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Lattice_Karak: Lattice structure generator for tissue engineering, lightweighting and heat exchanger applications

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ABSTRACT

Lattice structures result from biomimicry to create strong and lightweight materials. Triple Periodic Minimal Surface (TPMS) are complex geometry lattices which are highly challenging to design them using computer-aided drafting tools. Lattice_Karak resolves this problem by providing open-source software for generating TPMS. It has all the features for generating and modifying TPMS like density grading, cell size grading, hybridization and hierarchical unit cell. It also exports the generated TPMS into an STL file for further modeling and additive manufacturing. Lattice_Karak can generate scaffolds, heat sinks and porous structures, making it an excellent application for tissue engineering, lightweighting and heat exchanging.

Code metadata

Current code version	*v1.0*
Permanent link to code/repository used for this code version	https://github.com/SoftwareImpacts/SIMPAC-2022-125
Permanent link to reproducible capsule	https://codeocean.com/capsule/5793057/tree/v1
Legal code license	*MIT License*
Code versioning system used	*None*
Software code languages, tools and services used	*MATLAB*
Compilation requirements, operating environments and dependencies	
If available, link to developer documentation/manual	https://github.com/Kamal-k-s/Lattice/blob/main/Usage%20Manual%20for%20Lattice_Karak.pdf
Support email for questions	skamal37@hotmail.com/ 100062570@ku.ac.ae

1. Introduction

The progress of civilization has led to the development of sophisticated materials & structures [1]. Example, Pyramids to the Eiffel tower. Due to this rapid development, the new age structures must perform various functions. Increasing the design space of the product is an exclusive way to incorporate Multifunctionality. The orthodox way of product development includes controlling the product's final shape (dimensions in meters) and material (dimensions in micrometers) [2]. This approach excludes the dimensions between meters and micrometers. These untapped dimensions allow for integrating different functions without changing shape or material. The primary way to explore the untapped dimensions is by introducing lattice structures [3]. Lattice structures allow localized control of functional properties by controlling lattice structures' shape, size and features. Triple Periodic Minimal Surface (TPMS) is a unique kind of lattice structure with applications in aerospace, electrodes for batteries, scaffolds, catalysts, implants, tissue engineering, energy absorption, and lightweighting [4]. With these many applications, it is very much indispensable to have a free and open-source tool for generating TPMS lattice structures.

The complex shape of TPMS makes it a burdensome task to design them using computer-aided tools. Some free software for generating these lattice structures are MS Lattice [5], Minisurf [6] and TPMS Designer [7]; all the software mentioned, i.e. MS Lattice, Minisurf and TPMS Designer, does not have options for generating variable density, cell size grading, hybridization and Hierarchical. Even though MS Lattice can generate TPMS with variable density and cell size grading, but MS Lattice is not open-source software. These features

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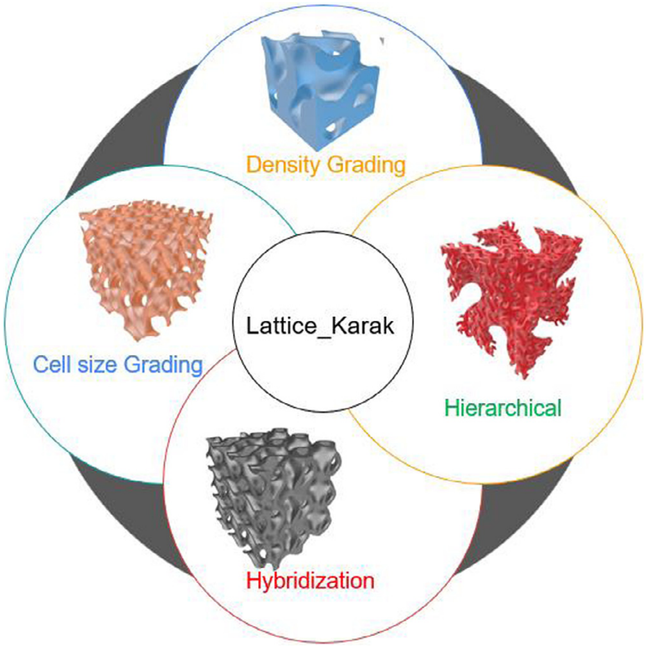

Fig. 1. Functions of Lattice_Karak.

make Lattice_Karak stand out from the rest of the software as it has all the essential features needed to design TPMS and control its topology. Students & Researchers can fully exploit the applications of TPMS when there is open-source availability of codes and Graphical User Interface (GUI)based applications for generating TPMS. Lattice_Karak satisfies all the demands: It is open-source software; it has GUI; it has features to generate density grading, cell size grading, hybridization and hierarchical lattice. The Fig. 1 shows the functions of the application. These features make Lattice_Karak a marvelous application for generating TPMS lattice. Helping students & researchers use the excellent properties offered by the TPMS.

2. Description & features

Lattice_Karak runs on MATLAB® compiler; it is also a standalone application, running without the user installing MATLAB®. GUI and features of the Lattice_Karak were created after brainstorming the needs of students & researchers so that it helps them to innovate and use it to the maximum extent possible. Being open-source allows them to change the codes as per their wish. The GUI was created in such a way that it is self-explanatory for the user to use it. The Fig. 2 Shows the user interface (UI) of the application.

The app's functionality includes variable density, cell size grading, hybridization and hierarchy. Lattice_Karak can control the number of cells in each direction, density control and the type of arrangement of structures (sheet/ skeletal). There are 12 inbuilt TPMS structures available. The visualization of TPMS takes up to 60% of the window. The generated structure can be made into an STL file for further processing and manufacturing using the export option available in the application. The Simple tab allows for creating a simple TPMS lattice; the TPMS lattice's density can be controlled by a level set knob in the UI. The cell parameters of TPMS are controlled by inputting the desired number of cells in the cell parameters section. The required TPMS lattice can be selected from the drop-down menu. The switch knob can choose the type of network (Sheet/ Skeletal). Pressing the plot button generates the TPMS lattice. The generated lattice can be exported into STL by pressing the export button (see Figs. 2 and 3).

The Key aspect of the TPMS is that it is highly found in nature [8], for example, butterfly wings [9], sea urchins [10], the exoskeleton of weevils [11] and biological membranes [12]. To imitate the TPMS found in nature and to satisfy the needs of the various structural properties [13] has led to the design of variable density [14], cell size grading [15], Hybridization [16], Hierarchical [17] and TPMS with complex external shapes [18]. The Variable density, Cell size grading, Hybridization and Hierarchical help in achieving the geometry control of TPMS; the geometry of TPMS has a predominant effect on various structural properties [13]. It is evident that for the complete application of the TPMS structure in various disciplines and applications [19–22], the software which generates TPMS must include features to create TPMS with Variable density, Cell size grading, Hybridization and Hierarchical; Lattice_Karak fits into the criteria.

A dedicated Tab is provided for each design criteria. The variable density tab allows for generating TPMS with varying densities along a particular direction. The Cell size grading tab allows for the varying porosity of TPMS without changing the density of the TPMS. The hybridization tabs allow the creation of a new TPMS with two different TPMS lattices. The. The hierarchy tabs allow for generating hierarchical TPMS lattice. Hybridization & Hierarchy options are only available in Lattice_Karak These features help create multifunctional lattice as per the requirements.

The TPMS is developed using the implicit method. The implicit method uses a single-valued function of three variables. The surface is the locus of points for which the function has some constant value. A zero-valued surface, known as a zero set or level set, represents the space's interface regions lying on, inside, and outside the space [23]. Example Schwarz Primitive TPMS can be generated by Eq. (1).

$$\varnothing_P \equiv \cos \alpha x + \cos \beta y + \cos \gamma z = c \tag{1}$$

Here α, β, and γ are the parameters that can control the unit cell size in the x, y, and z directions. The level set constant, i.e. C, can be changed to get the relative density of the structures. When c= 0, the resulting surface divides the space into sub-domains of equal volume. The volume of these subdomains is modified to get sheet-based structures ($c \leq \varnothing \geq c$) or skeletal-based structures ($\varnothing < c$ or $\varnothing > c$) [24]. All the features like Variable density, Cell size grading, Hybridization and Hierarchical are obtained by controlling the implicit function and level set constant.

3. Impact overview

Due to the vast applications of TPMS [25], the generation of lattice structures for various applications is a highly researched topic. Many commercial softwares like nTop (nToplogy), Sulis (Gen 3d), Grasshopper (Rhino 3D), Simpleware (Synopsys), Optistruct (Altair) and Creo Parametric (PTC), are being used to generate lattice structures. This highly expensive software prevents students & researchers from creating lattice structures. Lattice_Karak gives an open-source way to create these structures.

Lattice_Karak allows users to generate various types of TPMS lattices. Many researchers are working on the understanding mechanical behavior of the TPMS lattice [26–30]. This software allows the effortless generation of these lattices effectively as per the requirements. Finite Element Analysis is can be implemented on the output obtained by the Lattice_Karak (I.e. STL file). This analysis allows for a better understanding of lattice structures.

Due to the high surface area, TPMS are excellent to use as a scaffold. The pore connectivity is 100% in TPMS, which allows for better cell attachment, proliferation and differentiation [31]. The mechanical properties of the scaffold can be adjusted by varying the structure of TPMS to match the mechanical property of tissue at the site of implantation [1]. TPMS can easily be processed to form a variety of shapes and sizes. These all features make TPMS an excellent structure to use as a scaffold for tissue engineering applications [32–34]. Lattice_Karak allows the researchers to generate a TPMS lattice scaffold for tissue engineering.

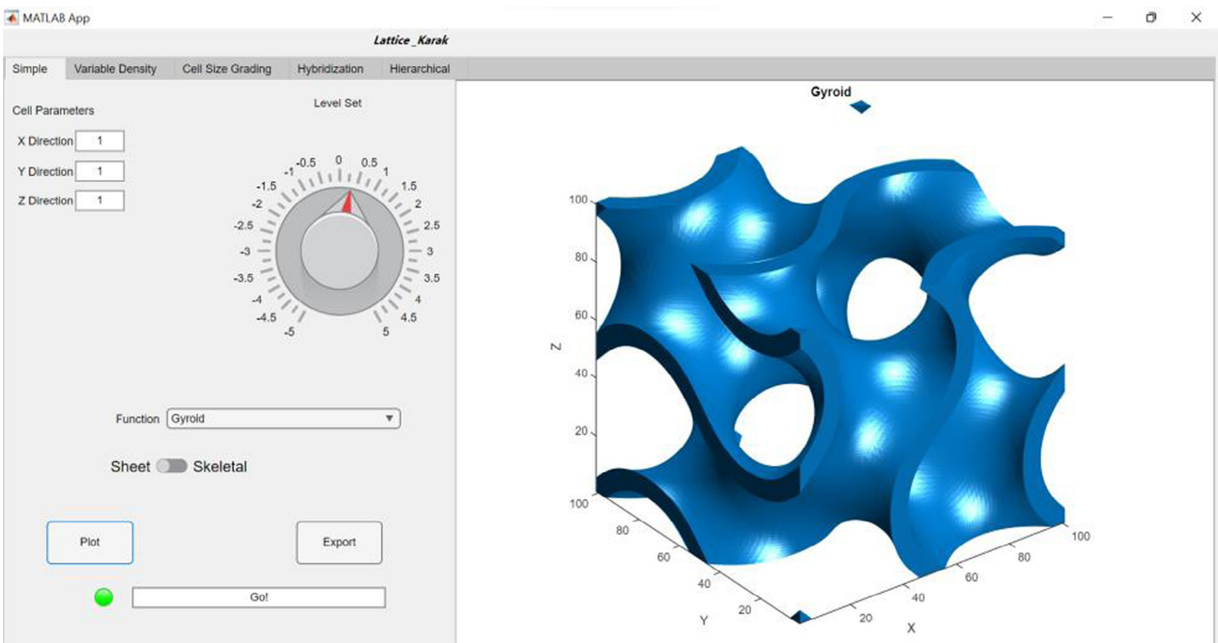

Fig. 2. UI of Lattice_Karak.

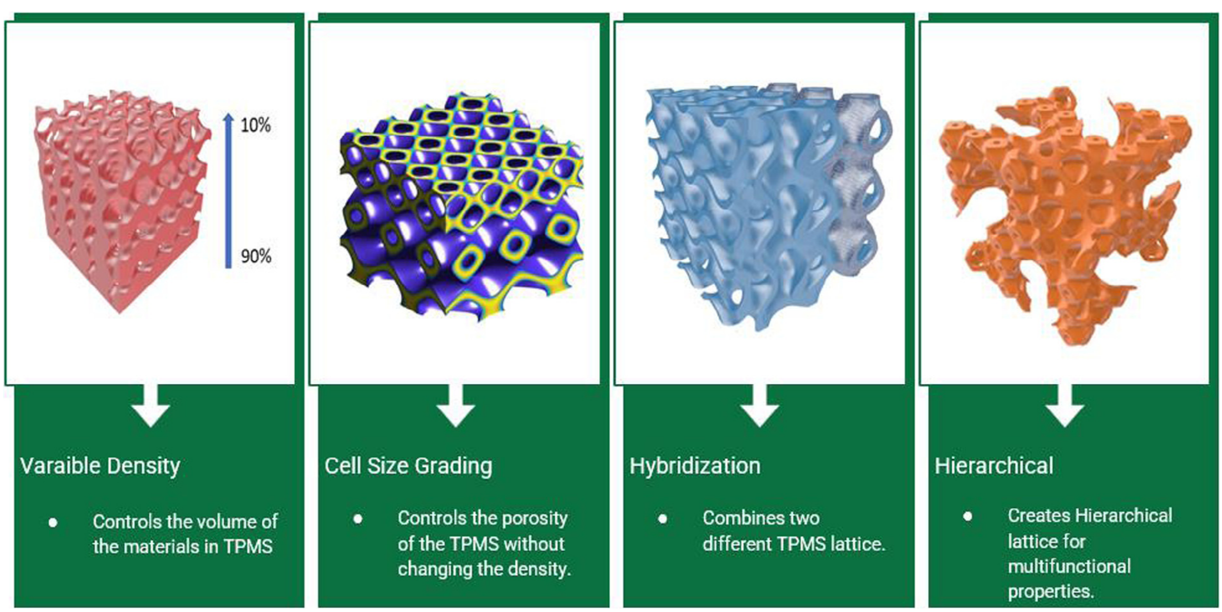

Fig. 3. Features of Lattice_Karak.

The Scaffolds for tissue engineering designed in the papers such as [24], [35–43] can be designed using Lattice_Karak. Lattice_Karak will also provide more features in developing scaffolds due to its features like Hybridization and Cell size grading.

The advent of high computing power requires sophisticated methods to remove heat so that electronics do not get damaged [44]. TPMS can act as an excellent heat sink due to its high surface area, especially the hierarchical TPMS can be used due to more surface area [45–47]. Lattice_Karak can quickly generate hierarchical TPMS lattice. Lattice_Karak allows the creation of the state of the art heatsinks. The Heatsinks and Heat Exchangers developed in the papers such as [48–51] can be generated using Lattice_Karak.

Lattice_Karak was used to develop energy absorption structures in our lab. Lattice_Karak was also used to generate lattice structures for lightweight applications, and we manufacture them using additive manufacturing equipment in our lab. The output file of Lattice_Karak is an STL file, a defacto input format for additive manufacturing [52].

Lattice_Karak will have a significant influence on multidisciplinary studies. Due to the multidisciplinary properties of TPMS [25].

4. Limitations

Lattice_Karak cannot fill an object with a TPMS lattice inside it.
Lattice_Karak cannot create a closed heat exchanger.

5. Conclusions and future improvements

This paper gives an open-source software for generating TPMS lattice structures. It has all the functions and capabilities for generating functionally graded TPMS. The software helps students & researchers to use TPMS in various applications without spending a great extent of time generating TPMS. The user-friendly GUI helps easy usage of Lattice_Karak even for the person unfamiliar with the design of TPMS. Lattice_Karak is all in one solution for generating TPMS lattice for applications like aerospace, catalysts, implants, tissue engineering, energy absorption, and lightweighting.

In future, the software will be updated to fill an entire complex object with a TPMS lattice. Even a feature for including the Finite element analysis will be added to the software so that Lattice_Karak will be a complete package for generating lattice structures and performing computational experiments.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.simpa.2022.100425.

References

[1] T.A. Schaedler, W.B. Carter, Architected cellular materials, Annu. Rev. Mater. Res. 46 (1) (2016) 187–210, http://dx.doi.org/10.1146/annurev-matsci-070115-031624.
[2] Materials Selection in Mechanical Design, Elsevier, 2011.
[3] J. Mueller, J.R. Raney, K. Shea, J.A. Lewis, Architected lattices with high stiffness and toughness via multicore–shell 3D printing, Adv. Mater. 30 (12) (2018) 1705001, http://dx.doi.org/10.1002/adma.201705001.
[4] O. Al-Ketan, R.K. Abu Al-Rub, Multifunctional mechanical metamaterials based on triply periodic minimal surface lattices, Adv. Eng. Mater. 21 (10) (2019) http://dx.doi.org/10.1002/adem.201900524.
[5] O. Al-Ketan, R.K. Abu Al-Rub, Mslattice: A free software for generating uniform and graded lattices based on triply periodic minimal surfaces, Mater. Des. Process. Commun. 3 (6) (2021) 0–3, http://dx.doi.org/10.1002/mdp2.205.
[6] M.T. Hsieh, L. Valdevit, Minisurf – a minimal surface generator for finite element modeling and additive manufacturing[formula presented], Softw. Impacts 6 (July) (2020) 100026, http://dx.doi.org/10.1016/j.simpa.2020.100026.
[7] A. Jones, M. Leary, S. Bateman, M. Easton, TPMS designer: A tool for generating and analyzing triply periodic minimal surfaces, Softw. Impacts 10 (2021) 100167, http://dx.doi.org/10.1016/j.simpa.2021.100167.
[8] L. Han, S. Che, An overview of materials with triply periodic minimal surfaces and related geometry: From biological structures to self-assembled systems, Adv. Mater. 30 (17) (2018) 1705708, http://dx.doi.org/10.1002/adma.201705708.
[9] V. Saranathan, et al., Structure, function, and self-assembly of single network gyroid (I4 132) photonic crystals in butterfly wing scales, Proc. Natl. Acad. Sci. USA 107 (26) (2010) 11676–11681, http://dx.doi.org/10.1073/pnas.0909616107.
[10] H.-U. Nissen, Crystal orientation and plate structure in echinoid skeletal units, Science (80-.). 166 (3909) (1969) 1150–1152, http://dx.doi.org/10.1126/science.166.3909.1150.
[11] A.E. Seago, P. Brady, J.-P. Vigneron, T.D. Schultz, Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles (Coleoptera), J. R. Soc. Interface 6 (suppl_2) (2009) http://dx.doi.org/10.1098/rsif.2008.0354.focus.
[12] Z. Almsherqi, F. Margadant, Y. Deng, A look through 'lens' cubic mitochondria, Interface Focus 2 (5) (2012) 539–545, http://dx.doi.org/10.1098/rsfs.2011.0120.
[13] J. Feng, J. Fu, X. Yao, Y. He, Triply periodic minimal surface (TPMS) porous structures: From multi-scale design, precise additive manufacturing to multidisciplinary applications, Int. J. Extrem. Manuf. 4 (2) (2022) http://dx.doi.org/10.1088/2631-7990/ac5be6.
[14] X. Zhou, Y. Jin, J. Du, Functionally graded scaffolds with programmable pore size distribution based on triply periodic minimal surface fabricated by selective laser melting, Mater. (Basel). 13 (21) (2020) 5046, http://dx.doi.org/10.3390/ma13215046.
[15] N. Yang, Y. Tian, D. Zhang, Novel real function based method to construct heterogeneous porous scaffolds and additive manufacturing for use in medical engineering, Med. Eng. Phys. 37 (11) (2015) 1037–1046, http://dx.doi.org/10.1016/j.medengphy.2015.08.006.
[16] D.-J. Yoo, Heterogeneous porous scaffold design for tissue engineering using triply periodic minimal surfaces, Int. J. Precis. Eng. Manuf. 13 (4) (2012) 527–537, http://dx.doi.org/10.1007/s12541-012-0068-5.
[17] D. Yoo, New paradigms in hierarchical porous scaffold design for tissue engineering, Mater. Sci. Eng. C 33 (3) (2013) 1759–1772, http://dx.doi.org/10.1016/j.msec.2012.12.092.
[18] J. Feng, J. Fu, C. Shang, Z. Lin, B. Li, Porous scaffold design by solid T-splines and triply periodic minimal surfaces, Comput. Methods Appl. Mech. Engrg. 336 (2018) 333–352, http://dx.doi.org/10.1016/j.cma.2018.03.007.
[19] A.A. Zadpoor, Mechanical performance of additively manufactured meta-biomaterials, Acta Biomater. 85 (2019) 41–59, http://dx.doi.org/10.1016/j.actbio.2018.12.038.
[20] L. Yuan, S. Ding, C. Wen, Additive manufacturing technology for porous metal implant applications and triple minimal surface structures: A review, Bioact. Mater. 4 (1) (2019) 56–70, http://dx.doi.org/10.1016/j.bioactmat.2018.12.003.
[21] D. Mahmoud, M.A. Elbestawi, Lattice structures and functionally graded materials applications in additive manufacturing of orthopedic implants: A review, J. Manuf. Mater. Process. 1 (2) (2017) 1–19, http://dx.doi.org/10.3390/jmmp1020013.
[22] D. Sharma, S.S. Hiremath, Additively manufactured mechanical metamaterials based on triply periodic minimal surfaces: Performance, challenges, and application, Mech. Adv. Mater. Struct. (2021) 1–31, http://dx.doi.org/10.1080/15376494.2021.1948151.
[23] O. Al-Ketan, R.K. Abu Al-Rub, Multifunctional mechanical metamaterials based on triply periodic minimal surface lattices, Adv. Eng. Mater. 21 (10) (2019) 1900524, http://dx.doi.org/10.1002/adem.201900524.
[24] F. Liu, Z. Mao, P. Zhang, D.Z. Zhang, J. Jiang, Z. Ma, Functionally graded porous scaffolds in multiple patterns: New design method, physical and mechanical properties, Mater. Des. 160 (2018) 849–860, http://dx.doi.org/10.1016/j.matdes.2018.09.053.
[25] J. Feng, J. Fu, X. Yao, Y. He, Triply periodic minimal surface (TPMS) porous structures: from multi-scale design, precise additive manufacturing to multidisciplinary applications, Int. J. Extrem. Manuf. 4 (2) (2022) 022001, http://dx.doi.org/10.1088/2631-7990/ac5be6.
[26] C. Crook others, Plate-nanolattices at the theoretical limit of stiffness and strength, Nature Commun. 11 (1) (2020) 1–11, http://dx.doi.org/10.1038/s41467-020-15434-2.
[27] Z. Wang, X. Wang, T. Gao, C. Shi, Mechanical behavior and deformation mechanism of triply periodic minimal surface sheet under compressive loading, Mech. Adv. Mater. Struct. 28 (19) (2021) 2057–2069, http://dx.doi.org/10.1080/15376494.2020.1829756.
[28] X. Fan, et al., Design, mechanical properties and energy absorption capability of graded-thickness triply periodic minimal surface structures fabricated by selective laser melting, Int. J. Mech. Sci. 204 (2021) 106586, http://dx.doi.org/10.1016/j.ijmecsci.2021.106586.
[29] Y. Lu, W. Zhao, Z. Cui, H. Zhu, C. Wu, The anisotropic elastic behavior of the widely-used triply-periodic minimal surface based scaffolds, J. Mech. Behav. Biomed. Mater. 99 (2019) 56–65, http://dx.doi.org/10.1016/j.jmbbm.2019.07.012.
[30] K. Krishnan, D.-W. Lee, M. Al Teneji, R.K. Abu Al-Rub, Effective stiffness, strength, buckling and anisotropy of foams based on nine unique triple periodic minimal surfaces, Int. J. Solids Struct. 238 (2022) 111418, http://dx.doi.org/10.1016/j.ijsolstr.2021.111418.
[31] B. Chan, K.W. Leong, Scaffolding in tissue engineering: general approaches and tissue-specific considerations, Eur. Spine J. 17 Suppl 4 (Suppl 4) (2008) 467–479, http://dx.doi.org/10.1007/s00586-008-0745-3.
[32] E.H. Khogalia, H.L. Choo, W.H. Yap, Performance of triply periodic minimal surface lattice structures under compressive loading for tissue engineering applications, 2020, 020012, http://dx.doi.org/10.1063/5.0001631.
[33] D.-J. Yoo, Computer-aided porous scaffold design for tissue engineering using triply periodic minimal surfaces, Int. J. Precis. Eng. Manuf. 12 (1) (2011) 61–71, http://dx.doi.org/10.1007/s12541-011-0008-9.
[34] J. Shi, J. Yang, L. Zhu, L. Li, Z. Li, X. Wang, A porous scaffold design method for bone tissue engineering using triply periodic minimal surfaces, IEEE Access 6 (2018) 1015–1022, http://dx.doi.org/10.1109/ACCESS.2017.2777521.
[35] A. Yánez, A. Cuadrado, O. Martel, H. Afonso, D. Monopoli, Gyroid porous titanium structures: A versatile solution to be used as scaffolds in bone defect reconstruction, Mater. Des. 140 (2018) 21–29, http://dx.doi.org/10.1016/j.matdes.2017.11.050.
[36] International Organization for Standardization, ISO 13314:2011 mechanical testing of metals – ductility testing – compression test for porous and cellular metals (ISO Standard No. 13314:2011(E)), Int. Organ. Stand. (1) (2011) 1–7, [Online]. Available: www.iso.org.
[37] H. Montazerian, E. Davoodi, M. Asadi-Eydivand, J. Kadkhodapour, M. Solati-Hashjin, Porous scaffold internal architecture design based on minimal surfaces: A compromise between permeability and elastic properties, Mater. Des. 126 (January) (2017) 98–114, http://dx.doi.org/10.1016/j.matdes.2017.04.009.
[38] X. Wang, et al., Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review, Biomaterials 83 (2016) 127–141, http://dx.doi.org/10.1016/j.biomaterials.2016.01.012.

[39] C.K. Chua, K.F. Leong, C.M. Cheah, S.W. Chua, Development of a tissue engineering scaffold structure library for rapid prototyping, part 2: Parametric library and assembly program, Int. J. Adv. Manuf. Technol. 21 (4) (2003) 302–312, http://dx.doi.org/10.1007/s001700300035.

[40] L. Germain, C.A. Fuentes, A.W. van Vuure, A. des Rieux, C. Dupont-Gillain, 3D-printed biodegradable gyroid scaffolds for tissue engineering applications, Mater. Des. 151 (2018) 113–122, http://dx.doi.org/10.1016/j.matdes.2018.04.037.

[41] B. Zhang, et al., The biomimetic design and 3D printing of customized mechanical properties porous Ti6Al4V scaffold for load-bearing bone reconstruction, Mater. Des. 152 (2018) 30–39, http://dx.doi.org/10.1016/j.matdes.2018.04.065.

[42] C. Yan, L. Hao, A. Hussein, P. Young, Ti-6Al-4V triply periodic minimal surface structures for bone implants fabricated via selective laser melting, J. Mech. Behav. Biomed. Mater. 51 (2015) 61–73, http://dx.doi.org/10.1016/j.jmbbm.2015.06.024.

[43] F.S.L. Bobbert, et al., Additively manufactured metallic porous biomaterials based on minimal surfaces: A unique combination of topological, mechanical, and mass transport properties, Acta Biomater. 53 (2017) 572–584, http://dx.doi.org/10.1016/j.actbio.2017.02.024.

[44] H.E. Ahmed, B.H. Salman, A.S. Kherbeet, M.I. Ahmed, Optimization of thermal design of heat sinks: A review, Int. J. Heat Mass Transfer 118 (2018) 129–153, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.10.099.

[45] D.W. Abueidda, A.S. Dalaq, R.K. Abu Al-Rub, I. Jasiuk, Micromechanical finite element predictions of a reduced coefficient of thermal expansion for 3D periodic architectured interpenetrating phase composites, Compos. Struct. 133 (2015) 85–97, http://dx.doi.org/10.1016/j.compstruct.2015.06.082.

[46] R. Attarzadeh, M. Rovira, C. Duwig, Design analysis of the 'Schwartz D' based heat exchanger: A numerical study, Int. J. Heat Mass Transfer 177 (2021) 121415, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2021.121415.

[47] D.A. Clarke, F. Dolamore, C.J. Fee, P. Galvosas, D.J. Holland, Investigation of flow through triply periodic minimal surface-structured porous media using MRI and CFD, Chem. Eng. Sci. 231 (2021) 116264, http://dx.doi.org/10.1016/j.ces.2020.116264.

[48] D. Shamvedi, O.J. McCarthy, E. O'Donoghue, C. Danilenkoff, P. O'Leary, R. Raghavendra, 3D metal printed heat sinks with longitudinally varying lattice structure sizes using direct metal laser sintering, Virtual Phys. Prototyp. 13 (4) (2018) 301–310, http://dx.doi.org/10.1080/17452759.2018.1479528.

[49] O. Al-Ketan, M. Ali, M. Khalil, R. Rowshan, K.A. Khan, R.K. Abu Al-Rub, Forced convection computational fluid dynamics analysis of architected and three-dimensional printable heat sinks based on triply periodic minimal surfaces, J. Therm. Sci. Eng. Appl. 13 (2) (2021) http://dx.doi.org/10.1115/1.4047385.

[50] W. Li, G. Yu, Z. Yu, Bioinspired heat exchangers based on triply periodic minimal surfaces for supercritical CO2 cycles, Appl. Therm. Eng. 179 (2020) 115686, http://dx.doi.org/10.1016/j.applthermaleng.2020.115686.

[51] J. Iyer, T. Moore, D. Nguyen, P. Roy, J. Stolaroff, Heat transfer and pressure drop characteristics of heat exchangers based on triply periodic minimal and periodic nodal surfaces, Appl. Therm. Eng. 209 (2022) 118192, http://dx.doi.org/10.1016/j.applthermaleng.2022.118192.

[52] I. Gibson, D. Rosen, B. Stucker, Additive Manufacturing Technologies, Springer New York, New York, NY, 2015.