MICROSTRUCTURE, DEFECTS AND FRACTOGRAPHY OF Ti6Al4V ALLOYS PRODUCED BY SLM AND DMLS

R. Konečná, G. Nicoletto, A. Bača, L. Kunz

Abstract

Laser assisted generative production techniques like Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are additive manufacturing techniques in which functional, complex parts can be created directly by selectively melting layers of metal powder using a highly focused laser beam. The specific process conditions, lead to a specific and complex microstructure and to mechanical properties that show a degree of directionality. In this contribution two commercial laser-assisted generative production techniques for the production of Ti6Al4V parts are compared in terms of microstructure, defect content, mechanical properties and fractographic evidence of the fatigue damage mechanisms. Identical specimens produced according to the recommended process parameters were produced and tested. A link between observed properties and microstructural and fractographic observations is sought.

Keywords: SLM, DMLS, Ti6Al4V, fractography, microstructure, fatigue mechanisms

INTRODUCTION

Laser-assisted generative production techniques like Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are suited for rapid manufacturing of small batches or even individual parts of a nearly unlimited geometrical flexibility and complexity and customization [1, 2]. A wide range of metal materials can be processed including stainless and hardenable steels, aluminum alloys, cobalt-chrome alloys, nickel alloys and titanium alloys. Laser-assisted generative techniques are in routine use in such fields as medicine, dentistry and aerospace where lots of complex high-added-value parts are needed.

Laser assisted generative production techniques are based on the principle of building near-net-shape parts by adding layers. Every layer contains specific two-dimensional geometrical information of the part. The laser beam is guided by mirrors and scans a powder bed in specified tracks melting the powder to different degrees (completely in SLM and partially in the DMLS). By adding layer on layer, three-dimensional parts are produced directly from CAD data without using any tools or molds [3].

According to their processing direction those parts feature mechanical properties comparable to those of conventionally fabricated ones. However, due to the layer-by-layer principle of part production, there are drawbacks like the non-optimal surface quality and the anisotropy of the mechanical properties.

Radomila Konečná, Adrián Bača, University of Žilina, Faculty of Mechanical Engineering, Žilina, Slovakia
Gianni Nicoletto, University of Parma, Department of Industrial Engineering, Parma, Italy
Ludvík Kunz, Institte of Physics of Materials, Academy of Sciences of the Czech Republic, Brno, Czech Republic

This paper focuses on the Ti6Al4V alloy and analyzes the microstructure and defect content of specimens produced by the two technologies, i.e. SLM and DMLS.

EXPERIMENTAL DETAILS

Part production systems

Two industrial systems were used to produce the specimens investigated in this study, namely a SLM system (AM 250, Renishaw plc, UK) and a DMLS system (EOSINT M270 by EOS GmbH, Germany) both owned and operated by the Italian company BEAM-IT, srl, Fornovo Taro, Italy. Both systems operate with a wide range of metallic materials including titanium alloys, Inconel etc. A brief introduction to the two technologies is given now.

Direct Metal Laser Sintering (DMLS) Laser sintering is possibly the most frequently used additive technology to make metal parts today. The powder delivery system uses a piston in a cylinder. The piston moves upward incrementally to supply a measured quantity of powder for each layer. Metal powder is then spread by a roller over the surface of the build cylinder. The piston in the build cylinder is moved down one layer thickness to accommodate the new layer of powder. The laser beam then traces the surface of this tightly compacted powder to selectively sinter and bond it to form a layer of the object. The entire fabrication chamber is maintained at a temperature just below the melting point of the powder so that heat from the laser need only elevate the temperature slightly to cause sintering. The cycle is repeated until the entire part is fabricated. After the part is fully formed, excess powder is removed and final finishing may be carried out. No supports are required with this method since overhangs and undercuts are supported by the solid powder bed. The cool-down time before the part can be removed from the machine may be long depending on part geometry and size.

Selective Laser Melting (SLM) Equipment applying this technology is currently sold by Renishaw plc (UK). SLM is similar to DMLS but, in contrast, fully melts metal powders to directly form fully-dense parts. The machine build chamber is a vacuum chamber filled with a controlled atmosphere of inert argon gas. Layer thickness is about 20 µm resulting in sharp edge definition. A high surface quality of the part is achievable.

Material

The metal considered in this work is the titanium alloy Ti6Al4V in the form of gas atomized powder. The powder particles are spheroidal, predominantly with a diameter range 6 to 15 µm and big particles range from 24 to 53 µm. Due to the typical process conditions, (i.e. layer by layer generative principle, short interactions, high temperature gradients and the high localization of this manufacturing process), the microstructure exhibits strong directionality and consequently anisotropic structural and mechanical properties, [4]. To characterize the structure, reference is made the Cartesian coordinate system that considers the laser scanning plane as X-Y and the build direction as Z. Since considerable differences of mechanical characteristics according to the processing direction of the part are expected, a variety of specimens for both tensile and fatigue tests were generated with their loading axis in the horizontal (i.e. in the X-Y plane or perpendicular to the build direction) as well as in the vertical (i.e. parallel to build Z axis) direction.

Mechanical tests

Tensile tests were performed at room temperature using a computer-controlled servo hydraulic MTS 810 testing machine equipped with a 25-mm-gage length MTS extensometer. The vertically- and horizontally-built samples were tested along their axis in displacement-control mode (with the rate 0.01 mm/s). Fatigue tests on miniature specimens having three different orientations were conducted under cyclic bending (i.e. stress ratio R = 0) at a frequency f = 20 Hz at room temperature. The tests were run up to failure or they were interrupted at 2 x 106 cycles (run-outs). The experimental data were plotted in terms of the S-N diagram, i.e. the number of cycles to failure, N_f, in dependence on the stress amplitude σ_a.

Structural and fracture characterization

The microstructure of the Ti6Al4V alloy produced by SLM and DMLS were investigated on polished and etched metallographic sections extracted from specimens in order to characterize material anisotropy by light microscopy. The Struers TegraPol-15 automatic system was used for metallographic preparation. The polished surfaces were observed in non-etched and in 10% HF etched conditions using a Neophot 32 and the Zeiss Axio Observer Z1M. Fracture surfaces were examined with Tescan LYRA 3 XMU FEG/SEM.

RESULTS AND DISCUSSION

Summary of mechanical test results

Considering that the aim of this work is the presentation and comparison of the material structure of two laser assisted generative production techniques, and their fractographic characteristics, here only the main results of the mechanical tests are summarized while detailed presentations can be found elsewhere, [5,6].

The mechanical response depends on the material generation process itself as well as on the post processing phase. In case of stress relieving treatment after material generation, the tensile specimens show a high strength (> 1200 MPa) and limited elongation to fracture (< 1 %). Therefore, a HIP (Hot Isostatic Pressing) treatment may be alternatively applied increasing the elongation (> 6 %) while the tensile strength is reduced (to about 1000 MPa).

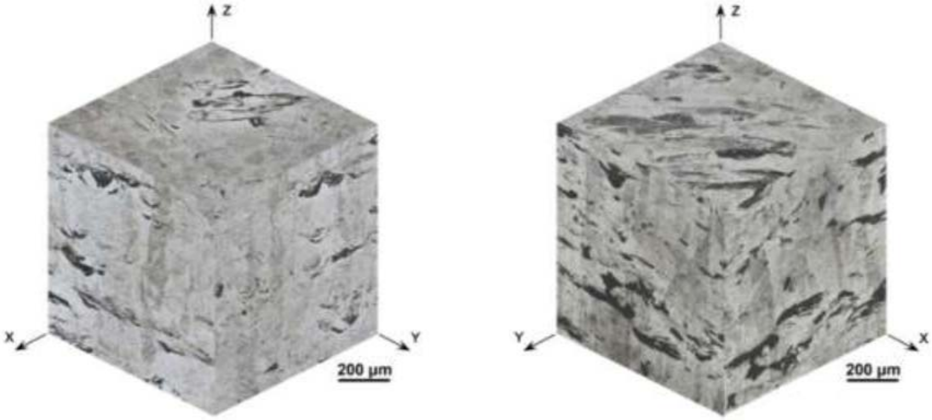
More interesting for this study was the difference in mechanical response associated to the specimen loading orientation vs. build direction, which is connected to structural anisotropy. Compared to specimens tested in the direction perpendicular to the build direction, the specimens tested in the direction parallel to the build direction show considerable lower tensile strengths and elongations. In the fatigue tests as well, the previous directional effects are confirmed with significantly higher fatigue strength (of the specimens tested in the direction perpendicular to the build direction with respect to the specimens tested in the direction parallel to the build direction.

Microstructure

The investigation of specimens microstructure prepared from the Ti6Al4V alloy powder by the two different technologies (DMLS and SLM) was aimed to characterize the inherent texture depending on the strategy of specimens building. The directionality of the microstructure was characterized by the machine-based Cartesian coordinate system where the X-Y plane is the laser scanning plane and the build direction of specimens is in the axis Z.

The characteristic structure on orthogonal section planes for both laser-assisted generative techniques (SLM and DMLS) are shown as three-dimensional cubes in Fig.1. The structure of specimens prepared by the two different technologies show the same characteristic texture in the cut planes X-Z, Y-Z and differs in the structure of the cut plane

X-Y axis. The X-Z and Y-Z planes are perpendicular to the raster laser tracks that locally melt the powder. Such tracks show as a series of dark areas generated by the local intense laser energy distribution. The percentage of dark areas is higher in the SLM specimens (Fig.1b) than in the DMLS specimens (Fig.1a) indicating the stronger energy flux of SLM. The system of dark areas also shows layer-wise material generation. The content of defects inside of dark spots is much lower in DMLS specimens than in SLM specimens. The distribution of defects in the lateral planes is parallel to the scan direction while are oriented according to the specific scan direction in the X-Y plane.



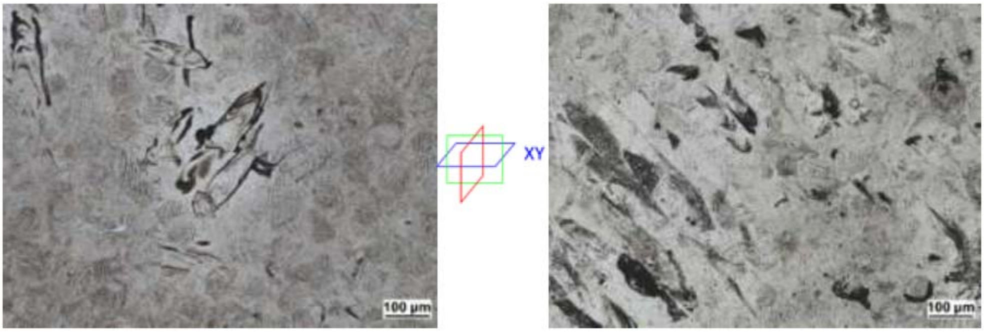
a) DMLS b) SLM

Fig.1. 3-D layered texture of Ti6Al4V specimens.

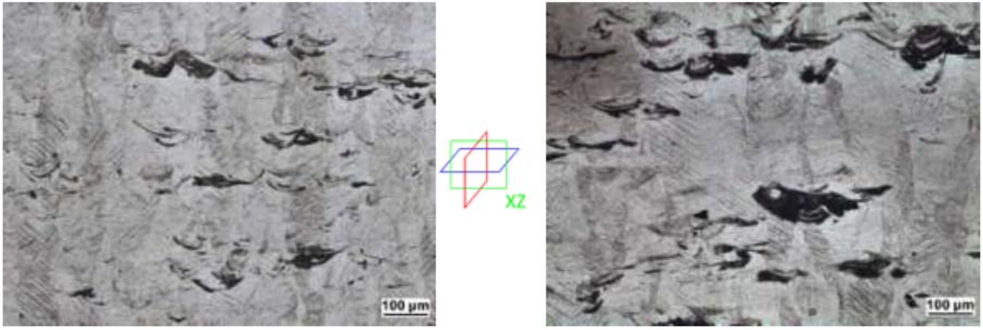
The micrographs at lower magnification reveal the layer-by-layer building-up process of the Ti6Al4V bulk common to both DMLS and SLM (Fig.2). The powder melt by laser pulses along a raster direction in the X-Y plane results in a sequence of rounded grains formed by the solidification of the melt pools. The structure is more regular in the DMLS specimens compared to the SLM specimens. The laser direction varies layer-by-layer. The elongated dark spots (Fig.2a, b) are oriented parallel to the scan direction. The two micrographs reflect the differences in the laser-powder bed interaction of the two technologies.

The microstructures of the Ti6Al4V alloy in the X-Z and Y-Z planes are similar for both technologies. They are characterized by large grains, elongated parallel to the build direction as shown in Fig.2c, d. The long columnar grains of Ti6Al4V correspond to the primary β-phase structure. They grow epitaxial during the material processing. These columnar grains are much longer than the layer thickness.

The high magnification structure of the additive manufactured Ti6Al4V alloy is shown in Fig.3. The dark spots (Fig.2 and 3a) show interlayer material where local defects (indicated by arrow in the detail in Fig.3a) are localized. In general they are perpendicular to the columnar grain growth direction. The high temperature gradient of the process results in the formation of the unstable acicular martensite inside the primary β grains as shown in Fig.3b [7]. The dark spots areas at high magnification are characterized by very fine needless of α’-martensite around black defect (Fig.3a.)

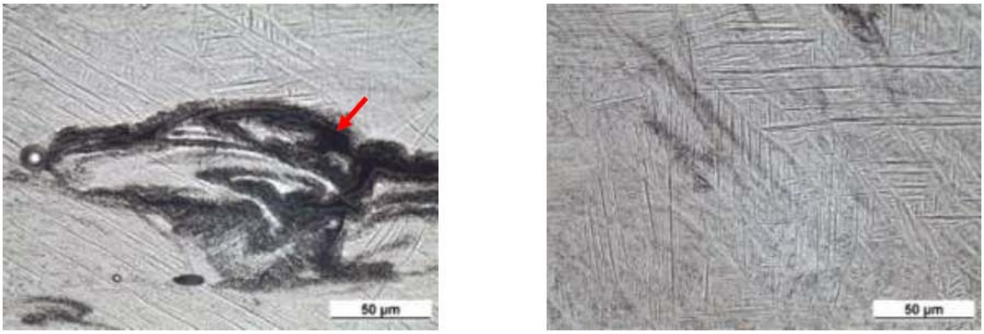


a) DMLS (plane X-Y) b) SLM (plane X-Y)



c) DMLS (plane X-Z) d) SLM (plane X-Z)

Fig.2. Microstructure of Ti6Al4V specimens.

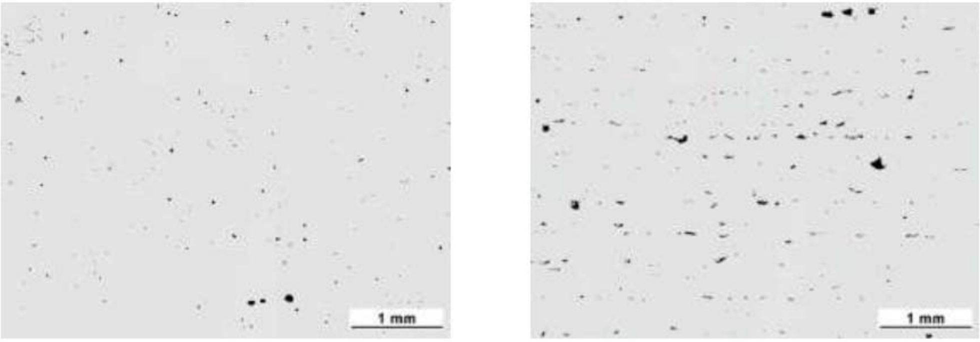


a) detail of dark spot with defect inside b) acicular α´-martensite

Fig.3. Details of Ti6Al4V microstructure.

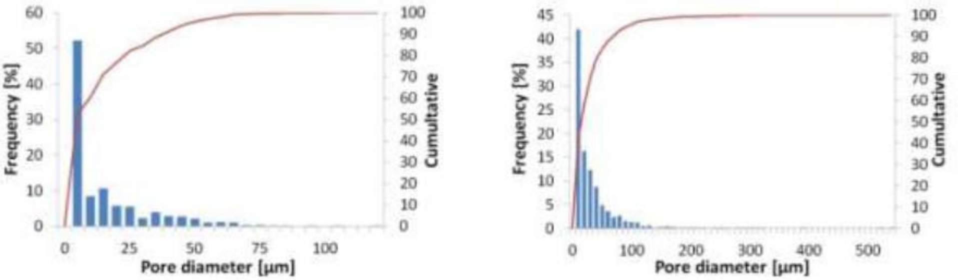
Defects

The complex process of material formation may generate porosity. Fig.4 shows distribution of defects in the polished un-etched specimens. The defects in DMLS specimens are randomly distributed and show predominantly rounded shape (Fig.4a). They can be specified as pores. The SLM specimens are characterized by array arrangement of defects (Fig.4b) with very complex shape (shrinkages), see Fig.3a. The different degrees of material melting between the two technologies affect porosity content. The porosity was evaluated on Neophot 32 light microscope equipped by NIS-Elements image analysis software. The average porosity of DMLS specimens was 0.24% while the porosity of SLM specimens was significantly higher with an average value of 3.87%.The pore size distribution for specimens produced by both technologies is shown in Fig.5. The size distribution of DMLS specimens (Fig.5a) was characterized by 52% of pores with a diameter in the range from 0 to 5 µm and the largest local pores reached the size of 120 µm. On the other hand, the size distribution in SLM specimens of Fig.5b shows that 43% of shrinkages have a diameter of 0 to 10 µm and the largest pores reach the size of 600 µm. For limits in the resolution, pores with diameter smaller than 0.5 µm could not be quantified.



a) DMLS b) SLM

Fig.4. Material defects, LM non -etched.

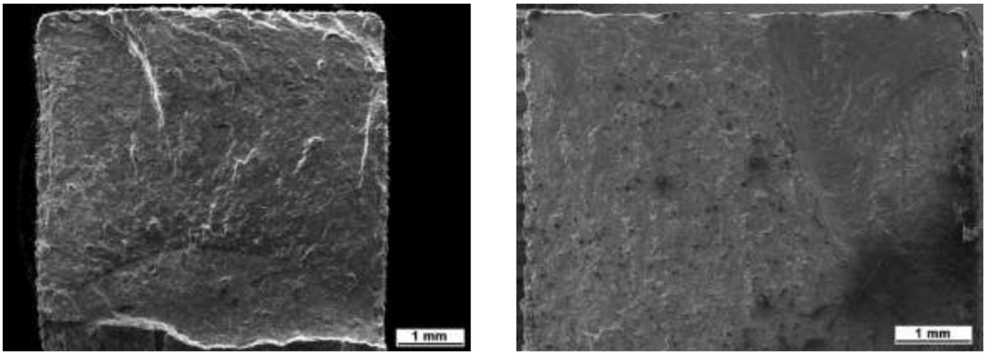


a) DMLS b) SLM

Fig.5. Average pore size distribution.

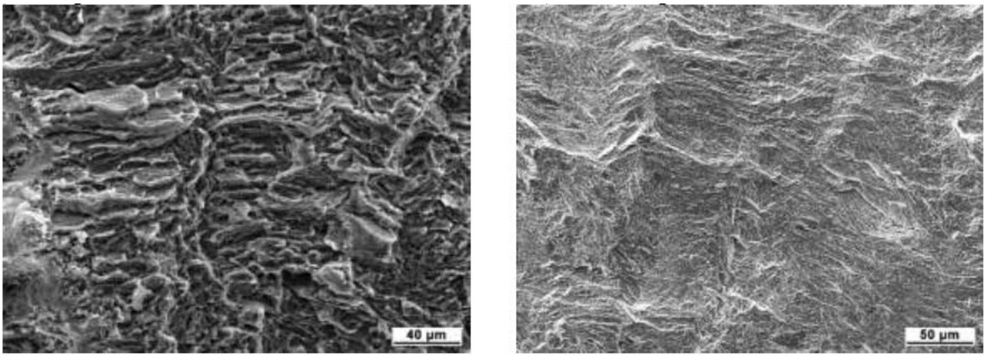
Fractography

The observations reported here refer to the fatigue specimens. In general the process of fatigue failure is characterized by crack initiation, crack propagation and final failure. Cracks usually initiate at the site with the highest stress concentration, either geometrical or related to the material structure [8]. In the present SLM and DMLS fatigue specimens, fatigue crack initiation occurred always at the surface due to the applied bending loading and due the natural roughness associated to the fabrication process. Fatigue experiments after surface polishing demonstrated a life extension confirming that the surface roughness of a specimen has a negative effect on fatigue.



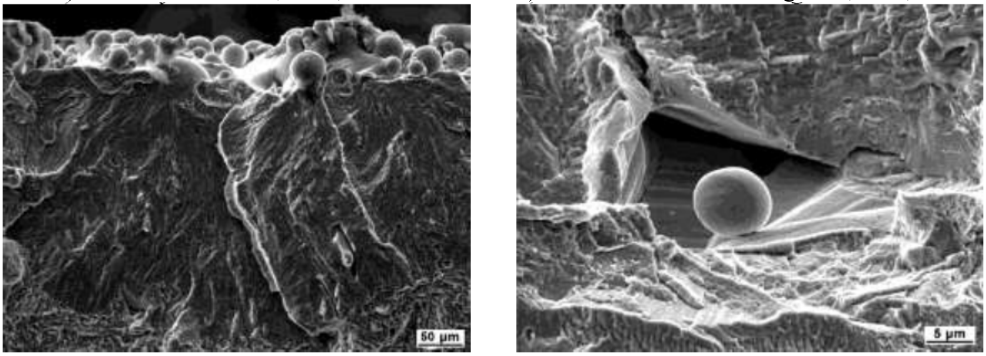
a) multiple initiation, Z-X orientation, DMLS

d)initiation place, Y-Z orientation, SLM



b) detail of striations, X-Y, DMLS

e) striations in columnar grains, Y-Z, SLM



c) initiation from rough surface, Y-Z, DMLS

f) detail from shrinkage, Y-Z, SLM

Fig.6. Fatigue fracture surfaces, SEM.

Inspection of fracture surfaces after fatigue testing does not show significant differences between SLM and DMLS generative production techniques. The main differences were found in terms of location and number of initiation places. The fracture surface of DMLS specimen oriented parallel to the build direction (Z) shows multiple initiations on the surface in tension (Fig.6a). Since the stress direction in this case is perpendicular to the layer stacking plane (Fig.2c, d), interlayer defects contribute to the fatigue damage process favoring multiple crack initiation. All the specimens oriented perpendicular to the build direction (Fig.6d) exhibit quite similar fracture surfaces independently of the formation (SLM or DMLS) process. A significant difference between the two manufacturing methods is in the surface finish. Un-melted and semi-melted spheroidal particles of Ti6Al4V powder were observed on the DMLS specimen surface generating a porous layer of about 60 µm (Fig.6c). The surface finish obtained by DMLS is rougher than that of the SLM process.

The classic feature associated with fatigue crack growth is the formation of fatigue striations. Magnified views of the fatigue region of fracture surface for DMLS, Fig.6b, show these fatigue striations. The fatigue region of SLM specimens with orientation perpendicular to the build direction is shown is shown in Fig.6e. The elongated valleys correspond to the primary β-phase long columnar grains which epitaxial grow during material generation.

CONCLUSIONS

The microstructure, defects and fatigue fracture mechanism of the Ti6Al4V alloy produced by the two additive manufacturing technologies, SLM and DMLS, have been investigated and compared. The main findings are the following:

- The microstructure of the two technologies show similar anisotropic characteristics due to the common layer-wise material generation process,
- The amount of porosity and the maximum defect size of SLM technology are greater than those of the DMLS.
- The outer surface obtained with the DMLS technology is apparently rougher than that of the SLM.

Acknowledgements

The company BEAM-IT Srl, Fornovo (PR) Italy is gratefully acknowledged for providing the specimens. The research was supported by project Slovak VEGA grant No. 1/0196/12 and the Slovak Research and Development Agency under the contract No. SK-CZ-2013-0047.

REFERENCES

[1] Abe, F., et al.: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 217, 2003, no. 1, p. 119
[2] Meier, H., Haberland, C.: Materialwiss. Werkst., vol. 39, 2008, no. 9, p. 665
[3] Kruth, JP., et al.: Rapid prototyping journal, vol. 11, 2005, no. 1, p. 26
[4] Simonelli, M., Tse, YY., Tuck, C.: Journal of Physics Conference Series, 2012, no. 07, p. 371
[5] Konečná, R., Nicoletto, G., Kunz, L., Fintová, S.: Structure, Texture and Tensile Properties of Ti6Al4V Produced by Selective Laser Melting. Materials Science (Medžiagotyra), 2015, To be published
[6] Nicoletto, G., Konečná, R., Kunz, L., Bača, A. In: Procs. 4th International Conference of Engineering against Failure (ICEAF IV). Skiathos, Greece, 2015
[7] Yadroitsev, I., Krakhmalev, P., Yadroitseva, I.: Journal of Alloys and Compounds, vol. 583, 2014, p. 404
[8] Gong, H., Rafi, K., Starr, T., Stucker, B. In: Solid Freeform Fabrication Symposium 2012