Original Article

Strength analysis of Ti6Al4V titanium alloy produced by the use of additive manufacturing method under static load conditions

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ABSTRACT

The technology of 3D printing from metal powder is gaining popularity due to the possibility of producing structural elements of any geometry, which making by the use of the methods applied so far is difficult or impossible. One of the most commonly used additive manufacturing methods is Direct Metal Laser Sintering (DMLS). The most commonly used material in DMLS technology is titanium alloy Ti6Al4V. Ti6Al4V titanium alloy belongs to α+β two-phase alloys and is applied in many industrial areas, among others in the field of medicine (dental implants), aerospace (production of selected engine components), etc. The aim of the paper is to present the mechanical properties tests results of titanium alloy Ti6Al4V carried out on the samples: manufactured by the use of additive manufacturing method DMLS and made of drawn bar by turning process. The scope includes conducting tests related to determining the mechanical properties of the alloy, determining hardness and presenting the macrostructure before and after the samples failure.

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1. Introduction

In recent years construction elements made of metal powders by the means of additive manufacturing technologies are commonly used in medicine area (i.e. dental implants injection), aerospace (selected engine components production), tool industry (production of forming inserts in molds for processing polymer materials) or motorsport (selected vehicle components production). The main advantage of these technologies is possibility to produced structural elements of complex geometry, which manufacturing by the use of conventional methods would be difficult or impossible to obtain. The producing cost of individual structural element with a complicated structure using additive method is lower compared to standard manufacturing process [1].

In the field of medicine, structural components (implants) are most commonly/frequently made of titanium alloy. This material owes its application in medicine area due to high mechanical properties, low density, excellent corrosion resistance and biocompatibility with human tissue [2,3]. For this reason, it is important to predict the fatigue life of compo-
nents that will be subjected to variable loads in the human body [4].

Ti6Al4V titanium alloy belongs to \( \alpha + \beta \) two-phase/dual-phase alloys. The occurrence of such a material structure is the result of the appropriate amount of alloying elements contained in the alloy that stabilize the \( \beta \) phase. The indicated alloy is subjected to the following heat treatment methods:

a) stress relief annealing,
b) recrystallization annealing,
c) isothermal annealing,
d) supersaturation and aging processes.

The wide application of the Ti6Al4V titanium alloy in medicine, and especially in personalized medicine, is connected with the use of additive manufacturing methods for the production of structural elements (implants) [3]. The element made of metal powder by the additive method requires heat treatment, which task is to modify the microstructure of the material and reduce residual stress. Orientation of grains depends on the heat transfer phenomenon during the printing process. The main microstructural features (i.e. the phase state of the alloy, grain size, porosity) have a significant impact on mechanical properties [5,6].

Metallographic analyzes carried out after heat treatment show slight differences compared to the original Ti6Al4V microstructure. As-build elements show a martenritic microstructure and are characterized by a higher yield point, tensile strength from heat-treated elements, but the elongation is lower [7]. By the use of heat treatment, e.g. aging, a material with increased mechanical parameters can be obtained [6]. One of the most frequently carried out heat treatment processes on elements made by additive manufacturing technology is hot isostatic pressing (HIP). Structural elements made with AM technologies and later processed with HIP show very different microstructures. This difference is not so high in the hardness test, but it has a significant impact on the mechanical properties. Martensitic microstructure allows as build samples to achieve higher strength and yield point values. While the higher ductility of the \( \alpha + \beta \) microstructure helps the sample after HIP treatment to obtain higher elongation. High tensile strength is given to metastable \( \alpha \)-martensite by a shorter effective slip length compared to the \( \alpha + \beta \) microstructure [8]. Higher elongation as well as lower yield point and tensile strength of HIP-treated elements result from the more plastic \( \beta \) phase and more number of independent slip planes compared to the \( \alpha \) phase [9].

In addition to the material's microstructure, roughness and surface defects also affect the material mechanical properties [10]. Hot isostatic pressing (HIP) reduces porosity and most preferably affects the mechanical properties and fatigue life of elements manufactured by additive manufacturing methods [11]. In the as-built condition, the largest porosity (about 0.35%) and the largest defects are in the outermost layer 0.4 mm thick and are the site of crack initiation. HIP provides effective reduction of porosity in the whole element (below 0.05%). Beyond the heat treatment, machining is also used to reduce surface roughness, as it affects the mechanical and fatigue strength of structural elements [12].

In the paper [13] the authors have noticed that the sintering parameters change of titanium produced by the additive manufacturing method does not allow to obtain appropriate standards in terms of strength values, and this creates high porosity and microstructure defects caused by insufficient energy density. It turns out that as the laser power increases, the tensile strength value and yield strength for the Ti6Al4V titanium alloy escalates. Further, increasing the speed of the laser during printing process reduces the tensile strength and yield point.

The tensile strength and fatigue life of construction materials manufactured by SLM or SLS technology are comparable with their counterparts made in a conventional way [14]. Ti6Al4V produced by additive manufacturing methods frequently shows higher strength values and yield point than its standard alloy [15]. However, its elongation is lower. Excellent mechanical properties in terms of tensile strength and plasticity for parts manufactured by laser sintering are attributed to almost full density [16].

The purpose of the work is to present the mechanical properties test results of the titanium alloy Ti6Al4V carried out on samples: manufactured by the additive manufacturing method DMLS and made of a drawn bar by turning technology.

The Ti6Al4V titanium alloy is marked differently depending on the standard. The European standard ISO 5832 defines the marking of titanium alloy with the Ti6Al4V. The German standard DIN 17851 means the same alloy as TiAl6V4, while the French standard BS 7252-3 defines it as TA6V4. In the American standard ASTM B 265, titanium alloy is described as R56400.

The scope of work includes conducting tests related to the determination of mechanical properties (\( S_{y0.2}, S_u, A, Z, E \)), microhardness and presenting the macrostructure before and after failure.

2. Experimental studies

2.1. Research sample

The test samples were made of Ti6Al4V titanium alloy according to ISO 5832 standard. The chemical composition of the alloy is presented in the Table 1.

The geometrical dimensions of the samples were assumed according to PN-74 / H-043227 standard and are presented in Fig. 1.

The test samples were made by two methods. The first group of samples was samples made of an annealed drawn bar with a diameter of 12 mm in the turning process. The phys-
Table 1 – Chemical composition of the Ti6Al4V titanium alloy according to ISO 5832.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>O</th>
<th>N</th>
<th>C</th>
<th>H</th>
<th>Ti</th>
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<tr>
<td></td>
<td>5.5–6.75</td>
<td>3.5–4.5</td>
<td>≤0.3</td>
<td>≤0.2</td>
<td>≤0.05</td>
<td>≤0.08</td>
<td>≤0.01</td>
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</tbody>
</table>

Fig. 2 – Physical form of research samples: (a) turned from a drawn bar, (b) manufactured by the additive method DMLS.

Fig. 3 – The production method of the test sample by the additive DMLS.

The physical form of the sample is shown in Fig. 2a. The second group of samples were made by the additive method DMLS (Fig. 2b) using the EOS M280W machine with the dimensions of the working platform 250 mm × 250 mm × 325 mm. The printing process was characterized by the following parameters: laser power 200 W, minimum layer thickness 30 µm, scanning speed up to 7 m/s. The sample print direction was consistent with the Z axis (Fig. 3). The laser beam path sintering the powder is shown in Fig. 4. Each layer of the element was created in the same way. After the DMLS sample was build, it was annealed.

A round sample in which the load distribution is evenly distributed during the tensile test was adopted. One of the factors affecting the load even distribution is the repeatable mounting method on the testing machine’s handles, which ensures that the symmetry axis of the sample coincides with the axis of the machine’s handles symmetry.

Due to the aim of the paper, the elements made with the additive DMLS method and samples made of a round drawn bar in the turning process were compared. The application of samples with a round cross-section is to ensure uniform load of the cross-section, which allows to assume that the structural changes in the material in the x–z plane and in the y–z plane will be the same. This allows to carried out structural research only for one of the above planes.

The samples used for the tests, made using the additive DMLS method and made of drawn bar, differ in surface roughness. The difference in roughness values is influenced by the method used to manufacture the element. In the article it was decided to compile the results of testing these samples, because DMLS technology aims to produce a structural element that is not possible to obtain by other methods and is not subject to further processing. Comparison of two samples with different roughness can be considered appropriate due to the fact that in paper [17] a slight influence of surface roughness on the change of structural elements strength was found.
2.2. Tests under static tensile loads

2.2.1. Research stand
The experimental tests included carrying out a static tensile test in accordance to PN-EN ISO 6892-1:2016 standard, consisting in axial stretching of the sample at a constant speed until its breaking. Destructive tests were carried out on the stand shown in Fig. 5, which was the INSTRON 8502 strength testing machine. The piston displacement speed was 0.05 mm/s. During the test, the value of the force which the sample was tensile and its elongation were measured using an extensometer.

2.2.2. Test results
By the means of tests under static load conditions, Ti6Al4V titanium alloy stress-strain diagrams were determined, on the basis of which the following parameters values were obtained: material strength $S_u$, yield point $S_{y0.2}$, longitudinal modulus of elasticity (Young's modulus) $E$, elongation $A$, narrowing $Z$. An example of stress-strain graphs for printed and turned sam-

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**Fig. 4** – The applying scheme one layer of the sample by the DMLS method.

**Fig. 5** – Test stand: (a) view of the Instron 8502 testing machine, (b) view of the mounted test sample in the machine holders with an extensometer mounted.

**Fig. 6** – An example of the stress-strain graph $S=f(\varepsilon)$ for: (a) printed samples using the DMLS method (specimen DMLS), (b) turned samples (specimen DB).
samples are shown in Fig. 6. Table 2 summarizes the average value of selected strength parameters.

The tests were carried out under tensile load conditions show that the samples produced by the DMLS additive technology are characterized by higher tensile strength $S_u$ and yield point $S_{0.2}$ compared to turned samples. Similar values of Young’s modulus $E$ were obtained for both sample production technologies. The average value analysis of the elongation $A$ for the technologies used indicates a double difference.

Fig. 7 shows the measuring parts of test samples after fracture. Based on them, it was found that a sample made using the conventional method at the crack site has a visible narrowing, while a sample made using the DMLS technology is characterized by its lack.

In the case of a printed sample, the form of damage corresponds to the cracking between successive layers of sintered material created during the printing process. Damage of a turned sample made of a drawn rod is elastic-plastic.

### Table 2 – Selected strength parameters of the Ti6Al4V titanium alloy under static tensile loads.

<table>
<thead>
<tr>
<th>Sample technology</th>
<th>$S_{0.2}$ MPa</th>
<th>$S_u$ MPa</th>
<th>$E$ MPa</th>
<th>$A$ %</th>
<th>$Z$ %</th>
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<td>1127</td>
<td>114510</td>
<td>15.5</td>
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<tr>
<td>Turning technology</td>
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<td>1010</td>
<td>113060</td>
<td>29.7</td>
<td>38.1</td>
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### 2.3. Hardness tests

#### 2.3.1. Research stand

In the microhardness tests of the titanium alloy Ti6Al4V, the Vickers method was used. It involves squeezing a diamond pyramid with a square base and an angle of 136 ° between opposing walls into the metal. The hardness parameter is the ratio of the load to the surface side of the permanent imprint.

The hardness measurement was carried out in accordance with the PN-EN ISO 6507-1:2018-05 standard: Metals. Hardness measurement using the Vickers method. Part 1: Test method. The test stand was equipped with a Vickers HV-10 hardness tester by HUATEC (Fig. 8).

During the research, an indenter in the form of a four-sided regular diamond pyramid with a point angle of 136 ° was used. The measuring load was 49.03 N, which allowed to determine the hardness on the HV5 scale.

Hardness, especially microhardness is used in the study of plastic deformation defects, properties anisotropy, phenomena near grain boundaries, and studies of the various factors influence and processes on the materials properties.

#### 2.3.2. Test sample

Samples for hardness tests were prepared on the basis of damaged (broken) samples during the previously performed tensile test. Test samples were made in two different technological processes:

a) turning samples from a drawn bar with a diameter of 612 mm;
b) sample cut out along the $z$ axis covering the grip part and the measuring part (Fig. 9a),
c) sample cut from the gripping section transversely to the $z$ axis (Fig. 9b),
d) metal powder selective laser sintering by DLMS technology before tensile tests:
e) sample cut out along the $z$ axis covering the grip part and the measuring part (Fig. 9c),
f) sample cut from the gripping section transversely to the $z$ axis (Fig. 9d).
g) metal powder selective laser sintering by DLMS technology after tensile tests:
2.3.3. Hardness test results

Hardness measurements were carried out on the prepared samples according to the scheme in Fig. 8. The results obtained:

a) from a drawn bar with a diameter of ∅12 mm are shown in Table 3,
b) produced by selective laser sintering of metal powder by DMLS method before static tests are presented in Table 4,
c) produced by the selective laser sintering of metal powder by DMLS method after tests performed under static load conditions are shown in Table 5.

h) sample cut out along the z-axis covering the grip part and the measuring part (Fig. 9e),
i) sample cut from the gripping section transversely to the z axis (Fig. 9f).

In Tables 3–5 columns 2, 4 and 6 give the designation of the measuring points (Fig. 10). In Table 3 columns 3, 5 and 7 give hardness results for turned samples from a drawn bar. In Table 4 columns 3, 5 and 7 for samples produced by selective laser sintering of metal powder using the DMLS method before static tests. Columns 3, 5 and 7 of Table 5 show the results for the samples produced by selective laser sintering of the metal powder by DMLS method after the tensile tests.
Table 3 – Vickers hardness measurement method of the turning drawn bar samples.

<table>
<thead>
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Table 4 – Vickers hardness measurement method of the samples produced using the DMLS method before static tests (designation: Specimen DMLS-1).

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Table 5 – Vickers hardness measurement method of the samples produced using the DMLS method after static tests (designation: Specimen DMLS-2).

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2.4. Studies on the microstructure of titanium alloy

2.4.1. Samples and test stand
The purpose of the Ti6Al4V titanium alloy macro- and microstructure studies was to assess the effect of tensile load on changing its structure. Samples for material macro- and microstructure tests (metallographic section) were taken from samples after tests of material strength under static load conditions.

Taken samples of the material were included in the resin. Then, grinding and polishing operations were carried out. Grinding was
carried out using abrasive papers with a gradation: 240, 400, 600, 800, 1000. During initial polishing, a suspension with a grain size of 10 μm was used, and a final one, 2 μm. Then the samples were digested with a solution with the chemical composition: 96 ml H₂O + 2 ml HNO₃ + 2 ml HF.

The test stand was equipped with a Carl Zeiss Jena optical model Eptyp 2 (Fig. 11).

2.4.2. Macro and microscopic results
The drawings present metallographic specifying the macrostructure:

- samples made of drawn bar cut out along the Z axis (Fig. 12a),
- samples made of drawn bar cut out from the grip part (Fig. 13a),
- samples made using the additive DMLS method before tensile tests (Specimen DMLS-1) cut out along the Z axis (Fig. 14a),
- samples made using the additive DMLS method before tensile tests (Specimen DMLS-1) cut from the shank (Fig. 15a),
- samples made using the additive DMLS method after tensile tests (Specimen DMLS-2) cut out along the Z axis (Fig. 16a),
- samples made using the additive DMLS method after tensile tests (Specimen DMLS-2) cut from the shank (Fig. 17a).

In the case of samples made of drawn bar (Figs. 12a and 13a), photos of the macrostructure show no significant changes resulting from the tensile load. The macrostructure of the sample made by the DMLS method before loading (Specimen DMLS-1) is repeatable over the entire tested surface (Figs. 14a and 15a). The macroscopic images of the sample made using the additive manufacturing DMLS method after the tensile load, two areas are visible that differ in the shape and direction of the material grains. This is due to the distribution of tensile load force lines during static tensile tests. In Figures: 12a, 13a, 14a, 15a, 16a and 17a are indicative points for taking pictures of material microstructures. Microstructure of samples made of drawn rod:

- along the Z axis are shown in the Fig. 12b, 12c, 12d,
- along the X axis are shown in the Fig. 13b, 13c.

The microstructure of samples made using the DMLS additive manufacturing method before tensile tests (Specimen DMLS-1):

- along the Z axis are shown in Fig. 14b, 14c, 14d,
- along the X axis are shown in the Fig. 15b, 15c.

The microstructure of samples made using the DMLS additive manufacturing method after tensile tests (Specimen DMLS-2):
Fig. 12 – Micro and macrostructure of a Ti6Al4V sample made of a drawn bar taken along the Z axis after static tests: (a) macrostructure of the sample fragment, (b) microstructure at point Cz, (c) microstructure at point Bz, (d) microstructure at point Az.

Fig. 13 – Micro and macrostructure of a Ti6Al4V sample made of a drawn bar taken from the gripping part after static tests: (a) macrostructure of the sample fragment, (b) microstructure at point Dz, (c) microstructure at point Ez.
Fig. 14 – Micro and macrostructure of a Ti6Al4V sample made using DMLS additive manufacturing method taken along the Z axis before static tests (Specimen DMLS-1): (a) macrostructure of the sample fragment, (b) microstructure at point Cz_3D-1, (c) microstructure at point Bz_3D-1, (d) microstructure at point Az_3D-1.

Fig. 15 – Micro and macrostructure of a Ti6Al4V sample made using DMLS additive manufacturing method taken from the gripping part before static tests (Specimen DMLS-1): (a) macrostructure of the sample fragment, (b) microstructure at point Dx_3D-1, (c) microstructure at point Ex_3D-1.
Fig. 16 – Micro and macrostructure of a Ti6Al4V sample made using DMLS additive manufacturing method taken along the Z axis after static tests (Specimen DMLS-2): (a) macrostructure of the sample fragment, (b) microstructure at point C_{x,3D}, (c) microstructure at point B_{x,3D}, (d) microstructure at point A_{x,3D}.

Fig. 17 – Micro and macrostructure of a Ti6Al4V sample made using DMLS additive manufacturing method taken from the gripping part after static tests (Specimen DMLS-2): (a) macrostructure of the sample fragment, (b) microstructure at point D_{x,3D}, (c) microstructure at point E_{x,3D}.
Fig. 18 – Cracking schematic presentation of samples produced using the DMLS additive manufacturing method: F - tensile force, g - thickness of the material layer produced by the additive manufacturing method, L - elementary material layer, P - adopted contact surface of the adjacent layers, C - hypothetical cracking process of sample subjected to axial tension, D - sample fracture along the contact surface of adjacent layers, R₁, R₂ - random crack initiation and its development along the contact surfaces of the layers.

- along the Z axis are shown in Fig. 16b, 16c, 16d,
- along the X axis are shown in the Fig. 17b, 17c.

3. Discussion of research results

3.1. Analysis of test results under static load conditions

The tests samples made of drawn bar (DB samples) and samples made using the DMLS additive manufacturing method (DMLS samples) under static load conditions allowed to determine strength parameters.

The received value of yield point 𝑆₀.2 and material strength 𝑆₃ for DMLS samples is about 11% higher than the results for DB samples.

The Young’s modulus E values for DB and DMLS samples are similar. The values of Young’s modulus E indicate that the sample production technology from titanium alloy Ti6Al4V does not affect its value. This type of property can be used to perform numerical calculations using the finite element method. Calculations of structural elements produced by the DMLS additive manufacturing method can be carried out using the properties of a titanium alloy manufactured by the traditional method.

The elongation A of DMLS samples is approximately 48% lower than the results for DB samples. The damage character of DB samples is typical for elasto-plastic materials demonstrating narrowing, while DMLS samples after tensile testing have no visible narrowing. The cracking method is parallel to the sample layers surface and with the decreasing cross-sectional area of the sample, the crack develops along one of the layers. The scheme of damage method for DMLS sample is presented in Fig. 18.

3.2. Analysis of hardness test results

The carried out hardness tests showed differences between the results obtained for the sample made from annealed drawn bar (Specimen DB) and the samples made using the DMLS additive manufacturing method: before (Specimen DMLS-1) and after (Specimen

Fig. 19 – Material hardness in the cross-section of the sample in the gripping part on the x-y plane.

Fig. 20 – Material hardness in the sample cross-section in the gripping part on the x-z plane.

Fig. 21 – Material hardness along the z axis.
DMLS-2) tensile tests. Differences in hardness also occur between the results received for individual planes of each sample.

The test results are presented in graphic form in Figs. 19–21. The highest hardness was obtained for the cross-section of samples taken from the gripping part parallel to the x–y plane (Fig. 19). For DB samples, the highest hardness value was obtained at the edges of cross-section (891 HV5), which decreased with approaching the sample axis (827 HV5). The difference in values is about 64 HV5. For the DMLS sample, higher hardness values were obtained compared to the results for the DB sample. For DMLS samples subjected to loads, the highest hardness values occur at the edges of cross-section (984 HV5) and decreases towards the sample axis (935 HV5). The difference in values is about 49 HV5. For the sample before static tests (Specimen DMLS-1), the difference in values is about 14 HV5 which indicates the repetitive mechanical properties of the sample made by the additive method. In the middle part of the sample the hardness varies slightly. For each samples type (DB samples and DMLS samples) the highest hardness was obtained at the edges of cross-section, and the difference between the highest values is about 93 HV5.

Fig. 20 presents the results of the hardness measurement in the sample gripping area in the x–z plane for DB and DMLS samples. In the case of the DB sample in the grip part for the x–z plane, the hardness changes are similar to the one observed for the x–y plane. The highest hardness value in the x–z plane for DB samples occurs at the edge of cross-section (807 HV5), and the lowest value occurs near the sample axis (739 HV5). The difference in hardness value at the cross-section edges between the x–y plane and the x–z plane is about 84 HV5, while in the middle section the difference is about 88 HV5.

For the DMLS sample before static tests (Specimen DMLS-1), the hardness varied from 798 HV5 to 820 HV5. Small changes in value indicate similar mechanical properties of the material produced using the DMLS method.

In the case of DMLS samples not subjected to loads (Specimen DMLS-2) in the x–z plane, the hardness varies from 802 HV5 to 846 HV5 and there is no tendency to change values. The difference in hardness value between the x–y plane and the x–z plane at the section edges is about 177 HV5, and about 130 HV5 in the sample axis.

The reason for the large differences in hardness between the x–y plane and the x–z plane can be the arrangement of the material grains resulting from printing methods. The samples were printed along the Z axis, and the x–y plane is perpendicular to the x–z plane. Plastic deformation resulting from the axial load acting along the Z axis may also be significant for hardness. The crystallographic mesh of the material has been deformed in accordance with the direction of the loading. The hardness results for the DMLS sample are higher than the values for the DB sample.

The hardness measurement along the Z axis (Fig. 21) for the DB sample and the DMLS sample showed significant differences. They mainly concern the trend of value changes. According to the measurement implementation scheme (Fig. 10a), the first measuring point is located in the sample gripping area, while the eleventh measuring point is located closest to the edge of the sample breakage. For the DB sample, the hardness near the sample crack (item 11 in Fig. 21) is 750 HV5. The indicated measuring point is in the area of large plastic deformations (A = 29.7%). Moving away from the edge of the sample crack, the hardness decreases, reaching a minimum (698 HV5) in the transition area (shoulder). For measuring points located in the grip part, the hardness value is about 750 HV5. It is assumed that in

Fig. 22 – Macrostructure of the Ti6Al4V material resulting from the DMLS additive manufacturing method taken from: (a) samples along the Z axis, (b) sample gripping part, (c) distribution of force lines in the sample during tensile force; I – the area of significant changes in the material structure resulting from the tensile force action, II – transitional area, III – area with limited impact of tensile force.
3.3. Analysis of titanium alloy macro- and microstructure results

Macrostructure of the Ti6Al4V titanium alloy (Figs. 12a and 13a) delivered in the form of an annealed drawn bar does not show significant changes after tensile force action. The macrostructure of the unloaded DMLS sample (Specimen DMLS-1) shows no structural changes in the cross-section and longitudinal section (Figs. 14a and 15a). In the case of DMLS sample subjected to load (Specimen DMLS-2), the macroscopic images (Figs. 16a and 17a) demonstrate structural changes resulting from external load. Their precise analysis allows to specify three areas (Fig. 22): I – the area of significant changes in the material structure resulting from the tensile force action, II – transitional area, III – area with limited impact of tensile force. In area I there were large plastic deformations due to the action of the tensile force, and the directionality of the structure (Fig. 22a) is related to the arrangement of the force lines (Fig. 22c). There is a transition zone between area I and area III (area II), which is indicated in Fig. 22(a and b). Area III is an area in which plastic deformation occurred with a much lower value than in area I.

The macrostructure analysis of the samples used in the research indicates that the tensile load causes significant changes in the structure of objects produced by the use of DMLS additive manufacturing method. It may result from additive technology, process implementation parameters, arrangement of material layers in relation to the expected direction of loading.

The samples used in the tests were produced along the Z axis, i.e. the contact surface of material subsequent layers was perpendicular to the direction of loading force.

The microstructure analysis of samples made from a drawn bar (Figs. 12d, 13b, 13c) corresponds to the structure for a two-phase alloy α + β. In the case of the structure taken from the narrowing area C2 (Fig. 12b) and the weaning area B2 (Fig. 12c) changes caused by plastic deformations are visible. The two-phase structure α + β of the alloy is transformed into a α structure under the influence of deformations caused by tensile force. The mechanism of α + β structure transformation is shown in Fig. 23.

For DMLS samples under static load condition, the material structural changes are even more significant than for DB samples. Fig. 16 shows material structures taken from three sample areas with different plastic deformation values. Structural changes in the material are part of the mechanism shown in Fig. 23. The DMLS sample before static tests (Specimen DMLS-1) has the microstructure of the biphasic titanium α + β, which is shown in Fig. 14.

4. Conclusion

1 The strength of sample made of a drawn rod is lower compared to a sample produced using DMLS additive technology.
2 Young E module values for PC and DMLS samples are similar. The values of parameter E indicate that the technology of making samples from titanium alloy Ti6Al4V does not affect its value.
3 Hardness tests showed different values on individual cross-section planes. The difference in results is related to the method of sample preparation by the additive technology and the external load it has been subjected to.
4 Slight changes in the hardness value in the x-plane of unloaded samples indicate similar mechanical properties of the material produced by the DMLS method.
5 The reason for the large differences in hardness between the x–y plane and the x–z plane may be the arrangement of the mate-
rrial grains resulting from printing methods, as well as the plastic deformations resulting from the axial load acting along the Z axis.

6. The crystallographic mesh of the material has been deformed according to the direction of the loading.

7. Analysis of the macrostructure of the samples used in the tests indicates that the tensile load causes significant changes in the structure of objects produced by the additive DMLS method. It may result from additive technology, process implementation parameters, arrangement of material layers in relation to the expected direction of loading.

8. Comparison of the macrostructure of the sample made by the additive method before and after loading indicates that the implementation of the load introduces plastic deformations, which are visible in the sample photos shown in the Fig. 2. The change in structure is associated with deformations resulting from the load line.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES


