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THE IMPACT OF ULTRASONIC POST-MANUFACTURING ON THE MICROSTRUCTURE OF THE METALLIC SHEET-BASED TRIPLY PERIODIC MINIMAL SURFACES MANUFACTURED BY ELECTRON BEAM MELTING

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ВЛИЯНИЕ УЛЬТРАЗВУКОВОЙ ОБРАБОТКИ НА МИКРОСТРУКТУРУ МЕТАЛЛИЧЕСКИХ ЛИСТОВЫХ ТРИЖДЫ ПЕРИОДИЧЕСКИХ МИНИМАЛЬНЫХ ПОВЕРХНОСТЕЙ, ПОЛУЧЕННЫХ МЕТОДОМ ЭЛЕКТРОННО-ЛУЧЕВОГО ПЛАВЛЕНИЯ

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Аннотация. *В настоящей работе описано влияние ультразвуковой контактной обработки на микроструктуру металлических метаматериалов на основе трижды периодических поверхностей с минимальной энергией типа гироид в форме куба, полученных аддитивным способом.*

Introduction. Triply periodic minimal surfaces (TPMS) are a novel approach of designing porous metamaterials that are promising candidates for biomedical implants. TPMS attract attention due to their zero-mean curvatures at every point, which assists bone tissue ingrowth [1]. Having no sharp geometric changes, they help avoid the creation of obvious stress-concentrating areas. The most promising TPMS structure is a gyroid because it exhibits higher stiffness than other structures, which have the same porosity and manufactured from the same material [2]. The complex shape of the gyroid is impossible to obtain using traditional methods and requires novel methods to be applied, such as additive manufacturing. The material surface properties, unit cell type and size are among the most critical parameters influencing implant-induced osteogenesis. A pore size in a range between 300 and 500 μm was concluded to be optimal for the migration and proliferation of osteoblasts and mesenchymal cells and further vascularization and ingrowth of bone [3]. However, structures with such pore sizes are quite dense and may cause difficulties for further exploitation. A small space in the unit cells reasoned the appearance of trapped powder inside the specimens. Therefore, post-manufacturing treatments were required to delete powder from the structure. To solve this problem an ultrasonic vibration (USV) post-treatment was suggested beyond conventional powder recovery system (PRS). However, it may affect microstructural and mechanical properties. The aim of the current investigation was to evaluate the impact of a dry USV on microstructure and elastic properties of the manufactured gyroids to predict the possible threat of the chosen method. The novelty of the research lies in the application of the non-conventional approach of post-manufacturing method to additively manufactured metamaterials, as well as the combination of design methods of TPMS and electron beam melting (EBM) manufacturing modalities.

Research methods. The shape of the gyroid is described with the following equation:

$$\sin(kx)\cos(ky) + \sin(ky)\cos(kz) + \sin(kz)\cos(kx) = 0 \quad (1)$$

The coefficient *k* was set at 2. A nominal wall thicknesses of 0.4 mm was chosen for the gyroid as it was the minimal achievable thickness of the sheet-based structures produced by EBM. A model with overall size of $15.7 \times 15.7 \times 15.7$ mm^3 was created using Wolfram Mathematica.

Standard parameter settings were applied to produce gyroids from Ti-6Al-4V powder using an ARCAM A2 EBM machine (Mölnlycke, Sweden) by ARCAM EBM with a layer thickness of 50 μm and processing temperature of 720 °C.

Dry USV post-manufacturing method was implemented beyond conventional PRS, which is a standard powder removal technique by Arcam EBM working with an air pressure of 5 bar. Specimens were subjected to PRS cleaning for a fixed time of 5 min. Trapped powder was observed inside the structure after it. Additional 10-15 minutes of PRS did not result in complete powder elimination. Therefore, USV treatment was applied. A USV system is based on the commercial Sonic SwissBoster 35 kHz 1:1.5 Alu equipment. The USV actuator head was mounted to the rigid stand of a commercial table drill with an added reinforcement bottom plate and fixated for the ultrasonic vibration head. The power supply from the commercial USV system allows for adjustment of the vibration power. Cleaning was performed in a single step by gently compressing the flat surfaces of the TPMS samples between the face of the vibrator and the rubber sheet placed over the bottom plate (equivalent force ~5 N). The USV power was set at 75 % of the maximum value and switched on for 15 s.

Electron backscatter diffraction (EBSD) measurements were performed to establish the microstructure changes after the post-processing. A field emission scanning electron microscope Tescan MIRA 3 LMU (TESCAN ORSAY HOLDING, Brno, Czech Republic), equipped with Oxford Instruments Nordlys EBSD detector and Oxford Instruments Ultim Max 40 EDX detector (Oxford Instruments, High Wycombe, UK) was used. Pieces of $8 \times 8 \times 4$ mm^3 were cut from the top part of the gyroids subjected to different post-manufacturing measures. A scanning step size of 1 μm was chosen for the EBSD mapping.

The elastic modulus and compressive strength of the samples after both post-manufacturing methods were established during the quasi-static uniaxial compression tests. The compression tests were performed at room temperature according to ISO 13314:2011 [31,32], using an INSTRON 3369 universal testing machine (Illinois Tool Works, Inc.) with a 50 kN load cell. The displacement of the top anvil was at a constant rate of 0.5 mm/min. The failure strain was set to 50 % stress.

Results. According to the inversed pole figures of the specimens after different post-treatment procedures, a typical Ti-6Al-4V microstructure (known as acicular, lamellar, or Widmanstatten) was observed. No preferred crystallographic orientation was detected. The absence of texture is typical for manufactured EBM-produced specimens from titanium alloys [4]. EBSD analysis of the samples microstructure after PRS and USV treatments revealed that these microstructures contain elongated grains and multidirectional lamellae of the α- and α'- phases with a negligible amount of β phase formed as a result of the high cooling rate of thinner isolated walls, compared with a solid bulk sample [5]. Misorientation diagrams revealed that the specimens possess the same boundary rotation angles. It is known that EBM-manufactured Ti-6Al-4V contains up to 10 % of boundary angles below 15 ° [6], though all boundary angles of the PRS- and USV- treated samples are above 15 °. Typical boundary angles for Ti-6Al-4V (around 60 ° and 90 °) were observed [6]. The presence of high grain misorientation is known to lead to the instability of the microstructure due to the high energy accumulated at the grain boundaries or at the dislocations. The high grain misorientation angles may act as the driving force of recrystallization during the post heat treatments, which are required to obtain homogenized microstructure [6]. Grain (lamellae) size and Aspect Ratio analysis were conducted. Grain size tends to follow the lognormal distribution. The width of lamellae does not surpass 6 μm, while the length of the lamellae can be several times more than width. The USV treated specimens possess lower average grain (lamella) size and higher average Aspect Ratio in comparison with the PRS ones. A part of small lamellae in the USV-treated specimens increased, and thus, it can be concluded that USV led to lamellae refinement. Aspect Ratios of all the specimens are low that indicates to acicular structure.

According to the results of the compression tests, the samples subjected to PRS and USV treatments have identical elastic behavior. Elastic modulus of the gyroids after PRS and USV treatments are about 4.6 and 4.7 MPa, compressive strength for these samples are 268 and 262 MPa, correspondingly. Therefore, no significant degradation of the mechanical properties was detected.

Conclusion. A novel post-treatment method of ultrasonic vibration was implemented for powder removal from dense sheet-based structures manufactured by EBM and compared with the conventional powder recovery system. As it was established using EBSD analysis, after both post-processing treatments the microstructures possess no preferred crystallographic orientation. However, the samples after ultrasound vibration treatment revealed lamellae refinement. The elastic modulus and compressive strength of the specimens subjected to both post-treatments were similar. Therefore, ultrasound vibration treatment can be recommended for sheet-based porous structures, as it does not cause degradation of mechanical properties.

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REFERENCES

1. Zadpoor, A.A. (2014) Bone Tissue Regeneration: The Role of Scaffold Geometry. Biomaterials Science [Electronic version]. no. 3 (2), pp. 231-245.
2. Li, X., Xiao, L., & Song, W. (2021) Compressive Behavior of Selective Laser Melting Printed Gyroid Structures under Dynamic Loading. [Electronic version]. Additive Manufacturing, no. 46, pp. 102054.
3. Wang, Z., Wang, C., Li, C., Qin, Y., Zhong, L., Chen, B., Li, Z., Liu, H., Chang, F., & Wang, J. (2017) Analysis of Factors Influencing Bone Ingrowth into Three-Dimensional Printed Porous Metal Scaffolds: A Review. [Electronic version]. Journal of Alloys and Compounds., no. 717, pp. 271-285.
4. Yamanaka, K., Saito, W., Mori, M., Matsumoto, H., & Chiba, A. (2015) Preparation of Weak-Textured Commercially Pure Titanium by Electron Beam Melting. [Electronic version]. Additive Manufacturing, no. 8, pp. 105-109.
5. Zhang, L.C., Liu, Y., Li, S., & Hao, Y. (2018) Additive Manufacturing of Titanium Alloys by Electron Beam Melting: A Review. [Electronic version]. Advanced Engineering Materials, no. 20 (5), pp. 1-16.
6. Wang, X., & Chou, K. (2018) EBSD Study of Beam Speed Effects on Ti-6Al-4V Alloy by Powder Bed Electron Beam Additive Manufacturing. [Electronic version]. Journal of Alloys and Compounds, no. 748, pp. 236-244.