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TRIPLY PERIODIC MINIMAL SURFACE STRUCTURES MANUFACTURED BY EBM IN DIFFERENT APPROACHES

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ПОЛУЧЕНИЕ ТРИЖДЫ ПЕРИОДИЧЕСКИХ ПОВЕРХНОСТЕЙ С МИНИМАЛЬНОЙ ЭНЕРГИЕЙ РАЗНЫМИ СПОСОБАМИ С ПОМОЩЬЮ МЕТОДА ЭЛП

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Аннотация. *В настоящей работе описано влияние режимов получения металлических метаматериалов на основе трижды периодических поверхностей с минимальной энергией, полученных аддитивным способом. В частности, описано влияние режимов на морфологические и механические свойства метаматериалов.*

Introduction. Porous metamaterials are promising candidates for biomedical implants and light-weight and energy-absorbing structures, which can be based on different types of unit cells [1]. The unit cell type and size as well as the material surface properties are among the most critical parameters influencing implant-induced osteogenesis. The unit cells, based on triply periodic minimal surfaces (TPMSs), have attracted attention due to their zero-mean curvatures at every point, which assists bone tissue ingrowth [2]. 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 with the same porosity and is manufactured from the same material [3]. It possesses more uniform axisymmetric stiffness [4]. The complex shape of the gyroid is impossible to obtain using traditional methods and requires novel methods, such as additive manufacturing.

TPMS can be produced by EBM using different manufacturing parameter sets commonly known as Themes. “Melt” Themes originally designed for manufacturing solid structural elements require a 3D model with predetermined material thickness. The “Wafer” Theme originally designed for manufacturing different support structures uses zero-thickness 3D models [5]. Taking into consideration the complexity of TPMS, the Wafer Theme may become a new key to controlling the specimen porosity and preventing the stress shielding effect.

Our initial assumption was that the specimens based on a 200 μm thick model manufactured using Melt Theme and the specimens based on a zero-thickness model manufactured using Wafer Theme would have identical sheet thickness and identical mechanical properties. This assumption was based on the fact that the beam spot diameter set in the ARCAM A2 machine is commonly 200 μm [5].

We address the relationship between structural performance and manufacturing modality, keeping porosity constant. The novelty of the research lies in the combination of design methods of TPMS and EBM-manufacturing modalities. The aim of the current investigation was to evaluate the worthiness of the Wafer Theme in comparison with the Melt Theme for TPMS structures fabrication from the mechanical point of view.

Research methods. The shape of gyroid structures was modeled using the gyroid equation:

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

The coefficient *k* influences the size of the unit cell. A zero-thickness model was prepared for Wafer Theme, and a model with a thickness of 200 μm was prepared for Melt Theme. The gyroid is presented in Figure 1. The second set of models was produced from the first one by assigning a thickness of 200 μm. The overall limits of the gyroid surfaces were chosen from -5/2 π to 5/2 π in all directions, which allowed us to obtain a total structure size of 15 × 15 × 15 mm^3.

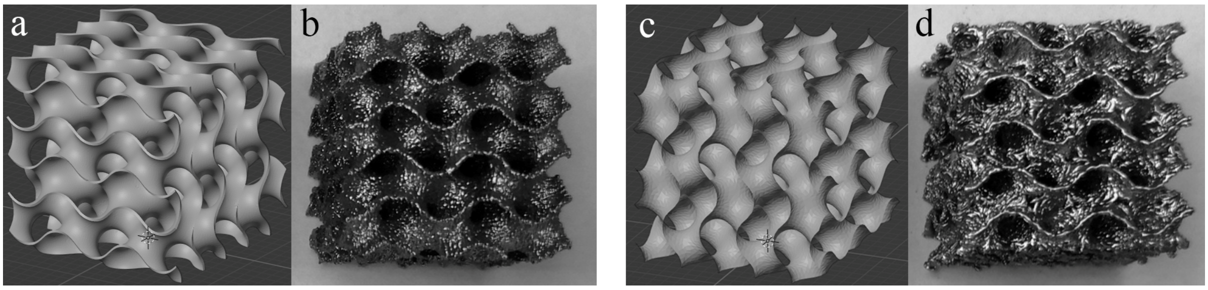

Fig 1. Gyroid models and manufactured specimens: a – 200 μm-thick model, b – a specimen manufactured using in Melt Theme, c – zero-thickness model, d – a specimen manufactured using in Wafer Theme

Gyroid structures were manufactured using an ARCAM A2 EBM machine (Mölnlycke, Sweden) from Ti-6Al-4V powder by ARCAM EBM with standard parameter settings for the chosen material with a layer thickness of 50 μm and processing temperature of 720 °C.

X-ray computed tomography (XCT) was used to evaluate the inner structure, surface roughness, and morphology, to reveal possible defects and calculate the average and maximum wall thickness and porosity of the scaffolds. A CT study was performed using a Sauervein Systemtechnik (RayScan Technologies GmbH) working with an X-ray tube voltage of 135 kV, a current of 70 mA, and a voxel size of 15.5 μm. The data were preprocessed using FiJi ImageJ software. VG Studio Max 3.1 software was used for image analysis and 3D rendering. Quasi-static uniaxial compression and tension tests were undertaken using an INSTRON 3369 universal testing machine (Illinois Tool Works, Inc.) with a 50 kN load cell. Testing of the lattice specimens was conducted according to ISO 13314:2011 [6]. All mechanical tests were performed at room temperature.

Results. Using the XCT data it was established that the average wall thickness for the gyroid manufactured in Wafer Theme is about 0.25, while the same parameter for the gyroid manufactured in Melt Theme is about 0.38 mm. The reason for the difference between the thicknesses of the designed structures and MT manufactured ones lies in additional thickness caused by 2 contours and, probably, wider than expected melt pool. Since the surface of the gyroid is curved, it is impossible to evaluate roughness by traditional methods. It is known that arithmetic roughness (Ra) for vertical struts of the EBM manufactured structures is about 40 μm, while the mean value of the maximum height of the surface profiles of vertical struts (R_t) is 212 μm [5].

Young`s modulus obtained after compression tests for both specimens is about 1.5 GPa, though they have different wall thickness and porosity. Young`s modulus obtained after tension tests for both specimens is about

1.2 GPa. However, yield strength σ_y after compression tests for the specimen manufactured in Melt Theme is about 65 MPa, while for the specimen obtained in Wafer Theme it is only 30 MPa. Yield strength σ_y after tension tests for the specimen manufactured in Melt Theme is about 37 MPa, while for the specimen obtained in Wafer Theme it is only 5 MPa.

The gyroids manufactured in Wafer Theme exhibit through-hole defects in the surface sections perpendicular to the building direction. They supposedly appear in each horizontal saddle point because the areas of the zero-thickness 3D model are not detected by slicing software and, therefore, are not processed by the beam. If it is confirmed, the respective CAD file corrections can be introduced, and WT gyroids with thinner walls could be manufactured with a minimum of through-hole defects.

Conclusion. TPMS gyroid sheet-based structures were for the first time successfully manufactured by EBM using Melt and Wafer Themes. The specimens manufactured using Melt and Wafer Themes have different wall thicknesses. The minimum mean wall thickness, which can be achieved using standard Melt Theme in ARCAM EBM A2 machine, is around 380 µm, while the minimum mean wall thickness with Wafer Theme is 250 µm. Despite the difference in thickness, Young`s moduli are approximately the same for compression (1.5 GPa) and tension (1.2 GPa) tests. Thus, the specimens manufactured in Wafer and Melt Themes behave identically at small strains up to 5 % (in the elastic range). The gyroids manufactured in Wafer Theme exhibit through-hole defects in the surface sections perpendicular to the building direction. The through-holes connect two separate void regions of TPMS, thus, enabling better fluid transport, tissue ingrowth, and differentiation.

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