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Design of bio-inspired irregular porous structure applied to intelligent mobility products

Diseño bio-inspirado de una estructura porosa e irregular aplicada a productos de movilidad inteligente

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ABSTRACT

Material structure is a crucial part of the design of any product where the intention is to dissipate loads and lighten material. Because some structures today are increasingly complex in geometry and internal structure, it becomes impossible to opt for traditional methods to manufacture them. In this sense, additive manufacturing enables the creation of complex structures with intricate geometries. As manufacturers seek to optimize material properties and performance in a variety of stress conditions, bio-inspired engineering looks at nature for solving the most complex human challenges. By imitating nature's patterns and shapes, we can optimize fracture resistance, energy absorption, and toughness in materials. In this work, we employ voronoi tessellation patterns and computer-aided design software to design an algorithm for the creation of irregular porous structures, similar to those found in nature (e.g., trabecular bone). This algorithm is scalable and applicable to any product that needs to comply with lightweight requirements and outstanding mechanical properties. Herein, the authors perform static compression tests to determine mechanical properties. The results indicated that the mechanical properties depend directly on the microstructural characteristics of the porous structure itself. Besides, surface area and porosity are the principal parameters to be controlled. Finally, the algorithm has a wide range of engineering applications in the automotive and aerospace industries.

Keywords: Biomimetic design, Porous structure, Tissue engineering, Additive manufacturing, Voronoi.

RESUMEN

La estructura de los materiales es una parte crucial del diseño de cualquier producto en el que se pretenda disipar las cargas y aligerar el material. Dado que algunas estructuras actuales son cada vez más complejas en cuanto a geometría y estructura interna, resulta imposible optar por los métodos tradicionales para fabricarlas. En este sentido, la fabricación aditiva permite crear estructuras complejas con geometrías intrincadas. Mientras los fabricantes buscan optimizar las propiedades de los materiales y su rendimiento en diversas condiciones de estrés, la ingeniería bioinspirada se fija en la naturaleza para resolver los retos más complejos del ser humano. Al imitar los patrones y las formas de la naturaleza, podemos optimizar la resistencia a la fractura, la absorción de energía y la tenacidad de los materiales. En este trabajo, empleamos patrones de teselación de Voronoi y software de diseño asistido por ordenador para diseñar un algoritmo para la creación de estructuras porosas irregulares, similares a las que se encuentran en la naturaleza (por ejemplo, el hueso trabecular). Este algoritmo es escalable y aplicable a cualquier producto que necesite cumplir con requisitos de ligereza y propiedades mecánicas sobresalientes. En este caso, los autores realizan ensayos de compresión estática para determinar las propiedades mecánicas. Los resultados indican que las propiedades mecánicas dependen directamente de las características microestructurales de la propia estructura porosa. Además, el área superficial y la porosidad son los principales parámetros a controlar. Por último, el algoritmo tiene una amplia gama de aplicaciones de ingeniería en las industrias de la automoción y aeroespacial.

Palabras claves: Diseño biomimético, Estructura porosa, Ingeniería de tejidos, Manufactura aditiva, Voronoi.

1. INTRODUCCIÓN

Bio-inspired engineering is an approach that imitates or reproduces nature's physical properties. Structures today are increasingly intricate and hard to manufacture. The integration of computational design and digital manufacturing process allows additive manufacturing to create macro-scale mechanical properties of objects that are directly influenced by the geometry of the microstructures, providing architects, engineers, and designers, practical use in structural engineering (Nguyen, 2019; Nguyen et al., 2019). Furthermore, structures are a crucial part of the design of any product where the intention is to dissipate loads and lighten material. Hence, they are a suitable option for efficiency and optimization in product design, both in materials and functionality. However, when difficulties related to fracture, resistance, dispersion of loads, and flexibility still exist, the exploration for new alternatives can be found in nature, where the answer will rely on bio-inspired engineering, where biomimicry can be applied (Benyus, 1997; O'Keefe and Mao, 2011; Gómez et al., 2016).

Initially, the process of designing and manufacturing structures using bio-inspired engineering is not a simple task. As a result, the design process uses CAD software (Liebschner, 2012) to enable the modeling of irregular shape geometries (nature patterns) by chaotic 3D configuration. Similarly, in the application of products, porous structures are created (Chua et al., 2003; Hutmacher, Sittinger and Risbud, 2004; Sun et al., 2004; Liebschner, 2012; Depriester and Kubler, 2019).

In this sense, this work shows a combination of biomimetic applications and CAD software, and a combination of different shapes to arrive at a final design employing voronoi tessellation pattern (Fantini, Curto and De Crescenzio, 2016; Fantini and Curto, 2018; Lee et al., 2018; Wang et al., 2018; Liang et al., 2019). However, even if information about specifications and modeling methods exists, it is difficult to control the diameter of the strut and the voronoi structure itself. As a result, the connections between the parameters of the design, which are: porosity and pore size distribution, and the mechanical properties are not clear. Besides that, the interconnected porosity and pore distribution both play a significant role in the dispersion of structural loads. Additionally, it is possible to find inspiration in natural configurations such as femur bone, honeycomb, spider web (as the organization of irregular areas), citrus lime (husk), and basketball sponge.

Subsequently, the morphology of these porous structures divides into regular and irregular, respectively. Then, the design method of the first category is the cellular unit, the methodology (Guarino et al., 2012; Liu et al., 2015), and the above periodic surface method is shown in triplicate (Gorgin Karaji et al., 2017). Also, this kind of structure has a regular pore morphology, which enables connectivity and provides controllable mechanical properties; this results in an extensive application within the field (Wang et al., 2016). On the other hand, irregular porous structures are implemented by computer programs and mathematical models (Mullen et al., 2009; Kou and Tan, 2010; Yan et al., 2013; Yang, Gao and Zhou, 2015; Gómez et al., 2016; Yang et al., 2019). This kind of structure allows geometries to be precisely designed or gradually distributed. In terms of other structure applications of chaotic configuration, the use of the Schwarz "W" models of trabecular bone prostheses made by Schoen and Gyroid is an option and the most common (Sun and Lal, 2002; Sogutlu and Koc, 2007; Kapfer et al., 2011). Furthermore, irregular structures can simulate complex or chaotic figures; this provides increased freedom within an organic design or bio-inspired design in topological optimization (Huo et al., 2021). Besides, the design approach for an irregular porous structure is another significant technology (Wang et al., 2018).

This research work aims to design an irregular porous structure using an algorithm that generates microstructures and applies them to a conventional product, whose composition has repercussions on natural geometries and patterns. Likewise, airless tires are the near future of vehicles. International companies have launched their proposals intending to mitigate the production, distribution, and maintenance times of conventional tires, but until now, they have only been prototypes. Moreover, the technology to manufacture the irregularly shaped structures, where there are interconnections of nodes and connectors, leaving a porous surface, is through additive manufacturing

2. METHODOLOGY

Generally, parametric modeling platforms and controlled volume simulations enable the design of 3D structures such as the Rhinoceros platform with the GrasshopperTM complement; for parametric modeling without restrictions. With the visual programming module and the use of random volume tools, it is possible to reorient the geometries in the form of points called seeds, sites, or generators. Further, each generator will have a corresponding region with all the closer points. Finally, this resulting region will be known as a Voronoi cell (Okabe et al., 2000).

Since its introduction, Voronoi diagrams have provided a high degree of efficiency for the emulation of bio-inspired type patterns on a large scale. Its characterization starts from the modeling of lines, points, and polygons of primitive origin. Then, large-scale primitive polygons build on lower-dimensional primitives. Also, in a 2D diagram, the Voronoi cells are separated from each other by line segments. Subsequently, it is possible to affirm that Voronoi cells consist of a convex polygon with no holes.

The modeling process starts from a finite Euclidean space with a certain number (n) of points (with n>1) called seeds. Around each seed, a circumference with an initial radius of 0 with an expansive property is reconstructed. As a consequence, a limiting line (border) is constructed when two circles have contact. Expansive circumferences will be chosen until their extension is a linear edge as shown in Fig. 1, the resulting graph would be the Voronoi diagram. Moreover, the composite diagram is equivalent to the contact areas of each point with its closest seed to the zone. Compared to the points that can be controlled as chess pieces on a Cartesian plane, the Voronoi diagram seeds are characterized by randomness. The mathematical equation (1) of the grouping V(pi) can be expressed in the following way (Okabe and Suzuki, 1997):

$$V(pi) = p/d(p, pi)d(p, pj);\ j = i;\ j = 1, \ldots;\ n \quad (1)$$

Where:
pi,…pn is a set of distinct seeds located in Rd;
d (p, pi) represents the Euclidean distance between location (p) and seed (pi).
V (pi) represents the ordinary Voronoi polygon associated with seed pi.

Therefore, the design procedure began with the identification of structural models. Initially, a volume of 23 mm3 and an allocation of points in the Euclidean plane were chosen as the nominal value. In this case, each (pk) site is simply a point, and its corresponding Voronoi (Rk). Each cell is obtained from the intersection of half-spaces, also referred to as convex polygons. In this method, the segments of the Voronoi diagram are equivalent to a point equidistant to two or more nearby sites and to the internal assignment of a specific distribution of points from which irregular polyhedral unit cells are obtained.

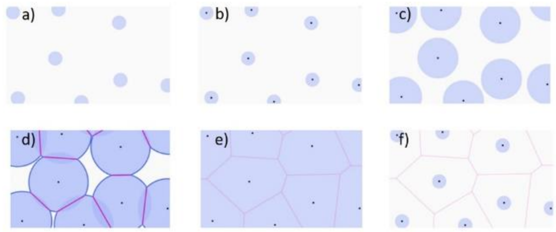


Figure 1. Design principle of porous scaffold (a) Regular lattice design, (b) Irregular lattice design (c) Voronoi cells obtained from an irregular lattice. (d) Construction of porous structures).

Similarly, to construct irregular and porous structures, some structural design parameters are used, such as the strut diameter (D), the distance unit (d), irregularity (I). The number of points used by GrasshopperTM is distributed randomly over the nominal volume of the sample created; this is known as the closed environment. The platform identifies the geometric location or spatial coordinates of each of these points. Subsequently, the pk points generate intersections on other pk equidistant perpetuating nodes. The final 3D point configuration was done with the software Rhinoceros3D© (Robert McNeill and Associated, v.6.0). Once the 3D cells are interconnected by their planes x, y, z of all points as shown in Fig. 2a-b, they are processed to produce independent sample models, this gives growth to the 3D voronoi structure as shown in Fig, 2c. Meanwhile, the three-dimensional properties are subjected to the equidistance of each pk point. An explosion of components occurs to derive the individual physical properties of the faces. The three-dimensional voronoi cell is composed of trabeculae (nodes or vertices that intersect corners forming faces). The reticular unit is evaluated with the properties of porosity, defining porosity (P) as the difference of vacuum of a body and trabecular thickness (eT), defining trabecular thickness as the quantity of volume of a node.

Therefore, by modifying the difference ((P) > (eT), it can be transferred to a module with a higher flexibility index or with return memory. Otherwise, a (P) < (eT) provides a structure with greater mechanical strength. The P-value can be modified by increasing or decreasing the amount of (pk). Further, Fig. 2d shows a close-up view of the porous structure.

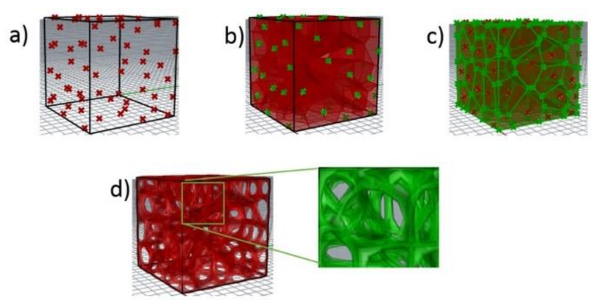


Figure 2. The design principle of porous scaffold. (a) Regular lattice design. (b) Irregular lattice design. (c) Voronoi cells obtained from an irregular lattice. (d) Construction of porous structures).

In the voronoi 3D cell, the boundaries between the lattice structures consist of planes and convex polyhedron cells without holes. Regarding the set of mechanical properties studied, it is clear that by varying the number of seeds (n) and the scale factor for the faces (Sf) and their scale volume (Sv) in the polyhedral cells within ranges of 0-1, it’s possible to determine the porosity index of the components and the pore size. The correlation between these inputs parameters (seed number and scale factor) and the target parameters (porosity percentage and the pore size) is based on the comparison of wireframes as the porosity index. To control the trabecular morphology of the Voronoi porous scaffold is necessary to identify the input parameters with the mechanical objectives of the final piece: The number of seeds (n) to be included in each volume, the scale factors (Sf), and (Sv). The objective parameters to consider are; The porosity index P% and the pore size. Subsequently, the percentage of porosity index P% can be determined by the following equation:

$$P\% = \frac{Vboundingbox}{(Vscaffold)(Vboundingbox)}(100) \tag{2}$$

Where

$$Vvoid = Vboundingbox - Vscaffold \tag{3}$$

It should be added that the number of seeds, scale factors (Sf), and, scale volume (Sv) have an impact on the percentage of porosity where (Sf) represents the scale factor of the polyhedral, and (Sv) represents the scale factor of the polyhedron volume. As a sample observation, a higher number of seeds represents a higher number of pores (holes), but in fact, a higher number of trabeculae balances the amount of empty volume. A wired structure with a higher porosity index is equivalent to a unit with a higher density, which provides superior structural stiffness compared to a structure with a lower porosity index in the same controlled volume as shown in Figure 3.

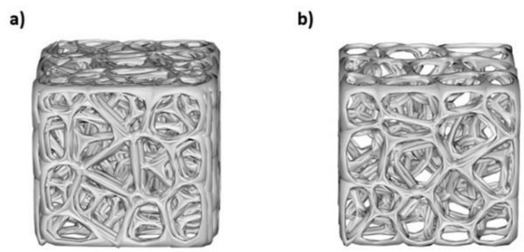


Figure 3. Sample of scaffold ($23mm^3$) with variation on porosity percentage; (a) Sf = Sv = 75%. (b) Sf = Sv = 50%.

The seed number (seed density) can be given to meet a target pore size for the scaffold. Therefore, it is a significant parameter that must be identified and quantified. In this way, the ideal seed population input number (n) is estimated as the ratio of the total target of the void volume, and the volume of the sphere to the diameter (Dp) represents the largest pore size. Therefore, a static compression test is applied to determine the organization of trabeculae and their efficient morphology in the values pk, P, and eT.

Consequently, the relationships between the parameters of the structural design like porosity (P), and the properties of the trabecular thickness (eT) are determined by establishing three regression equations using the response surface methodology (Du et al., 2020). The Young´s module and the Poisson ratio are two parameters that describe isotropic elastic materials. Young´s module captures how rigid or soft an object is, while Poisson´s relationship captures how one dimension extends from another. Following the aim of this study, we focus on the variation of Young´s module while conserving Poisson´s ratio. Concerning the base material (Martínez et al., 2018), samples with a design varying from the cross-sectional structure of the sample in the form of a honeycomb, as shown in Fig. 4a, and samples with a vertical column design, as shown in Fig. 4b, he examples proposed by the bio-inspired structure in the composition of the microporous reticular structure of a healthy horse bone or also referred as a femur, as shown in Figure 3. In addition, Figure 4d, shows a close-up view of the voronoi structure.

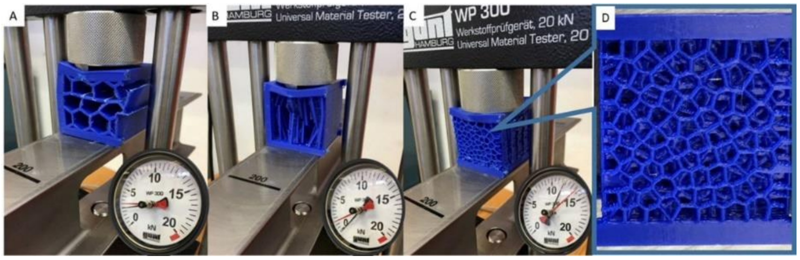


Figure 4. Bending-pressure test performed on structural models. (a) Honeycomb structure. (b) Bar structure. (c) Voronoi structure. (d) Close-up view of the voronoi structure.

The models evaluated were manufactured using additive manufacture (AM) by performing an export of the sample to 3D printing software. The material selected for the manufacturing process is Polylactic Acid (70% filling in the surface). The tested models have the same sample weight. The success of the lattice structure depends on several factors related to the shape of the lattice and the material used for its manufacture. Through additive manufacturing, it is possible to control the internal morphology of the reticular sample. The limitations related to 3D printed samples are due to the homogeneity of the materials, the manufacturing time, and the machine´s accuracy.

3. RESULTS AND DISCUSSION

Initially, Voronoi tessellations are used to design three-dimensional porous structures. Then, when processing data with a computer design software, this structure similar to the properties and characteristics of a femur shows having identical 3D virtual isotropic porous interconnected nodes. Therefore, the methodology proposed with the Voronoi diagram indicates that they are suitable to create porous structures in irregular tessellations, as shown in Fig. 4d, to imitate the structural characteristics that nature shows as efficient models in the distribution of efforts, besides the possibility of being part of an infinite range of products.

Variation in design irregularities and compressive strength (Craeghs et al., 2011; Wauthle et al., 2015; Yang et al., 2016) exhibited a wide range of fluctuations, as well as increasing inconsistency (Mullen et al., 2009; Wang et al., 2018). Besides, the design stiffness depended considerably on the sample´s porosity and irregularity. In this context, it is observed that the number of (pk) points have a direct impact as determining variables for porosity. By increasing the number of pk points, the variation in the percentage of porosity increases, affecting the trabecular thickness in its capacity to cause volume; this generates an excellent property for functions such as stiffness and solidification compared to a reverse sample with a higher eT index. The number of generators (or seed density) can be given to achieve the target pore size of the tessellation. The seed density is a significant parameter that must be identified to control cell properties. Also, the number of generators provides information about the number of pores within the reticular structure. Consequently, if the irregularity increases, more support is generated to change from vertical or horizontal to an inclined position, which allows a reduction in the stiffness of the structure, and this, in turn, favors flexibility where the product requires it.

Also, the mechanical properties of porous structures must have at least three variable parameters depending on the material (porosity, irregularity, and mechanics) (Wang et al., 2018). The proposed methodology for the development of irregular lattice structures enables the control of stiffness and flexibility rates in different volumes of interest; this provides greater efficiency and stability in the use of materials applied to products.

Figure 5 shows the implementation of the voronoi diagrams, applied to a conventional tire, by taking inspiration from a healthy femur bone. This methodology is a useful tool for the design and interpretation of lattice structures with natural inspiration. Moreover, the manufacturing process plays an important role.

For this reason, the capabilities of additive manufacturing precede numerous benefits for the solution of problems with innovative techniques. Table 1 shows the static stress under compression conditions for each fabricated model. Based on the table, the displacement of the voronoi structure is minor than in the other two models; this means less deformation when it is under the action of loads. On the other hand, the static stress and the maximum Von Mises stress in the voronoi model are much larger than in the other models; this indicates that it has an efficient design. In terms of structural material, it is capable of resisting high stress when it is under the action of compressing loads. The mentioned above indicates that the design of a porous structure inspired by natural models (biomimetic) using parametric modeling platforms and controlled volume simulations delivers high strength and lightweight structural materials employing additive manufacturing.

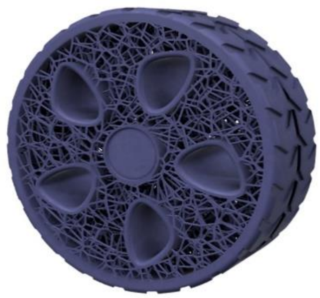


Figure 5. The final design represents the optimized unit controlled. The thicknesses of the central nodes, generate a higher irregular porous concerning the outside, and the rounding applied causes the section not to be uniform on the trabecula.

Tabla 1. Results of measurements of the static stress for different models.

Model	Material	Force (N)	Displacement (mm)	Maximum Von Mises Stress (Mpa)	Static stress (kN)
Voronoi	ABS Plastic	6000	0.31	272.6	14
Bar	ABS Plastic	6000	0.82	55.96	1.5
Honeycomb	ABS Plastic	6000	0.63	45.77	3

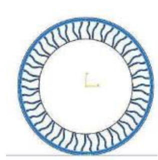
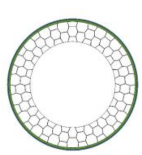
Over the last decade, the design of structures applied to non-pneumatic tires has been widely investigated. Therefore, Table 2 displays the main two structures found in the state of the art. Equally important, it also represents a comparison between the models suggested by researchers in the field and the one proposed in this study. For further information, visit the section of *Supplementary Material*.

As suggested by a group of researchers from the University of Helwan in Egypt (Aboul-Yazid et al., 2015) tires with the linear geometric arrangement and a slight curvature at the top of each spoke demonstrates, in mechanical tests, that its geometry reduces rolling resistance. It also reaches a significant reduction in the contact pressure and ensures a uniform distribution of stress in its spokes, but the vertical stiffness maintains a high value. Compared to the structural arrangement of Voronoi, it shows that the randomness of trabecula generates a considerable decrease in mechanical resistance. As far as accommodation is concerned, the variation of the density gradient affects its contact index. A higher density index causes a considerable decrease in vertical stiffness. Whereas a lower density index increases the flexibility index, this ensures a uniform distribution on contact due to its multi-modal spokes.

Tests carried out at the State Key Laboratory for Strength Validation and Vibration Mechanical Structures in China (Jin et al., 2018) suggested a new optimized hexagonal structure pattern for airless tires. The proposed pattern was analyzed together with two models under static and dynamic loads. From this test, based on the parameters of stiffness, tensile strength, and static compression, an optimal model was obtained. The optimal model presented a small angle of expansion in each cell, together with a thickness of 2 mm. Concerning the Voronoi-type reticular structure, the cells generated from irregular polygons are interconnected by density difference and by set gradient value. The optimal model works under the principle of fractality, and the trabecula thickness is a constant variable. Plus, the organization of the nodal points is established using a finite element method (FEM) simulation. Then, the resulting model can be adapted to n contact possibilities.

Finally, the mechanical properties of the Voronoi reticular pattern illustrate the application of natural components for performance in functional products. The skeletal structure is found in a great diversity of organisms. The structural optimization of the sample makes the external and internal tensions as uniform as possible throughout the structure. The CAD software design proposal allows the reconfiguration of stress zones by readjusting the equilibrium point at high-stress points.

Table 2. Comparison of structures applied to airless tires.

Design	Structure	Properties	Deliverables	References
	Voronoi	The process of constructing artificial bone with porous gradient structures. Porous scaffolds with gradient distribution of porosity.	The highest deformation of nodes occurs at the edges of contact with the surface based on the gradient deformation. Density is defined by the area of material need when suffering a stress deformation. Variable radios of the Voronoi cell provide mechanical resistance to energy distribution. Strong cell structure CAD controls the stress relief via simulation of material needs.	This work
	Linear	Spokes with curvature, thickness, and derived from the radial line. Spokes are paired and placed at equal intervals along the circumference. The structure is derived from 3 circumferences	The vertical stiffness of the model, under a load of 3000 N, showed a value of 608.51 N/mm. The minimum value of deflection was 4.93mm. The tire showed appropriate results.	(Aboul-Yazid *et al.*, 2015)
	Honeycomb	. Vertical cell length of 36.66 mm. Inclined cell length of 26.25 mm. Cell expanding angle of 15.76. The cell wall thickness of 2 mm.	The highest deformation of spokes occurs at the edges of contact with the surface. Displacement of 10 mm at a vertical force of 20kN in the center of the hub, which means a high load-carrying capacity. Stress concentration of 2.088 MPa appears in the joint location of the cellular wall edges. Low mass. High-stress concentration in spokes when it is under dynamic conditions	(Jin *et al.*, 2018)

4. CONCLUSIONS

In conclusion, this study demonstrates that it is feasible to employ the biomimicry methodology and the voronoi diagrams to create new porous structures for industrial applications. Undoubtedly, the existence of a mathematical method that is linked to natural systems, together with the appropriate computer-aided design software and additive manufacturing technology, enables the production of bio-inspired structures by means of bio-inspired engineering, i.e by imitating natural properties at all levels (microstructural, mechanically, and biologically).

As a consequence, the results of the proposed design prove that the mechanical properties of voronoi structures applied to products depend directly on the microstructural characteristics of the porous structure. Furthermore, the surface area and porosity are the principal parameters to be controlled. Other indices are; the thickness of the connectors to each node, the separation, and the number of connectors. Finally, all indices are controlled by the proposed voronoi design methodology. According to the proposed design, the rigidity of the structure is higher when the irregularity is less. Also, by optimizing the proposed design features, such as test methods and process parameters, the apparent elastic modulus of porous structures can be further improved.

Finally, the higher the porosity is, the greater the load required for the fracture. Besides, the porous structure not only has a potential application mechanically but also has a wide range of application possibilities in engineering design and manufacturing product applications.

REFERENCIAS

Aboul-Yazid, A. M. et al. (2015) 'Effect of spokes structures on characteristics performance of non-pneumatic tires', International Journal of Automotive and Mechanical Engineering, 11(1), pp. 2212–2223. doi: 10.15282/ijame.11.2015.4.0185.

Benyus, J. M. (1997) Biomimicry: Innovation Inspired by Nature.

Chua, C. K. et al. (2003) 'Development of a tissue engineering scaffold structure library for rapid prototyping. Part 2: Parametric library and assembly program', International Journal of Advanced Manufacturing Technology, 21(4), pp. 302–312. doi: 10.1007/s001700300035.

Craeghs, T. et al. (2011) 'Determination of geometrical factors in Layerwise Laser Melting using optical process monitoring', Optics and Lasers in Engineering. Elsevier, 49(12), pp. 1440–1446. doi: 10.1016/j.optlaseng.2011.06.016.

Depriester, D. and Kubler, R. (2019) 'Radical Voronoï tessellation from random pack of polydisperse spheres: Prediction of the cells' size distribution', CAD Computer Aided Design. Elsevier Ltd, 107, pp. 37–49. doi: 10.1016/j.cad.2018.09.001.

Du, Y. et al. (2020) 'Design and statistical analysis of irregular porous scaffolds for orthopedic reconstruction based on voronoi tessellation and fabricated via selective laser melting (SLM)', Materials Chemistry and Physics. Elsevier B.V., 239(July 2019), pp. 1–9. doi: 10.1016/j.matchemphys.2019.121968.

Fantini, M. and Curto, M. (2018) 'Interactive design and manufacturing of a Voronoi-based biomimetic bone scaffold for morphological characterization', International Journal on Interactive Design and Manufacturing. Springer Paris, 12(2), pp. 585–596. doi: 10.1007/s12008-017-0416-x.

Fantini, M., Curto, M. and De Crescenzio, F. (2016) 'A method to design biomimetic scaffolds for bone tissue engineering based on Voronoi lattices', Virtual and Physical Prototyping, 11(2), pp. 77–90. doi: 10.1080/17452759.2016.1172301.

Gómez, S. et al. (2016) 'Design and properties of 3D scaffolds for bone tissue engineering', Acta Biomaterialia, 42(June), pp. 341–350. doi: 10.1016/j.actbio.2016.06.032.

Gorgin Karaji, Z. et al. (2017) 'Additively manufactured and surface biofunctionalized porous nitinol', ACS Applied Materials and Interfaces, 9(2), pp. 1293–1304. doi: 10.1021/acsami.6b14026.

Guarino, V. et al. (2012) 'Bio-inspired composite and cell instructive platforms for bone regeneration', International Materials Reviews, 57(5), pp. 256–275. doi: 10.1179/0950660812Z.00000000021.

Huo, Y. et al. (2021) 'A Critical Review on the Design, Manufacturing and Assessment of the Bone Scaffold for Large Bone Defects', Frontiers in Bioengineering and Biotechnology. doi: 10.3389/fbioe.2021.753715.
Hutmacher, D. W., Sittinger, M. and Risbud, M. V. (2004) 'Scaffold-based tissue engineering: Rationale for computer-aided design and solid free-form fabrication systems', Trends in Biotechnology, 22(7), pp. 354–362. doi: 10.1016/j.tibtech.2004.05.005.

Jin, X. et al. (2018) 'Investigation on the static and dynamic behaviors of non-pneumatic tires with honeycomb spokes', Composite Structures, 187, pp. 27–35. doi: 10.1016/j.compstruct.2017.12.044.

Kapfer, S. C. et al. (2011) 'Minimal surface scaffold designs for tissue engineering', Biomaterials. Elsevier Ltd, 32(29), pp. 6875–6882. doi: 10.1016/j.biomaterials.2011.06.012.

Kou, X. Y. and Tan, S. T. (2010) 'A simple and effective geometric representation for irregular porous structure modeling', CAD Computer Aided Design. Elsevier Ltd, 42(10), pp. 930–941. doi: 10.1016/j.cad.2010.06.006.

Lee, M. et al. (2018) 'Support-free hollowing for 3D printing via Voronoi diagram of ellipses', CAD Computer Aided Design. doi: 10.1016/j.cad.2018.03.007.

Liang, H. et al. (2019) 'Trabecular-like Ti-6Al-4V scaffolds for orthopedic: fabrication by selective laser melting and in vitro biocompatibility', Journal of Materials Science and Technology. The editorial office of Journal of Materials Science & Technology, 35(7), pp. 1284–1297. doi: 10.1016/j.jmst.2019.01.012.

Liebschner, M. A. . (2012) 'Chapter 9 A Neural Network Technique for Remeshing', in Computer-aided tissue engineering, pp. 135–141. doi: 10.1007/978-1-61779-764-4.

Liu, Y. J. et al. (2015) 'Processing and properties of topologically optimised biomedical Ti-24Nb-4Zr-8Sn scaffolds manufactured by selective laser melting', Materials Science and Engineering A, 642, pp. 268–278. doi: 10.1016/j.msea.2015.06.088.

Martínez, J. et al. (2018) 'Polyhedral voronoi diagrams for additive manufacturing', ACM Transactions on Graphics, 37(4), pp. 1–15. doi: 10.1145/3197517.3201343.

Mullen, L. et al. (2009) 'Selective laser melting: A regular unit cell approach for the manufacture of porous, titanium, bone in-growth constructs, suitable for orthopedic applications', Journal of Biomedical Materials Research - Part B Applied Biomaterials, 89(2), pp. 325–334. doi: 10.1002/jbm.b.31219.

Nguyen, D. S. et al. (2019) 'Creation of Lattice Structures for Additive Manufacturing in CAD Environment', in IEEE International Conference on Industrial Engineering and Engineering Management. doi: 10.1109/IEEM.2018.8607271.

Nguyen, D. S. (2019) 'Design of lattice structure for additive manufacturing in CAD environment', Journal of Advanced Mechanical Design, Systems and Manufacturing. doi: 10.1299/jamdsm.2019jamdsm0057.

O'Keefe, R. J. and Mao, J. (2011) 'Bone tissue engineering and regeneration: From discovery to the clinic-an overview', Tissue Engineering - Part B: Reviews, 17(6), pp. 389–392. doi: 10.1089/ten.teb.2011.0475.
Okabe, A. et al. (2000) Spatial Tessellations: Concepts and Applications of Voronoi Diagrams. John Wiley and Sons, Inc. doi: 10.2307/2687299.

Okabe, A. and Suzuki, A. (1997) Locational optimization problems solved through Voronoi diagrams, European Journal of Operational Research.

Sogutlu, S. and Koc, B. (2007) 'Stochastic Modeling of Tissue Engineering Scaffolds with Varying Porosity Levels', Computer-Aided Design and Applications, 4(5), pp. 661–670. doi: 10.1080/16864360.2007.10738500.

Sun, W. et al. (2004) 'Computer-aided tissue engineering: application to biomimetic modelling and design of tissue scaffolds', Biotechnology and Applied Biochemistry, 39(1), p. 49. doi: 10.1042/ba20030109.

Sun, W. and Lal, P. (2002) 'Recent development on computer aided tissue engineering - A review', Computer Methods and Programs in Biomedicine, 67(2), pp. 85–103. doi: 10.1016/S0169-2607(01)00116-X.

Wang, G. et al. (2018) 'Design and Compressive Behavior of Controllable Irregular Porous Scaffolds: Based on Voronoi-Tessellation and for Additive Manufacturing', ACS Biomaterials Science and Engineering, 4(2), pp. 719–727. doi: 10.1021/acsbiomaterials.7b00916.

Wang, X. et al. (2016) 'Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review', Biomaterials. Elsevier Ltd, 83, pp. 127–141. doi: 10.1016/j.biomaterials.2016.01.012.

Wauthle, R. et al. (2015) 'Effects of build orientation and heat treatment on the microstructure and mechanical properties of selective laser melted Ti6Al4V lattice structures', Additive Manufacturing. Elsevier B.V., 5, pp. 77–84. doi: 10.1016/j.addma.2014.12.008.

Yan, D. M. et al. (2013) 'Efficient computation of clipped Voronoi diagram for mesh generation', CAD Computer Aided Design. doi: 10.1016/j.cad.2011.09.004.

Yang, N., Gao, L. and Zhou, K. (2015) 'Simple method to generate and fabricate stochastic porous scaffolds', Materials Science and Engineering C. Elsevier B.V., 56, pp. 444–450. doi: 10.1016/j.msec.2015.06.039.

Yang, Y. et al. (2016) 'System development, formability quality and microstructure evolution of selective laser-melted magnesium', Virtual and Physical Prototyping, 11(3), pp. 173–181. doi: 10.1080/17452759.2016.1210522.

Yang, Y. et al. (2019) 'Additive manufacturing of bone scaffolds', International Journal of Bioprinting, 5(1), pp. 1–25. doi: 10.18063/IJB.v5i1.148.

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