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INVESTIGATION OF SHAPE ACCURACY OF SELECTIVE LASER MELTED Ti6Al4V LATTICE STRUCTURE BY COMPUTER TOMOGRAPHY

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Abstract: Selective laser melting is a widely applied additive manufacturing technology for metals, especially Ti6Al4V alloy today. Manufacturing of lattice structures stands in focus of scientific research, because of special technological advantages of those, like production of lightweight parts, opportunity of combination with other materials utilizing pores, biomedical applications, several scenarios of production resulting in tuned mechanical properties. In our experiments tensile test specimens were produced with periodic trabecular structure. Pore size of structure were varied. Shape accuracy of test specimens were measured by computer tomography. Size accuracy of the total specimen, size and shape accuracy of pores, places of material defects and excesses were identified and described quantitatively. Our experiments showed that most part of test specimens were precise enough. However special areas were identified with high inaccuracies. Moreover most dangerous errors, material absence and cracks also observed.

Keywords: lattice structure, Ti6Al4V, selective laser melting, shape accuracy, dimensional accuracy

INTRODUCTION

In 20th century manufacturing technologies went through the most extraordinary advancement in history of mankind [1–3]. Beside several areas of technological development additive manufacturing (AM) brought a revolutionary change opening up new doors of integration of production with other systems of economy like remanufacturing, informatics, robotics [4], logistics [5], commerce, construction [6] and medicine [7–9]. Flexibility of AM strongly contributes to mass customization production emerging in the frame of industry 4.0 [10]. Number of research publications related to AM increase exponentially since 2000 [11]. AM with its new opportunities and challenges [12] also transforms even way of thinking in engineering design [13–15]. AM today is applicable for composing new materials with designed and tuned properties, like composites [16, 17] and special microscopic-level mixtures [18].

Standard ISO/ASTM 52900 introduces a nomenclature for AM technologies and concepts connected with AM [19]. This standard specifies seven class of AM technologies: binder jetting (BJT), directed energy deposition (DED), material extrusion (MEX), material jetting (MJT), powder bed fusion (PBF), sheet lamination (SHL) and vat photo polymerization (VPP).

Distinctive feature of PBF technology is that during the process thermal energy fuses a part of a powder bed. PBF technologies can be applied to many different materials, most frequent ones are plastics and metals. In the followings we deal with metals

Fusion comes true in two main ways, sintering and melting. The process is called sintering if original powder particles do not completely melt. When all powder particles are melted, it is called melting. Source of thermal energy is usually laser beam or electron beam.

Selective laser melting (SLM) is a PBF method which uses laser beam for full melting of material to be fused [20]. When it is applied for metals it is often called direct metal selective laser melting (DMSLM). This paper presents result of DMSLM applied on Ti6Al4V material, and we refer to this briefly as SLM, because there is no risk of ambiguity.

Feedstock material of SLM is metal powder. Such kind of powders differ from base materials of powder metallurgy. Today a complete industrial background exists to supply AM market with powders of several metals and alloys. Most important properties of AM metal powders are particle size distribution, average size, particle shape, nominal chemical composition, and level of accuracy of chemical composition. Quality of metallic parts produced by AM depends of quality of metal powder which it is made of [21, 22].

SLM is a production method with several process parameters. Significant part of scientific literature treats how properties of parts produced depends of SLM process parameters [23–26].

Dimensional and shape accuracy are also dependent from SLM process parameters [27–32].

AM technologies in themselves are rarely able to produce ready to use parts. Commonly so-called postprocessing methods are used to achieve required quality of the product. Aims of postprocessing are surface modification in order to improve shape accuracy , wear resistance [33, 34], surface roughness [35–37].

Computer tomography first gained ground in biomedicine is a cost and expertise demanding method, at the same time it is increasingly applied also in other fields of industry for three-dimensional imaging of complex structures. This is especially true for inspection of additively manufactured lattice structures which form a new and promising class of parts [38, 39].

In this paper we introduce an experimental study on shape and size accuracy of a lattice structure produced by SLM from Ti6Al4V alloy. Since a lattice structure has numerous details inside, where those can not be observed by optical methods, computer tomography (CT) has been applied as imaging procedure. Aim of this study was to show out dimensional and shape deviations, material excess and lack, as well as cracks and fractures originated from manufacturing procedure.

MATERIAL AND METHODS

— Material Ti6Al4V

Samples were produced from Ti6Al4V ELI powder by SLM. Ti6Al4V is known as a widely applied metal alloy in industry, which is also intensively studied in science. In our experiments we used a special form of Ti6Al4V containing extra low interstitials (ELI). Chemical composition of Ti6Al4V ELI in weight% is 5.5-6.75% Al, 3.5-4.5% V, C ≤ 0.08%, O ≤ 0.2%, N ≤ 0.05%, H ≤ 0.015%, Fe ≤ 0.4%. All other elements must be present in less than 0.1%, and total amount of other elements must be less than 0.4% [40].

This metal alloy has remarkable advantages like low mass density, good mass-strength ratio, chemical endurance and biocompatibility. It is applied in biomedical, pharmaceutical, vehicle, nuclear industries and several other fields [41, 42].

— Sample production

The shape of the sample is identical to a standard tensile test specimen with rectangular cross section expected that active zone (which part is used to break away) of it has lattice structure. Lattice is periodical. Unit cell is cubic with 2.5 mm edge length. Figure 1 shows overall shape of the test specimen and middle part with lattice structure magnified.

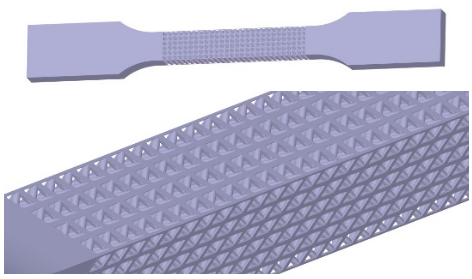

Figure 1. A standard tensile test specimen with modified active zone. It has lattice structure built up from cubic unit cells

This sample was produced in horizontal orientation with its smallest faces down as left side of Figure 1 sows. Manufacturing machine was an EOS M290 400W. Production parameters were set to default values.

— Computer tomography

Computer tomography is often applied for inspection of additively manufactured metallic parts [38] [39].

Computer tomography may be known for most people from medical practice. Aim of such a measurement is to gain a 3D representation of internal structure of a body, which is not observable by optical methods. In industry aim is the same. Difference from medical machines is that specimen rotates and X-ray source stands, and usually it applies stronger X-ray for inspection.

A computer tomograph uses X-ray to radiograph the sample. By this way a projection of internal structure is captured like a shadowed plane image. As the sample rotates several such an image are taken. Spatial representation of internal structure is gained by numerical mathematical methods in digital form, usually as an STL (standard triangulation/tessellation language) model. Resolution is characterized with so-called voxel size, which depends on acceleration voltage, size of sample and distance of sample and source.

In our experiment a Werth industrial computer tomograph (CT) machine was applied with maximum 225 kV accelerating voltage.

In this study shape of the lattice was imaged, which is really the surface of the solid body. Now microstructure inside the material was not revealed.

RESULTS AND DISCUSSION

After CT measurement we had two electronic body representation of the specimen in STL format. First is the CAD body model which was the base of manufacturing. This is the ideal shape of the specimen. Second body model was resulted from CT inspection by processing software of the measurement system. This represents the realized shape of the body. The two STL file were compared with each other.

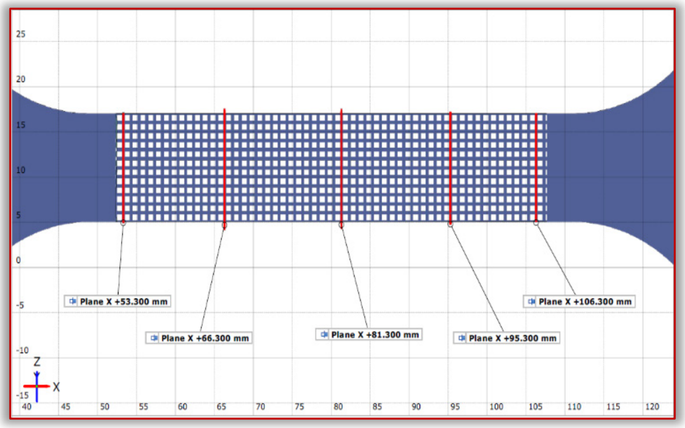

Figure 2. Section planes of CT generated STL body model for measurements and observations

Figure 2 shows planes in which measured STL file was sliced and digital dimensional measurements and observations was taken.

Two STL files were fit to each other by least squares method. Figure 3 shows deviations of measured shape from designed (ideal) shape. This image represent absolute value of deviations with color code. It is observable that maximum deviation on the flags is +0.213 mm. Compared to classical manufacturing technologies this is a bad value. However we must not forget that there are biomedical applications where this accuracy is sufficient. For example a bone implant needs not higher accuracy since bone grows around it.

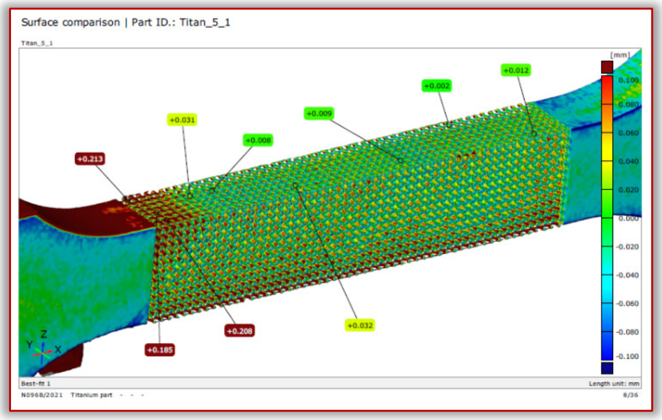

Figure 3. Deviations of measured shape from ideal shape of test specimen. On this image z coordinate is represented in mm units

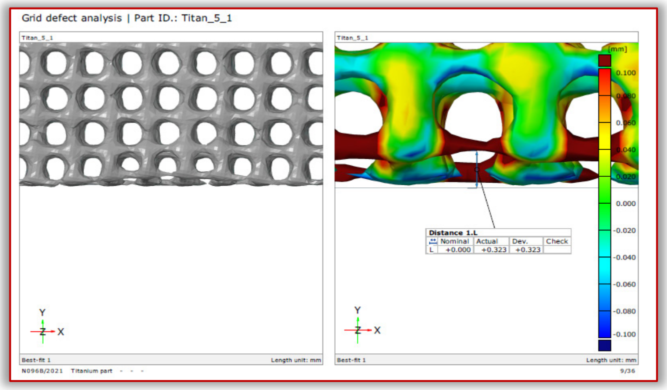

Figure 4. Pores of the lattice structure, and deviation from designed shape by color code

On Figure 4 we can see a highly important phenomenon. Original designed shape is rectangular with plane faces and sharp corners. In contrast to it, manufactured (realized) shape is quite rounded. This follows from principle of SLM. When particles of metal powder are melted those moves as fluid drops and their movement is determined by two factors: surface tension and wetting the underneath not melted metal part. Both effects makes the material arrange along rounded shapes and will never form either sharp corners or plane faces. Manufactured shape seems as it was designed from unit cells with spherical holes. SLM will never create sharp corners in micro scale.

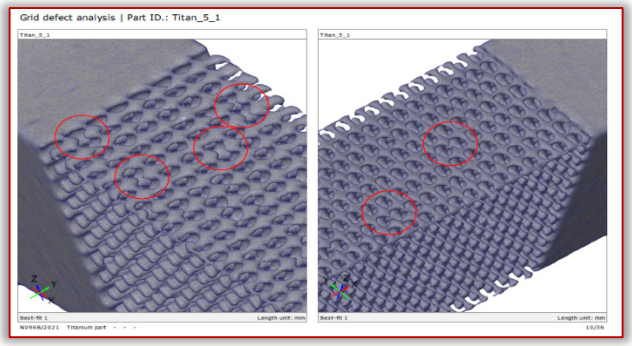

Figure 5. Red circles show material defects and excesses

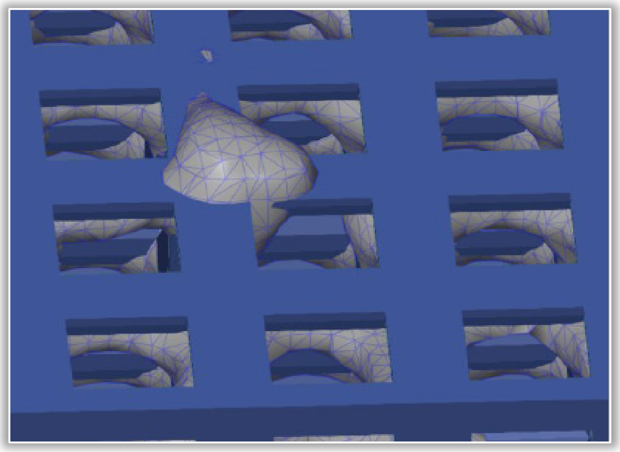

Figure 6. A special region with material excess. Blue color shows designed ideal shape, and measured shape is visible in grey

On Figure 5 several material defects are demonstrated. This may come from contractile effect of surface tension. The higher is the temperature the stronger is this effect. It means that overheating is to be considered and corrected if we can see high number of such material defects.

Figure 6 shows a material excess. This may come from uneven powder spreading or splatter phenomena, which is similar to what is well known in case of welding.

SUMMARY AND CONCLUSIONS

In this study a tensile test specimen with lattice structure in the middle was investigated. The test specimen was produced by SLM in horizontal direction. Material of the specimen is Ti6Al4V. Shape and dimensional accuracy of the specimen was studied by CT inspection. Both designed and measured shape was available in STL files. Two body model were fit to each other and deviations were visualized and characterized numerically.

The following conclusions can be stated:

- Largest dimensional deviation of manufactured specimen from designed shape is in the magnitude of 0.2-0.3 mm. This is not sufficient in most mechanical engineering applications, but may be eligible for biomedical purposes.
- In macro scale the shape of the specimen stands close to the design.
- In micro scale shape of lattice details are rounded even if the original design was rectangular, brick-like with

plane faces and sharp corners. Shape of pores is not cubic, indeed spherical or circular.

- Material defects can be observed at several locations of the model in the lattice structure. Thin rod-like fractions and fine details tend to be rounded by fluid behavior during the SLM process. This is valid for details with size under 1 mm.
- Material excess can also be observed. This may come from inaccuracies of powder spreading of splatter.

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References

[1] B. Esmaeilian, S. Behdad, and B. Wang, 'The evolution and future of manufacturing: A review', J. Manuf. Syst., vol. 39, pp. 79–100, 2016.
[2] J. J. Beaman, D. L. Bourell, C. C. Seepersad, and D. Kovar, 'Additive Manufacturing Review: Early Past to Current Practice', J. Manuf. Sci. Eng., vol. 142, no. 11, 2020.
[3] N. K. Katiyar, G. Goel, S. Hawi, and S. Goel, 'Nature-inspired materials: Emerging trends and prospects', NPG Asia Mater., vol. 13, no. 1, Art. no. 1, Jul. 2021.
[4] T. J. Wallin, J. Pikul, and R. F. Shepherd, '3D printing of soft robotic systems', Nat. Rev. Mater., vol. 3, no. 6, Art. no. 6, 2018.
[5] J. Kern, 'Additive Manufacturing: Shaping the Supply Chain Revolution?', in The Digital Transformation of Logistics, 1st ed., M. Sullivan and J. Kern, Eds. Wiley, 2021, pp. 41–60.
[6] A. Paolini, S. Kollmannsberger, and E. Rank, 'Additive manufacturing in construction: A review on processes, applications, and digital planning methods', Addit. Manuf., vol. 30, p. 100894, 2019.
[7] B. Bhaskaran and J. R.S., 'Additive Manufacturing: A Review', pp. 2349–3976, 2022.
[8] P. Bindiganavile Anand, N. Lokesh, A. Buradi, and S. N., 'A comprehensive review of emerging additive manufacturing (3D printing technology): Methods, materials, applications, challenges, trends and future potential', Mater. Today Proc., vol. 52, 2021.
[9] A. Rajic, E. Desnica, I. Palinkaš, D. Nedelcu, and L. Vulicevic, '3D Printing Technology with Plastic Materials for Hip Implant Master Patterns Manufacturing', Mater. Plast., vol. 56, pp. 882–890, 2019.
[10] M. Sanguedolce, G. Rotella, M. R. Saffioti, and L. Filice, 'Functionalized additively manufactured parts for the manufacturing of the future', Procedia Comput. Sci., vol. 180, pp. 358–365, 2021.
[11] B. Durakovic, 'Design for additive manufacturing: Benefits, trends and challenges', Period. Eng. Nat. Sci. PEN, vol. 6, no. 2, Art. no. 2, 2018.
[12] L. E. J. Thomas-Seale, J. C. Kirkman-Brown, M. M. Attallah, D. M. Espino, and D. E. T. Shepherd, 'The barriers to the progression of additive manufacture: Perspectives from UK industry', Int. J. Prod. Econ., vol. 198, pp. 104–118, 2018.
[13] M. Dotcheva, J. Favrot, K. Dotchev, and J. Zekonyte, 'Planning for Metal Additive Manufacturing', Procedia Manuf., vol. 51, pp. 710–716, 2020.
[14] A. Wiberg, J. Persson, and J. Ölvander, 'Design for additive manufacturing – a review of available design methods and software', Rapid Prototyp. J., vol. 25, no. 6, pp. 1080–1094, 2019.
[15] I. Knežević et al., 'Application of 3D Printed Fixtures for Welding', vol. 22, pp. 15–18, 2019.
[16] V. Monfared, H. R. Bakhsheshi-Rad, S. Ramakrishna, M. Razzaghi, and F. Berto, 'A Brief Review on Additive Manufacturing of Polymeric Composites and Nanocomposites', Micromachines, vol. 12, no. 6, Art. no. 6, 2021.
[17] J. Sun et al., 'A review on additive manufacturing of ceramic matrix composites', J. Mater. Sci. Technol., 2022.
[18] T. Zhang et al., 'In situ design of advanced titanium alloy with concentration modulations by additive manufacturing', Science, vol. 374, no. 6566, pp. 478–482, 2021.
[19] 'ISO/ASTM 52900:2021(en), Additive manufacturing — General principles — Fundamentals and vocabulary'. https://www.iso.org/obp/ui#iso:std:iso-astm:52900:ed-2:v1:en (accessed Sep. 07, 2022).
[20] C. Y. Yap et al., 'Review of selective laser melting: Materials and applications', Appl. Phys. Rev., vol. 2, no. 4, p. 041101, 2015, doi: 10.1063/1.4935926.
[21] A. Khorasani, I. Gibson, J. Kozhuthala Veetil, and A. Ghasemi, 'A review of technological improvements in laser-based powder bed fusion of metal printers', Int. J. Adv. Manuf. Technol., vol. 108, pp. 1–19, 2020.
[22] A. H. Maamoun, Y. F. Xue, M. A. Elbestawi, and S. C. Veldhuis, 'Effect of Selective Laser Melting Process Parameters on the Quality of Al Alloy Parts: Powder Characterization, Density, Surface Roughness, and Dimensional Accuracy', Materials, vol. 11, no. 12, Art. no. 12, 2018.
[23] A. Khorasani, I. Gibson, U. S. Awan, and A. Ghaderi, 'The effect of SLM process parameters on density, hardness, tensile strength and surface quality of Ti-6Al-4V', Addit. Manuf., vol. 25, pp. 176–186, 2019.
[24] W. Shi, J. Li, Y. Jing, Y. Liu, Y. Lin, and Y. Han, 'Combination of Scanning Strategies and Optimization Experiments for Laser Beam Powder Bed Fusion of Ti-6Al-4V Titanium Alloys', Appl. Sci., vol. 12, no. 13, Art. no. 13, 2022.
[25] H. Shipley et al., 'Optimisation of process parameters to address fundamental challenges during selective laser melting of Ti-6Al-4V: A review', Int. J. Mach. Tools Manuf., vol. 128, pp. 1–20, 2018.
[26] G. R. Buican, G. Oancea, C. Lancea, and M. A. Pop, 'Influence of Layer Thickness on Internal Structure of Parts Manufactured from 316-L Steel Using SLM Technology', Appl. Mech. Mater., vol. 809–810, pp. 369–374, 2015.
[27] F. Bartolomeu et al., 'Predicting the output dimensions, porosity and elastic modulus of additive manufactured biomaterial structures targeting orthopedic implants', J. Mech. Behav. Biomed. Mater., vol. 99, pp. 104–117, 2019.
[28] G. Dezső and P. Kósa, 'Dimensional and shape accuracy of cylindrical and paralellepiped-like parts made by selective laser melting technology', vol. XVIII, no. 1, pp. 39–45, 2020.
[29] G. Miranda, S. Faria, F. Bartolomeu, E. Pinto, N. Alves, and F. Silva, 'The Influence of Laser Power and Scan Speed on the Dimensional Accuracy of Ti6Al4V Thin-Walled Parts Manufactured by Selective Laser Melting', Metals, vol. 12, p. 1226, 2022
[30] S. Pal, V. Kokol, N. Gubeljak, M. Hadzistevic, R. Hudak, and I. Drstvensek, 'Dimensional errors in selective laser melting products related to different orientations and processing parameters', Mater. Tehnol., vol. 53, no. 4, pp. 551–558, 2019.
[31] L. Zhang, S. Zhang, H. Zhu, Z. Hu, G. Wang, and X. Zeng, 'Horizontal dimensional accuracy prediction of selective laser melting', Mater. Des., vol. 160, pp. 9–20, 2018.
[32] D. Michal, R. Hrušecký, P. Košťál, and I. Molnár, 'Analysis of Shape and Dimensional Deformation of the Model with a Precision Circular Hole Produced by Digital Light Processing (DLP) Additive Technology', Mater. Sci. Forum, vol. 994, pp. 213–220, 2020.
[33] H. Kato, H. Ueki, K. Yamamoto, and K. Yasunaga, 'Wear Resistance Improvement by Nanostructured Surface Layer Produced by Burnishing', Mater. Sci. Forum, vol. 917, pp. 231–235, 2018

[34] G. D. Revankar, R. Shetty, S. S. Rao, and V. N. Gaitonde, 'Wear resistance enhancement of titanium alloy (Ti–6Al–4V) by ball burnishing process', J. Mater. Res. Technol., vol. 6, no. 1, pp. 13–32, 2017
[35] N. S. Qu, X. L. Fang, Y. D. Zhang, and D. Zhu, 'Enhancement of surface roughness in electrochemical machining of Ti6Al4V by pulsating electrolyte', Int. J. Adv. Manuf. Technol., vol. 69, no. 9–12, Art. no. 9–12, 2013
[36] C. Cosma, N. Balc, M. Moldovan, L. Morovic, P. Gogola, and C. Borzan, 'Post-processing of customized implants made by laser beam melting from pure Titanium', J. Optoelectron. Adv. Mater., vol. 19, pp. 738–747, 2017.
[37] G. Varga, G. Dezső, and F. Szigeti, 'Surface Roughness Improvement by Sliding Friction Burnishing of Parts Produced by Selective Laser Melting of Ti6Al4V Titanium Alloy', Machines, vol. 10, no. 5, Art. no. 5, 2022.
[38] P. Sperling, A. du Plessis, and G. Schwaderer, 'Challenges and Approaches for Metrology of Additive Manufactured Lattice Structures by Industrial X-Ray Computed Tomography', Adv. Mater. Res., vol. 1161, pp. 131–136, 2021.
[39] C. Sen, G. Dursun, A. Orhangul, and G. Akbulut, 'Assessment of Additive Manufacturing Surfaces Using X-ray Computed Tomography', Procedia CIRP, vol. 108, pp. 501–506, 2022
[40] 'Titanium Alloy: Ti-6Al-4V'. http://www.metalspiping.com/titanium-alloy-ti-6al-4v.html (accessed Aug. 15, 2022).
[41] M. Fousová, D. Vojtěch, J. Kubásek, E. Jablonská, and J. Fojt, 'Promising characteristics of gradient porosity Ti-6Al-4V alloy prepared by SLM process', J. Mech. Behav. Biomed. Mater., vol. 69, pp. 368–376, 2017.
[42] S. Liu and Y. C. Shin, 'Additive manufacturing of Ti6Al4V alloy: A review', Mater. Des., vol. 164, p. 107552, 2019.

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