mechanical properties of Ti6Al4V alloy produced by additive technologies

Work parameter needed for the damage		
1	2	3
DMLS technology	kJ	63.1
Drawn bar	kJ	15362.8

3.3 The sample damage method analysis during a tensile test

Performing the assessment samples breakthroughs of after damage, it is noticed that in the sample made of a drawn rod in the measuring part at the crack site, a visible narrowing is occurred. On the sample made with DMLS technology this narrowing is not visible.

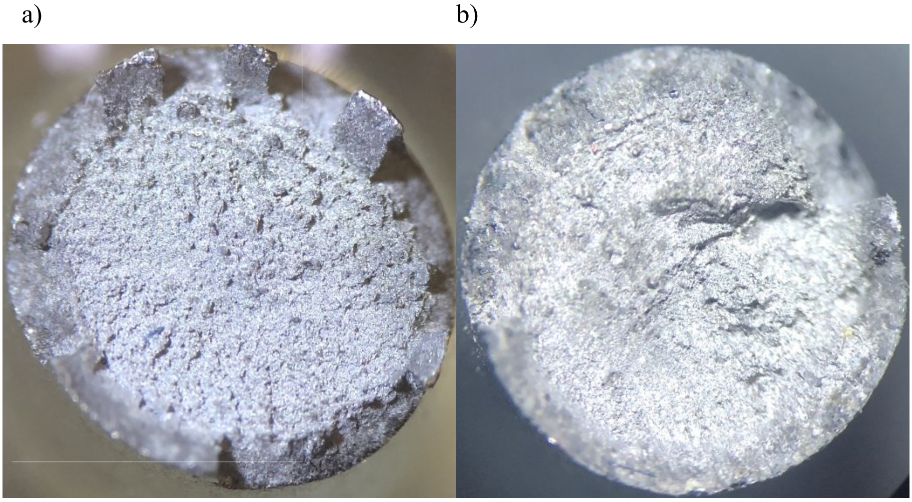

Fig. 5. Microscopic photos of samples breakthroughs after damage performed: a) DMLS, b) from the drawn rod.

Figure 6 shows the samples damage method as a result of a static tensile test. In the case of a printed sample, the form of the damage corresponds to the cracking between the layers of material created by 3D printing. After damage to the outer the cross-section part, further damage to the sample occurred along the sintered layers (Fig. 6a). Damage to a turned sample made of a drawn rod is elastic-plastic.

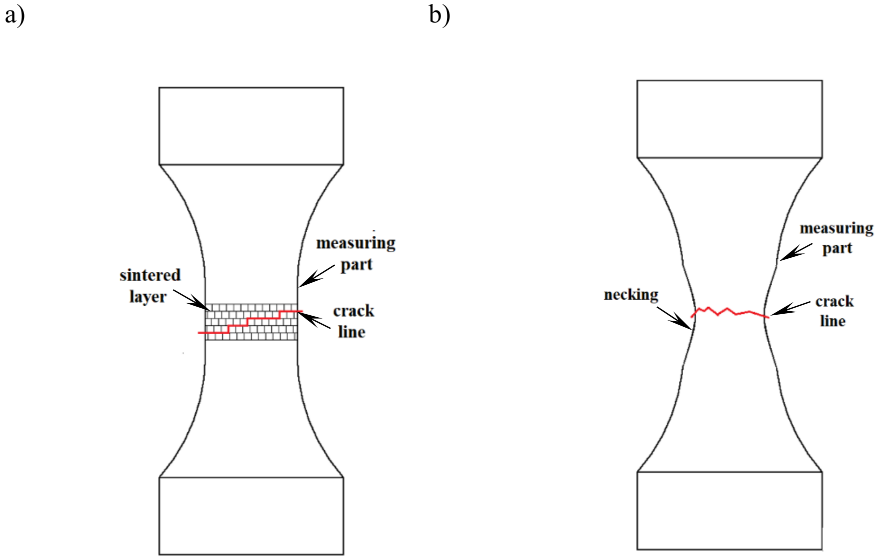

Fig. 6. Method of sample damage during a tensile test: a) for a sample made with DMLS technology, b) for a sample made of a drawn rod

4 Conclusion

The experimental and literature data show that the Ti6Al4V material produced with the DMLS additive technology is characterized by a higher value of the S_u strength and the yield stress $S_{y0.2}$ than the material produced by the traditional (metallurgical) method. Differences between the strength values S_u, the yield point $S_{y0.2}$, elongation A and Young's modulus E obtained as a result of the author's research and the literature data result from the printing parameters and its various technologies, material porosity and grain size. The obtained test results under static loading conditions of the Ti6Al4V alloy produced DMLS additive technology and drawn rod allow to conclude that the elongation of the test sample made DMLS technology is lower than the value for the material delivered in the form of a drawn rod. However, the narrowing of the test specimen made DMLS technology is lower than the value for the material delivered in the form of a drawn rod.

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