International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 06 | June – 2025 DOI: 10.55041/ISJEM04561
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Comparative Finite Element Analysis of 3D Printable Dental Implants with Various Lattice Structures

Mohd Altaf Ansari[1], Shaheen Beg Mughal[1], Amber Gautam[1], Aagam Jain[1]

[1]Department of Mechanical Engineering,

Prestige Institute of Engineering Management and Research Indore, India

Abstract:- Purpose: This study looks at how well lattice-structured titanium dental implants—Gyroid, X-Cell, and Diamond designs—work when made with two different levels of porosity (20% and 40%) and compared to a totally solid implant.

Methods: We used Finite Element Analysis (ANSYS) to model physiological axial loading. The most important numbers were the maximum von Mises stress, the maximum deformation, and the average deformation for all implant types.

Results: Higher porosity always lowered peak stress but raised deformation, showing a trade-off between stiffness and compliance. The X-Cell structure had the best mechanical balance at 20% porosity, while the Gyroid design was better at handling stress with little deformation. Diamond, on the other hand, had too much compliance at 40% porosity, which made it less useful under high load.

Conclusion: The mechanical behaviour is greatly affected by the lattice geometry and porosity. X-Cell (20%) and Gyroid (20%) arrangements look like they could be good ideas for implants that work well mechanically and respond to biological signals. The results show how important it is to optimise the structure of next-generation dental prosthesis.

Keywords :- Lattice Implant, FEA Simulation, Porosity, Titanium Implant, Biomechanics

1. Introduction :-

The growing need for dental implants that are made just for each patient has led to the quick development of new manufacturing technologies, especially additive manufacturing (AM), which is also called 3D printing. With AM, it's possible to make highly customised implants with complicated internal shapes that couldn't be made with standard subtractive processes. One of the best things about AM is that it makes it possible to make porous lattice structures inside implants. These structures can be changed to make osseointegration better, encourage vascularization, and better imitate the mechanical properties of normal bone [1,2]. One of the biggest problems in dental implantology is dealing with the fact that dense titanium implants don't fit well with the surrounding cancellous or cortical bone. This difference can cause stress shielding, bone loss, and the implant to fail [3,4]. Adding porous structures to the implant body makes it possible to change the stiffness so that it is more like that of natural bone. This improves mechanical compatibility and long-term clinical success [5]. To reach this goal, other lattice shapes have been suggested, including gyroid, diamond, and cubic-octahedron. Each shape has its own structural and biomechanical qualities [6,7]. Porosity affects how well an implant works in two ways. On the one hand, making things more porous helps tissues grow and makes biological fixation better [8,9]. Too much porosity, on the other hand, could make things less stable and less able to hold weight [10]. So, it's very important to find the right balance between mechanical integrity and biological performance by optimising both the lattice topology and the porosity level. Studies have shown that lattice constructions with 20–40% porosity tend to work well for integrating bone without greatly affecting how well they work mechanically [11–13]. A lot of people now use Finite

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 06 | June – 2025 DOI: 10.55041/ISJEM04561
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Element Analysis (FEA) to check how well these complicated porous structures work mechanically. FEA lets you simulate physiological loading situations and gives you information about stress distribution, deformation patterns, and effective stiffness without having to make physical prototypes [14,15]. FEA has been used in the past to look into how the topology of the lattice, the size of the pores, and the orientation of the unit cell affect the compressive behaviour and elastic modulus of dental and orthopaedic implants [16–18].

These analyses provide a cheap and quick way to check the design of an implant before it is built. Gyroid structures,

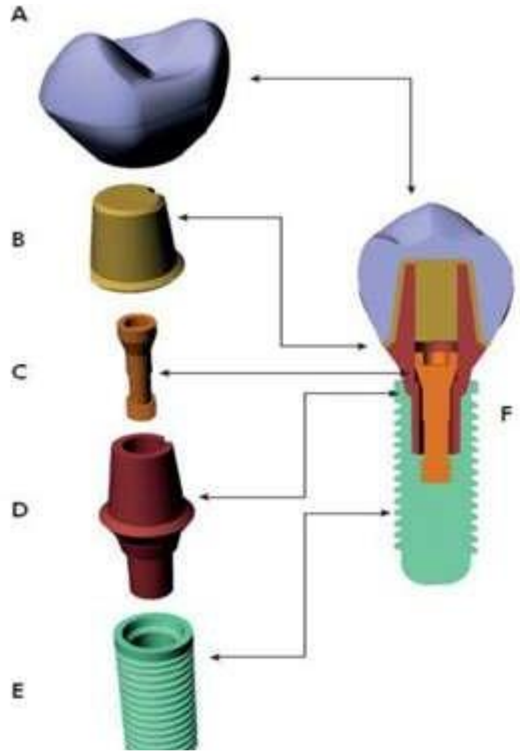
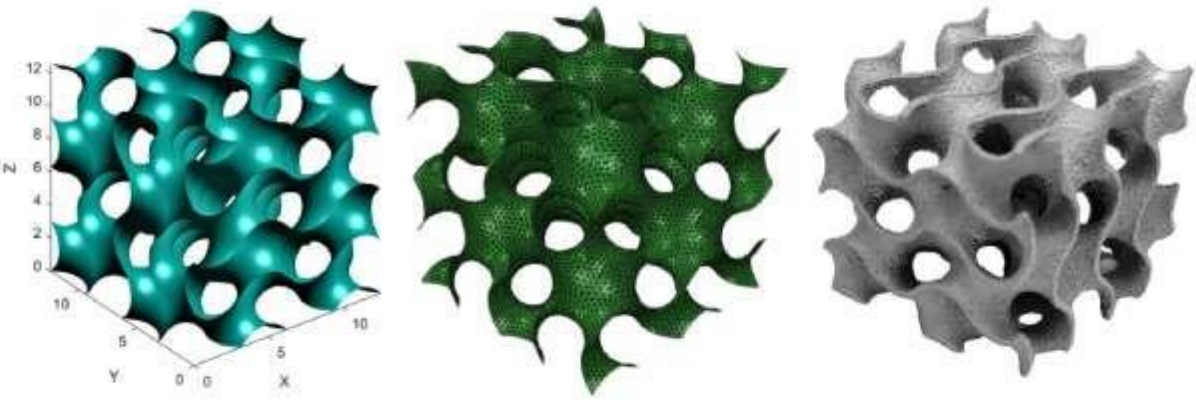


Figure. 1.1 Parts of Dental Implant

A. Monolithic crown B. Cement C. Retaining screw D. Abutment E. Implant and F. Dental implant

which fall under the category of Triply Periodic Minimal Surfaces (TPMS), have become quite popular because they have a constant curvature, a large surface area, and are mechanically isotropic [19,20]. They have done well with both static and dynamic loads, which makes them good candidates for dental applications that need to hold weight [21]. Diamond lattices have a high strength-to-weight ratio because their nodes link to each other. Octet trusses, on the other hand, are recognised for being very rigid and not buckling when compressed [22,23]. There aren't many research that compare these shapes, though, especially when it comes to controlled changes in porosity utilising simulation-based methods. In the past few years, a number of studies have looked at the mechanical and biological effects of lattice-based implants. For example, Wally et al. [24] showed that lattice structures with graded porosity made loads distribution as well as bone-matching modulus better in selective laser melted Ti-6 Al-4V



scaffolds. In the same way, Xu et al. [11] created functionally graded scaffolds based on gyroids and tested their design with FEA and real-world compression tests. But these studies usually only look at one type of lattice or a set level of porosity, and they don't look at how different designs work under the same simulation conditions. Also, while some FEA studies have shown that porous implants are safe for orthopaedic and cranial use [25–27], not many have looked at dental implants that are put under normal bite forces. For instance, Takaki et al. [30] discovered that the average occlusal loads might be between 200 and 700 N, depending on the patient's age and where the tooth is located. This shows how important it is to design implants that are mechanically strong. Before using these structures in real life, it would be helpful to test them by simulating these kinds of forces on them. This study intends to fill in the gaps by doing an organised finite element analysis of 3D printed dental implant models with three different the lattice topologies—gyroid, diamond, and octet—each tested at two levels of porosity (20% and 40%). Using Ti-6Al-4V as the implant material, the implants are tested under compressive loading conditions that are similar to occlusal forces. To measure and compare biomechanical performance, we use mechanical metrics such von Mises stress, overall displacement, and effective elastic modulus. The goal is to find the lattice–porosity combination that gives the best balance between durability and design freedom that depends on porosity. This study adds to the expanding body of research by directly comparing different types of lattices and levels of porosity under the same loading and boundaries. The results are meant to help with the early design of dental implants, which will make it less necessary to use trial-and-error prototyping and move towards safer, more effective solutions for each patient.

2. Literature Review :-

2.1 Evaluation of 3D printing in Dental Implantology:-

Additive manufacturing (AM), especially 3D printing, has changed the way dental implants are designed by allowing for customisation, complicated shapes, and biomimetic architecture. Early uses were mostly on making implants that fit each patient based on CT scans [2]. This has now led to the creation of porous scaffolds that look like trabecular bone, with the goal of improving osseointegration and mechanical compatibility [1][5][6]. The implementation of additive manufacturing in oral surgery is not solely cosmetic or geometric; it has a direct impact on clinical outcomes. Demonstrated that 3D printed surgical guides decrease operative duration, [3] [4] and their synergy with biocompatible materials facilitates functionally graded implants. [5]

2.2 Lattice Structure and Mechanical Optimization

Lattice design is an important part of implant engineering since it makes the implants strong and works like biological systems. Researchers have looked at the load distribution and stress absorption features of structures like gyroid, diamond, and cubic-octahedron in great detail [10][11][12]. Cubic-octahedron and gyroid lattices make the biomechanical response better when there is a load [10]. Gyroid-based functionally graded porous scaffolds, on the other hand, mirror the anisotropy of human bone [11]. Gyroid lattice structures can mimic how trabecular bone behaves when it is compressed, which makes them good for use in cancellous bone implants [12]. Gyroid lattices made with selective laser melting (SLM) are very good at withstanding dynamic impacts, which makes them even better for use in mouth prosthesis [14]. Finite element analysis (FEA) also backs up the usage of 3D printed Co-Cr lattices for testing under real-world clinical circumstances [13].

2.3 FEA in Implant Design

FEA is an essential technique for modelling how implants work in complicated anatomical settings [1]. Lattice trends are very important for simulation models that try to guess how implants would work when chewing forces are applied [16]. ANSYS simulations have shown that strut-based cranial implants are mechanically reliable [17]. Researchers have found that changing the size of the struts and pores in a unit cell can change the von Mises stress, deformation, and coefficient distributions [11][13]. The mechanical-biological sweet spot was found to be between 20% and 40% porosity, which gave both strength in structure and tissue ingrowth [11, 14, 19].

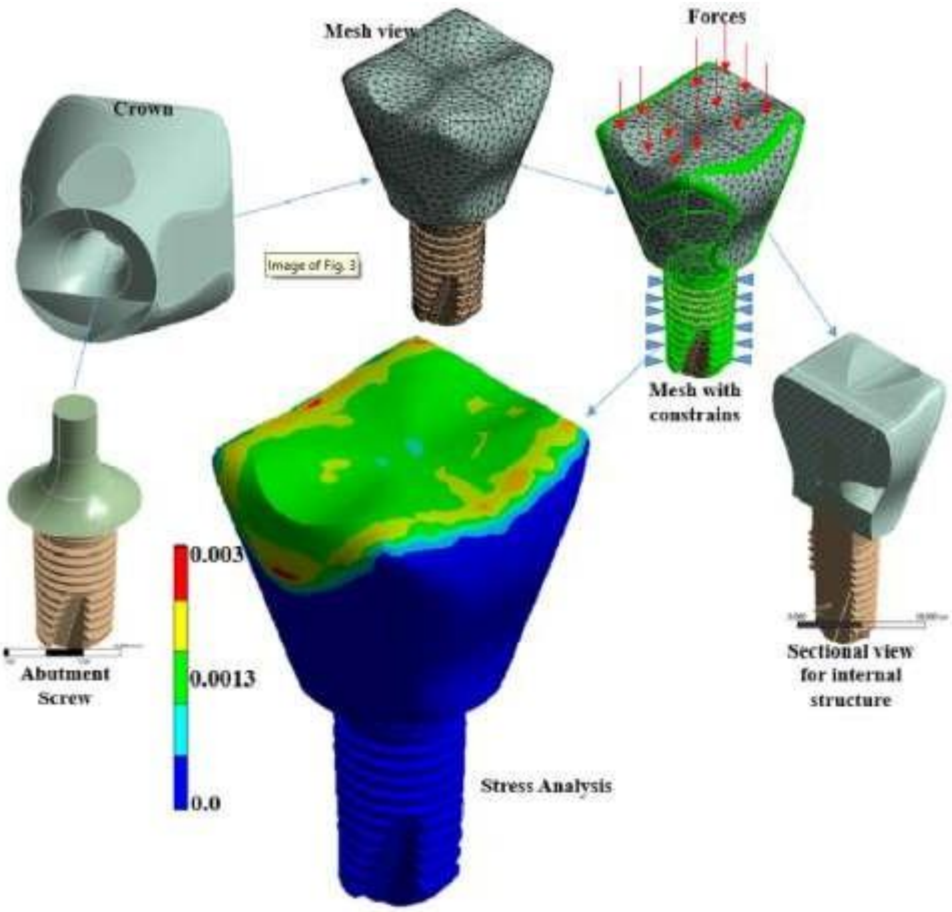


Figure.2.1 FEA Process for Dental Implant

2.4 Material Selection and Surface Engineering

The materials that make up an implant are very important to how well it works. Titanium and its alloys, especially Ti–6Al–4V, are still the best since they are strong for their weight and don't rust [23][24]. Optimising the microstructure of titanium alloys makes them more resistant to fatigue and lasts longer [23]. Graded porous titanium lattices made with SLM make both mechanical anchoring and osseointegration better [24]. Zirconia/alumina composites are good for your health and look good, thus they could be used in ceramic implants [18]. Osteoconductivity can be improved even further by changing the surface with topological and biological coatings [27].

2.5 Design Innovation and Functional Integration

Design changes like Voronoi and topology-optimized structures better mimic the structure of real bones and spread stress in a more natural way [28][29]. Studies comparing 3D printed scan bodies have revealed that how accurately they are made has a direct effect on how well the implant fits and how well it integrates with the bone [32]. Recent FEA studies that looked into porous TPMS (Triply Periodic Minimal Surface) implants and typical solid implants found that the porous ones had much less micromotion and were more stable across a range of bone densities [33]. To make sure that implants work well and are comfortable for a long time, implant biomechanics must also take into account the range of bite forces that patients of different ages can handle [30].

3. Material and Methods

3.1 Implant Design and lattice implementation

The outside shape of a conventional dental implant was made with Solid Edge software to match the anatomical measurements that are important in a clinical setting. Three distinct lattice structures—Gyroid, X-cell, and Diamond—were chosen for analysis since they are already used in load-bearing orthopaedic applications. [1] We used Fusion 360 to make the lattice geometries. This programme lets you regulate the size of the unit cells and the thickness of the struts in a parametric way. There were six different types of porous implants, each modelled with two different levels of porosity: 20% and 40%. A solid implant model without any internal porosity was also made as a control for mechanical comparison.

3.2 Material Assignment

All of the implant designs were given the mechanical properties of Ti–6Al–4V, a titanium alloy that is often utilised in dental and orthopaedic implants. The following were the qualities of the material: The Young's Modulus is 110 GPa, the Poisson's ratio is 0.33, and the yield strength is 880 MPa.[2] We chose these values based on data from the literature on SLM-made titanium and used them the same way in all models so that they could be compared.

3.3 Finite Element Simulation Setup

ANSYS Workbench 2021 R2 was utilised for finite element analysis (FEA). To ensure the answer was right, we added extra detail around the lattice struts and meshed the implant models with tetrahedral elements. To ensure that the figures were stable, we investigated mesh convergence for the Gyroid 20% model using coarse, medium, and fine mesh densities. The implant was placed inside a basic cylindrical bone model in the simulation area. A vertical axial load of 200 N was applied to the implant's upper surface in order to simulate occlusal stress. To simulate cortical fixation, the bottom of the bone model was totally restricted. It was believed that the osseointegration was complete as all of the connections between the implant and the bone were bonded.[3]

3.4 Model Validation

We looked at three main factors to see how well each implant model worked: von Mises stress, total deformation, and fatigue life. We got these numbers straight from the ANSYS simulation output. We used von Mises stress to find areas that were likely to yield under normal loads and total deformation to measure how stiff the structure was. Stress-based analysis was used to estimate the fatigue life under the assumption of a cyclic load state in order to assess long-term durability [4]. We compared the data from the porous implants to the baseline of the solid implant to see how the internal lattice shape changed performance, either for the better or for the worse.

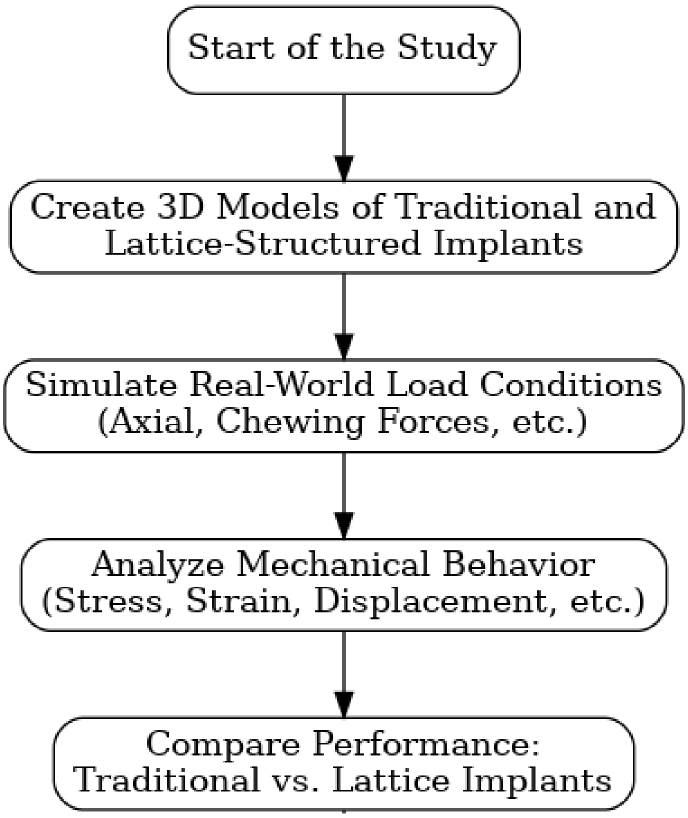


Figure: 3.1 Methodology Flowchart

3.5 Model Validation

This work was based on simulations and only included a few design options (six porous models and one solid control), hence there was no direct experimental validation. Instead, validation was done using a mix of comparative benchmarking, internal control analysis, and mesh convergence testing. These are all common methodologies used in early-stage implant research.

A solid implant model was used as a control to set a baseline for mechanical performance. The porous designs always showed lower peak stress concentrations and smoother stress distribution, which is what we expected to see with lattice-structured implants. Also, the trends in von Mises stress and deformation were the same as those found in earlier investigations of titanium implants made with additive manufacturing and gyroid and strut-based designs. This adds to the credibility of the model's results under physiological load conditions.

To make sure the calculations were reliable, a mesh sensitivity analysis was done on a sample model (Gyroid 20%). This revealed that the stress values didn't change by more than 5% between medium and fine mesh densities. The loading and boundary conditions were based on clinically relevant occlusal forces and were modelled using recognised FEA frameworks that have been used in biomechanical dental research.

It would be good to do experiments to confirm the results in the future, but the current modelling technique gives us useful information on how lattice structure and porosity affect the mechanics of implants. The results can be used as a scientifically sound basis for future experiments or studies on living organisms.

ISSN: 2583-6129
DOI: 10.55041/ISJEM04561

4. Result and Discussion

4.1 Mechanical Behaviour of porous and solid Implant

This study looked at how three lattice-based dental implant designs—Gyroid, X-Cell, and Diamond—responded mechanically when they had 20% and 40% porosity. A totally solid titanium implant was used as a comparison. We used ANSYS to do Finite Element Analysis (FEA) under normal axial compressive loading. To find out how much weight each implant architecture could hold and how well it fit, we looked at von Mises stress distribution, maximum deformation, and average deformation.

4.1.1 Control: Solid Implant

The control implant (0% porosity) had the least amount of deformation (0.00210 mm) and a moderate von Mises stress of 74.26 MPa, which shows how stiff it is and how well it can handle loads. This design has the least amount of average deformation (0.000118 mm), making it the standard for structural rigidity.

4.1.2 Implants with a Gyroid Lattice

20% Porosity: The maximum stress was 77.19 MPa, with a deformation of 0.00207 mm and an average deformation of 0.00011 mm. The performance was most like the solid control when it came to both stress and displacement.

40% Porosity: Stress went down a little to 74.54 MPa, but deformation went up to 0.00221 mm. The average deformation was 0.00015 mm, which clearly showed that compliance went up with porosity.

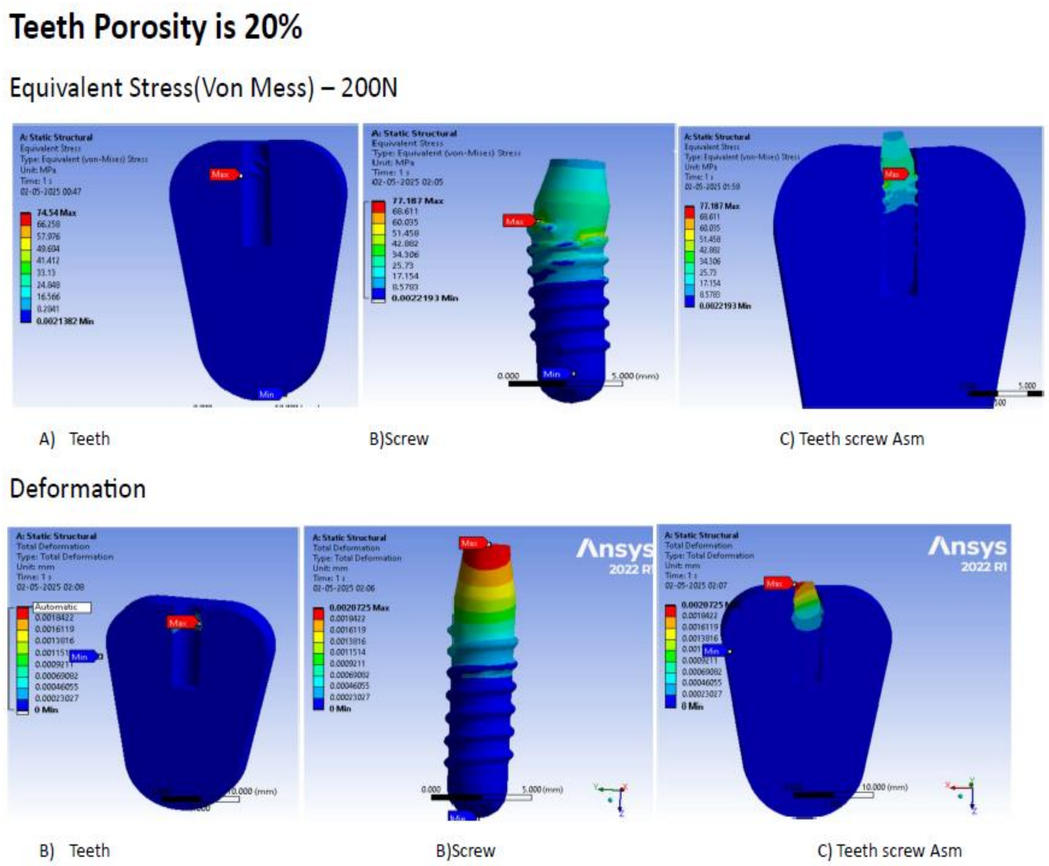


Figure: 4.1 Stress and Displacement in Implant with Gyroid Lattice 20% Porosity

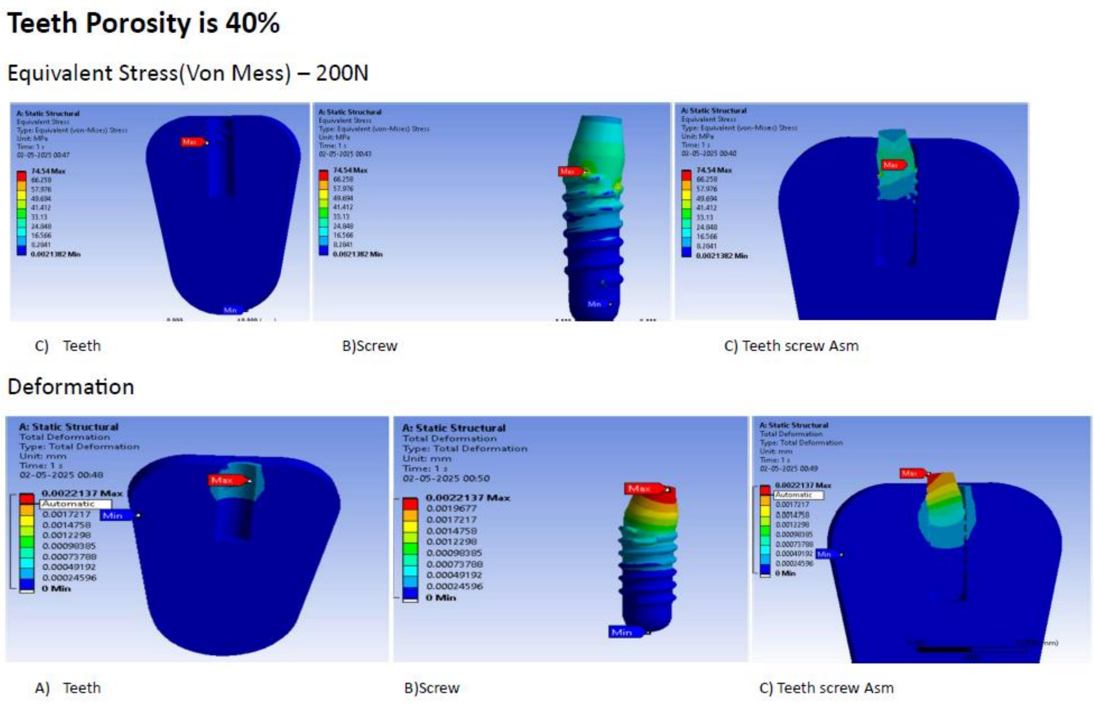


Figure: 4.2 Stress and Displacement in Implant with Gyroid Lattice 40% Porosity

4.1.3 Implants with Diamond Lattice

20% Porosity: It showed a von Mises stress of 76.56 MPa and a deformation of 0.00211 mm, with an average deformation of 0.00012 mm. These numbers show that the reaction is well-balanced between stiffness and load accommodation.

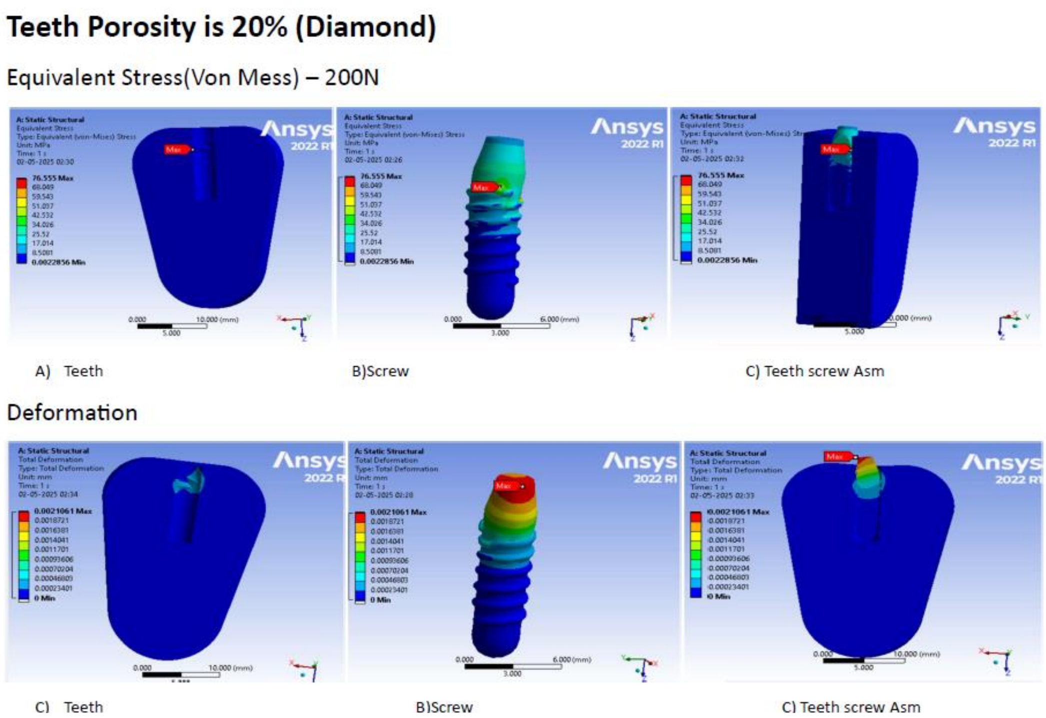


Figure: 4.3 Stress and Displacement in Implant with Diamond Lattice 20% Porosity

40% Porosity: It had the lowest stress (73.67 MPa) but the maximum deformation (0.00226 mm) and average deformation (0.00017 mm), which means it might not be able to handle significant occlusal forces.

4.1.4 Implants with X-Cell Lattice

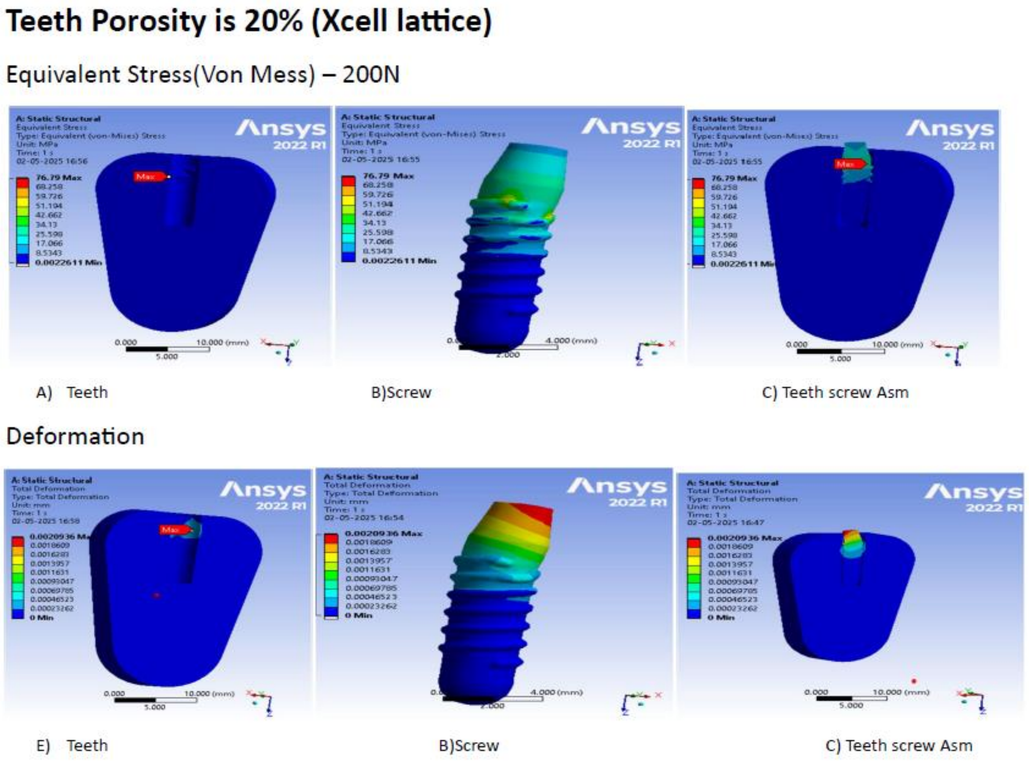


Figure: 4.4 Stress and Displacement in Implant with Diamond Lattice 40% Porosity

20% Porosity: The implant had a von Mises stress of 76.79 MPa and a deformation of 0.00209 mm, with an average deformation of 0.00012 mm. This means that the implant will keep its rigidity despite being lighter.

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 06 | June – 2025 DOI: 10.55041/ISJEM04561
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

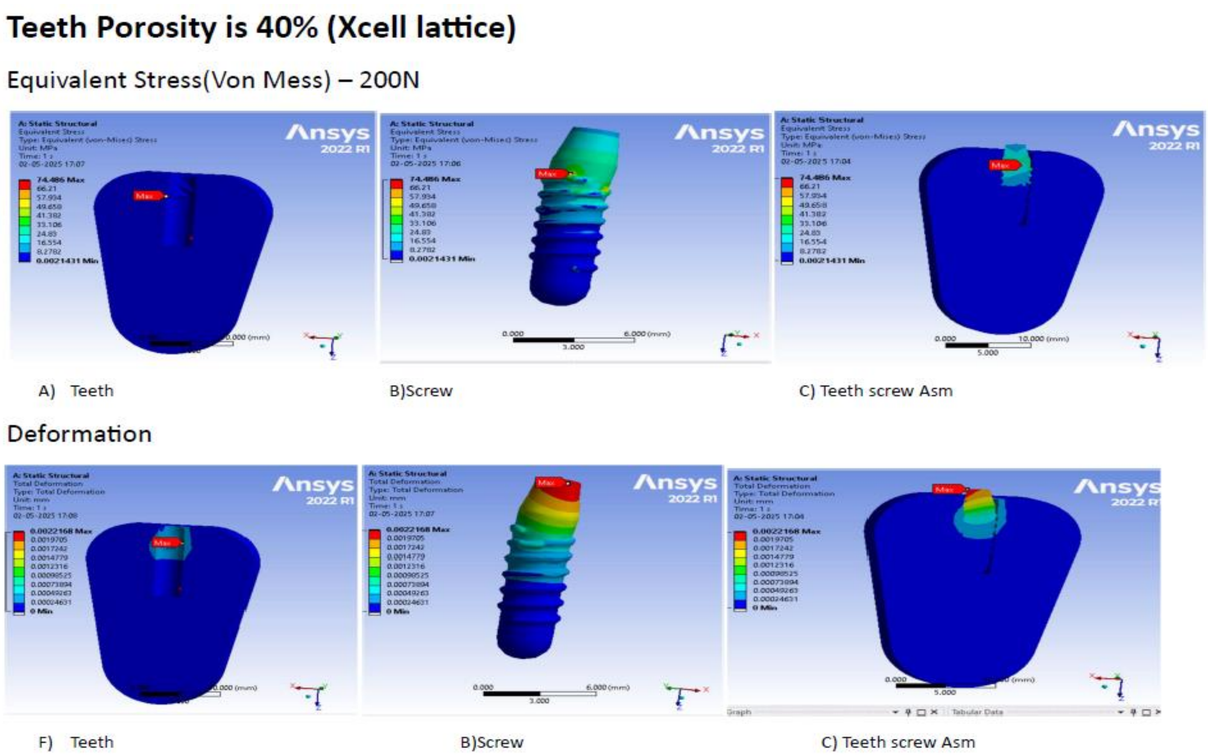


Figure: 4.5 Stress and Displacement in Implant with X-Cell Lattice 20% Porosity

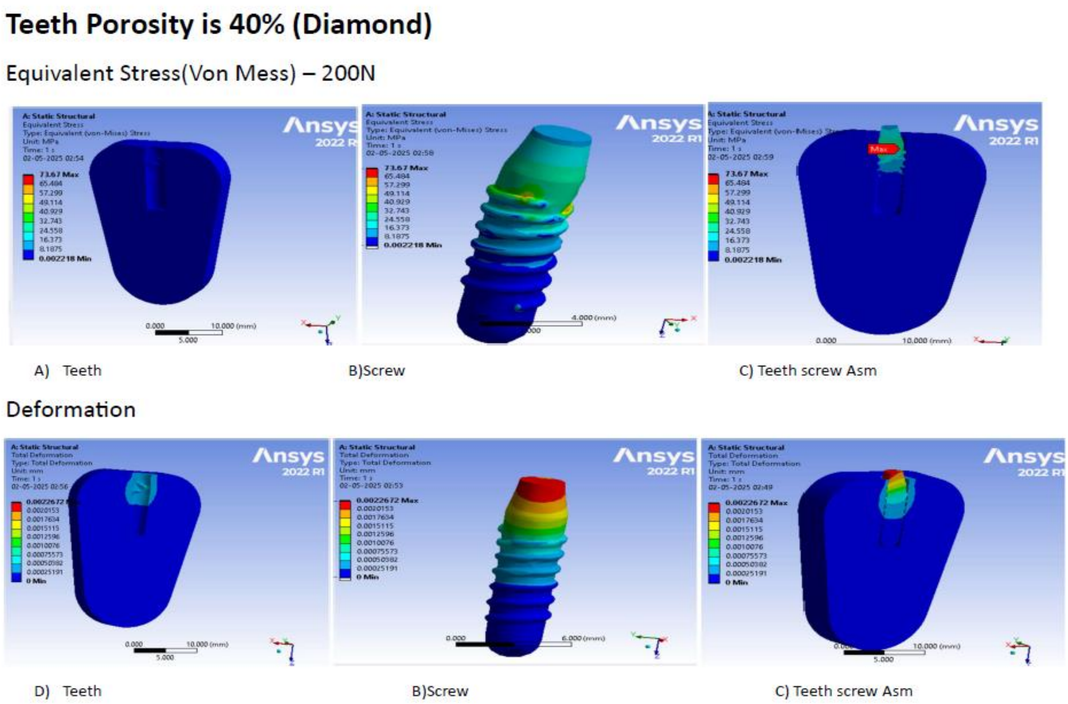


Figure: 4.6 Stress and Displacement in Implant with X-Cell Lattice 40% Porosity

ISSN: 2583-6129
DOI: 10.55041/ISJEM04561

40% Porosity: The maximum stress dropped to 74.49 MPa, and the deformation rose to 0.00222 mm. The average deformation went up to 0.00015 mm, which means that the material was less rigid at increasing porosity.

4.1.5 Combined Comparative Analysis Result

Simulation results show that there is a continuous inverse connection between porosity and mechanical stiffness across all lattice configurations. As porosity goes up from 20% to 40%, peak von Mises stress goes down, but maximum and average deformations go up. This shows the natural trade-off between strength and compliance, which is a key factor in the design of porous implants.

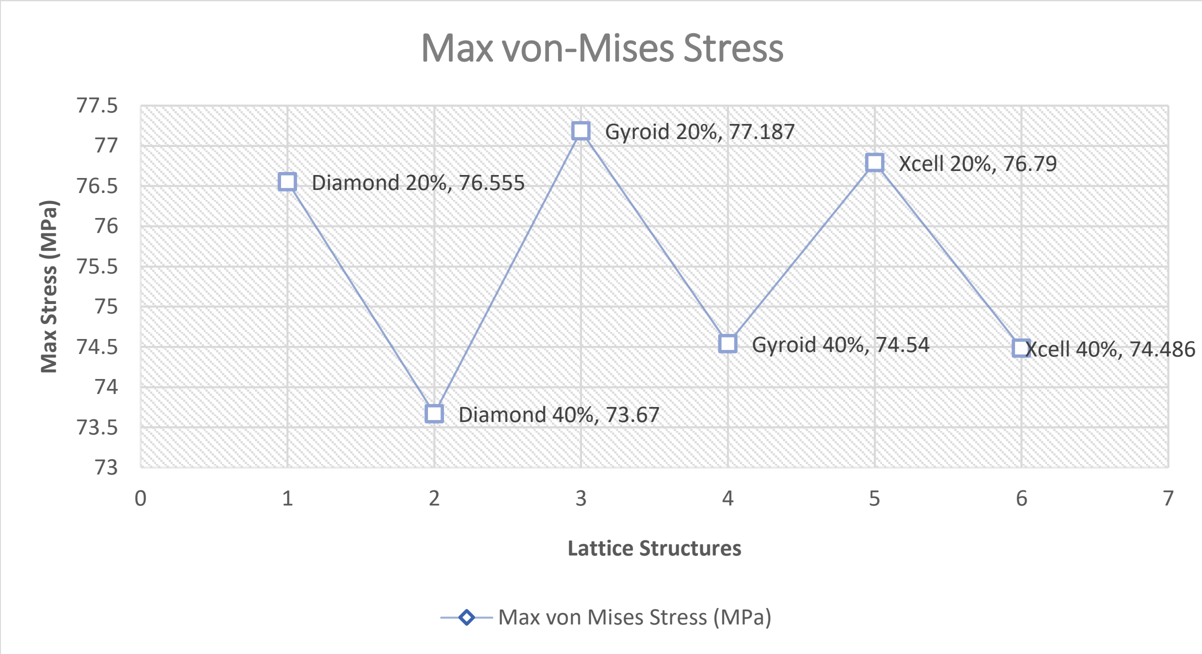


Figure : 4.7 Max Von Mises Stress Under 200N Axial Load

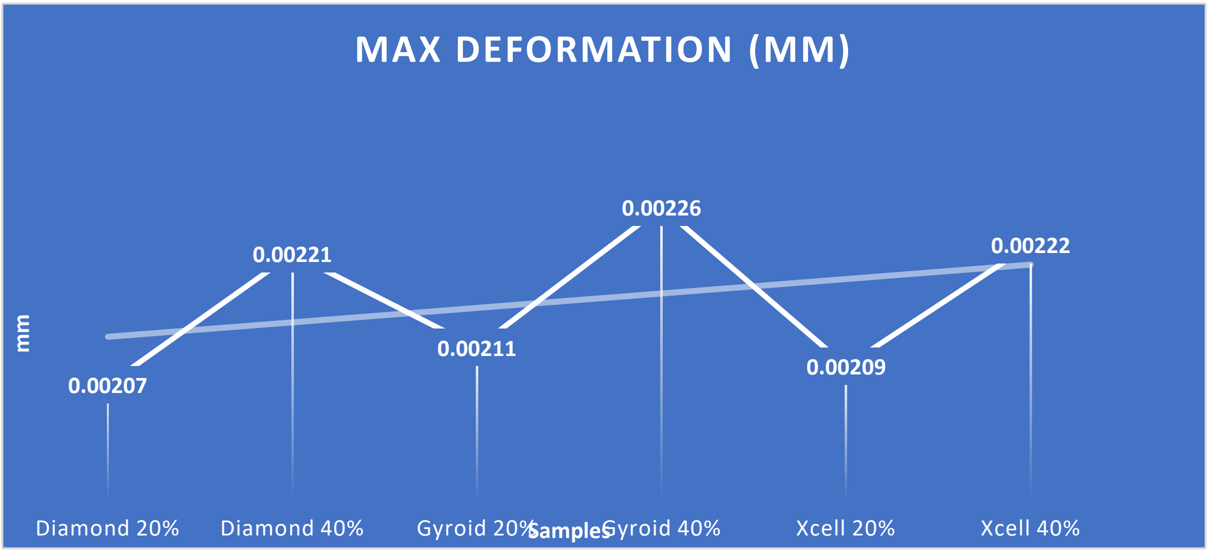


Figure : 4.8 Max Deformation Under 200N Axial Load

In comparison:

1. Gyroid (20%) had the best stress distribution and the lowest average deformation (0.00011 mm), making it the best choice for keeping stiffness while reducing stress shielding.
2. X-Cell (20%) had almost the same rigidity as the solid implant but was lighter, making it the best overall mechanical compromise.
3. Diamond (40%) had the lowest peak stress but the maximum deformation, which suggests that it may be less rigid under functional loading and may need reinforcement in high-stress situations.

These patterns show how important it is to choose lattice geometry and porosity together, based on the individual therapeutic needs, such as improving osseointegration, load accommodation, or long-term fatigue performance.

5. Conclusion

Using Finite Element Analysis under physiologically appropriate loads, this study looked at how titanium dental implants with lattice-structured bases (particularly Gyroid, X-Cell, and Diamond geometries) behaved mechanically at two levels of porosity (20% and 40%). When compared to a fully solid implant, it was shown that lattice topology and porosity have a big effect on how stress is spread out and how well the structure can bend. The X-Cell structure with 20% porosity was the best balance between mechanical rigidity and deformation. It nearly resembled the solid implant while greatly lowering the volume of material. Gyroid structures, especially those with 20% porosity, did a great job of reducing stress concentrations and average deformation. This makes them good for use in applications that aim to reduce stress shielding. On the other hand, Diamond with 40% porosity showed the most deformation, which suggests that it may not be able to handle occlusal stresses unless it is utilised in low-stress areas or with extra support. These results show that topology-optimized lattice implants could improve mechanical performance while also encouraging biological integration. This is a step towards designing the next generation of dental implants.

References :

1. Ouldyerou A, Aminallah L, Merdji A, Mehboob A, Mehboob H. Finite element analyses of porous dental implant designs based on 3D printing concept to evaluate biomechanical behaviors of healthy and osteoporotic bones. Mechanics of Advanced Materials and Structures. 2023 Jun 3;30(11):2328-40
2. Balamurugan P, Selvakumar N. Development of patient specific dental implant using 3D printing. Journal of Ambient Intelligence and Humanized Computing. 2021 Mar;12(3):3549-58.
3. Fang C, Cai L, Chu G, Jarayabhand R, Kim JW, O'Neill G. 3D printing in fracture treatment: Current practice and best practice consensus. Die Unfallchirurgie. 2022 Dec;125(Suppl 1):1-7.
4. Ballard DH, Mills P, Duszak Jr R, Weisman JA, Rybicki FJ, Woodard PK. Medical 3D printing cost-savings in orthopedic and maxillofacial surgery: cost analysis of operating room time saved with 3D printed anatomic models and surgical guides. Academic radiology. 2020 Aug 1;27(8):1103-13.
5. Mishra A, Srivastava V. Biomaterials and 3D printing techniques used in the medical field. Journal of Medical Engineering & Technology. 2021 May 19;45(4):290-302.
6. Tuomi J, Paloheimo K, Björkstrand R, Salmi M, Paloheimo M, Mäkitie AA. Medical applications of rapid prototyping—from applications to classification. Proceedings of the VR. 2009 Oct.
7. Li L, Luo Z, Guan H, Yang Y, Ju X, Jiang S, Jiang J. Design and localization algorithm of flap guide plate for jaw defect based on digital 3D printing. Preventive Medicine. 2023 Aug 1;173:107557.
8. Song YL, Yu N, Danny BP, Chew MT. A pilot study on three-dimensional printing of stainless steel arch bars for orthognathic segmental jaw surgeries. Annals of 3D Printed Medicine. 2022 Jun 1;6:100055.
9. Ramos H, Santiago R, Soe S, Theobald P, Alves M. Response of gyroid lattice structures to impact loads. International Journal of Impact Engineering. 2022 Jun 1;164:104202.

10. Oladapo BI, Kayode JF, Karagiannidis P, Naveed N, Mehrabi H, Ogundipe KO. Polymeric composites of cubic-octahedron and gyroid lattice for biomimetic dental implants. Materials Chemistry and Physics. 2022 Sep 15;289:126454.
11. Xu W, Yu A, Jiang Y, Li Y, Zhang C, Singh HP, Liu B, Hou C, Zhang Y, Tian S, Zhang J. Gyroid-based functionally graded porous titanium scaffolds for dental application: Design, simulation and characterizations. Materials & Design. 2022 Dec 1;224:111300.
12. Yánez A, Herrera A, Martel O, Monopoli D, Afonso H. Compressive behaviour of gyroid lattice structures for human cancellous bone implant applications. Materials Science and Engineering: C. 2016 Nov 1;68:445-8.
13. Cantaboni F, Ginestra P, Tocci M, Colpani A, Avanzini A, Pola A, Ceretti E. Modelling and FE simulation of 3D printed Co-Cr Lattice Structures for biomedical applications. Procedia CIRP. 2022 Jan 1;110:372-7.
14. Guimarães G, Rocha A, Rego R, Barreiros L, Mascheroni J, Kretzer A. Compressive Behavior of Gyroid Structures Manufactured Through SLM with Carburizing Steels: A Numerical and Experimental Study. Procedia Structural Integrity. 2021 Jan 1;34:26-31.
15. Cosma SC, Balc N, Leordean D, Sorin M. Dental implants with lattice structure fabricated by selective laser melting. InInternational Virtual Research Conference in Technical Disciplines, Zilina, Slovacia 2014 (pp. 17-21).
16. Jain S, Soni S, Lodhi S, Khan R, Jain A, Khare B, Thakur BS, Jain PK. Contemporary Trends in Dental Implants. Asian Journal of Dental and Health Sciences. 2022 Dec 15;2(4):48-54.
17. Khan MZ, Bhaskar J, Kumar A. Design and analysis of strut-based lattice structure cranial implant. Journal of Mechanical Engineering and Sciences. 2023 Mar 23:9307-14.
18. Zhang L, Liu H, Yao H, Zeng Y, Chen J. Preparation, microstructure, and properties of ZrO2 (3Y)/Al2O3 bioceramics for 3D printing of all-ceramic dental implants by vat photopolymerization. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers. 2022 Jun 1;1(2):100023.
19. Benedetti M, Du Plessis A, Ritchie RO, Dallago M, Razavi SM, Berto F. Architected cellular materials: A review on their mechanical properties towards fatigue-tolerant design and fabrication. Materials Science and Engineering: R: Reports. 2021 Apr 1;144:100606.
20. Merkani MS, Kazemi A, Mohammadi M, Abrinia K. Impact of additive manufacturing on advances in the design and production of the dental implants. Journal of Computational Applied Mechanics. 2023 Jun 1;54(2):323-35.
21. Tuzzolo Neto H, Tuzita AS, Gehrke SA, de Vasconcellos Moura R, Zaffalon Casati M, Mikail Melo Mesquita A. A comparative analysis of implants presenting different diameters: Extra-narrow, narrow and conventional. Materials. 2020 Apr 17;13(8):1888.
22. 2Li L, Lee J, Amara HB, Lee JB, Lee KS, Shin SW, Lee YM, Kim B, Kim P, Koo KT. Comparison of 3D-printed dental implants with threaded implants for osseointegration: An experimental pilot study. Materials. 2020 Oct 28;13(21):4815.
23. Zherebtsov S, Salishchev G, Galeyev R, Maekawa K. Mechanical properties of Ti–6Al–4V titanium alloy with submicrocrystalline structure produced by severe plastic deformation. Materials transactions. 2005;46(9):2020-5.
24. Wally ZJ, Haque AM, Feteira A, Claeyssens F, Goodall R, Reilly GC. Selective laser melting processed Ti6Al4V lattices with graded porosities for dental applications. Journal of the Mechanical Behavior of Biomedical Materials. 2019 Feb 1;90:20-9.
25. Jelena, M. and Miroslav, T., 2007. Medical applications of rapid prototyping. Facta Univ Ser Mech Eng, 5(01), pp.79-85.
26. Yadav D, Garg RK, Ahlawat A, Chhabra D. 3D printable biomaterials for orthopedic implants: Solution for sustainable and circular economy. Resources Policy. 2020 Oct 1;68:101767.
27. Qin Z, He Y, Gao J, Dong Z, Long S, Cheng L, Shi Z. Surface modification improving the biological activity and osteogenic ability of 3D printing porous dental implants. Frontiers in Materials. 2023 May 31;10:1183902.

28. Johnson JW, Gadomski B, Labus K, Stewart H, Nelson B, Seim III H, Regan D, von Stade D, Kelly C, Horne P, Gall K. Novel 3D printed lattice structure titanium cages evaluated in an ovine model of interbody fusion. JOR Spine. 2023:e1268.

29. Echeta I, Dutton B, Leach RK, Piano S. Finite element modelling of defects in additively manufactured strut-based lattice structures. Additive Manufacturing. 2021 Nov 1;47:102301.

30. Takaki P, Vieira M, Bommarito S. Maximum bite force analysis in different age groups. International archives of otorhinolaryngology. 2014 Jul;18:272-6.

31. Kovács ÁÉ, Csernátony Z, Csámer L, Méhes G, Szabó D, Veres M, Braun M, Harangi B, Serbán N, Zhang L, Falk G. Comparative Analysis of Bone Ingrowth in 3D-Printed Titanium Lattice Structures with Different Patterns. Materials. 2023 May 20;16(10):3861.

32. Hopfensperger, L.J., Talmazov, G., Ammoun, R., Brenes, C. and Bencharit, S., 2023. Accuracy of 3D printed scan bodies for dental implants using two additive manufacturing systems: An in vitro study. Plos one, 18(4), p.e0283305.

33. Sharma, D., & Sharma, V. (2025). Biomechanical analysis of triply periodic minimal surfaces-based porous dental implants versus solid implants: impact of peri-implant bone density on micromotion. *Computer Methods in Biomechanics and Biomedical Engineering*, 1-21.

34. Alqutaibi, A. Y., Alghauli, M. A., Aljohani, M. H. A., & Zafar, M. S. (2024). Advanced additive manufacturing in implant dentistry: 3D printing technologies, printable materials, current applications and future requirements. *Bioprinting*, e00356.

35. Gul, B. C., Demirci, F., Baki, N., Bahce, E., & Özcan, M. (2025). Mechanical analysis of 3D printed dental restorations manufactured using different resins and validation with FEM analysis. *BMC Oral Health*, *25*(1), 131.

36. Layeb, N., Barhoumi, N., Oldal, I., & Keppler, I. (2025). Improving the strength properties of PLA acetabular liners by optimizing FDM 3D printing: Taguchi approach and finite element analysis validation. *The International Journal of Advanced Manufacturing Technology*, 1-16.

37. Alemayehu, D. B., Todoh, M., & Huang, S. J. (2025). Hybrid Biomechanical Design of Dental Implants: Integrating Solid and Gyroid Triply Periodic Minimal Surface Lattice Architectures for Optimized Stress Distribution. *Journal of Functional Biomaterials*, *16*(2), 54.

38. Mehboob, H., Mehboob, A., Abbassi, F., Ahmad, F., Khan, A. S., & Miran, S. (2022). Bioinspired porous dental implants using the concept of 3D printing to investigate the effect of implant type and porosity on patient's bone condition. *Mechanics of Advanced Materials and Structures*, *29*(27), 6011–6025.

39. Banothu, D., Kumar, P., Reddy, R., Dhanapalan, S., & Gobinath, R. (2025). Design, 3D printing, and fatigue analysis of bone implant lattices: a study on structural integrity and failure mechanisms. Smart Materials and Structures.

40. Shaikshavali, G., Yadav, G. P. K., Goud, E. V. G., Reddy, K. M., & Reddy, Y. M. (2025, March). 3D Printing of Scaffolds for Medical Application using Digital Light Processing Technique. In International Conference on Advanced Materials, Manufacturing and Sustainable Development (ICAMMSD 2024) (pp. 611-631). Atlantis Press.

41. Koppunur, R., Ramakrishna, K., Manmadhachary, A., Kumar, D. K., & Sridhar, V. (2025). Topology optimization and manufacturing of maxillofacial patient specific implant using FEA and AM. Bioprinting, e00412.

42. Ansari, M. A. A., Jain, P. K., & Nanda, H. S. (2025). Influence of Pore Geometry on the Compressive Strength and Cell–Materials Interaction of 3D Printed PLA Scaffolds. Polymer-Plastics Technology and Materials, 1-14.

43. Gompana, S. H., & Koona, R. (2025). Study of adaptive multi-scale optimization of lattice structures: A novel framework for engineering applications. Mechanics of Advanced Materials and Structures, 1-18.

44. Kumar, A., & Chhabra, D. (2024). Parametric topology optimization approach for sustainable development of customized orthotic appliances using additive manufacturing. Mechanics of Advanced Materials and Structures, 31(21), 5276-5289.

45. Moghariya, J., & Gurrala, P. K. (2025). Finite element studies on Triply Periodic Minimal Surfaces (TPMS)–based hip replacement implants. The International Journal of Advanced Manufacturing Technology, 136(1), 263-277.
46. Zheng, W., Zeng, S., Wang, J., Bai, G., & Ye, J. (2024). Structural Design and Mechanical Properties Analysis of Gradient Primitive Porous Dental Implant Based on Selective Laser Melting. Journal of Materials Engineering and Performance, 1-16.
47. Alkentar, R., Máté, F., & Mankovits, T. (2022). Investigation of the performance of Ti6Al4V lattice structures designed for biomedical implants using the finite element method. Materials, 15(18), 6335.
48. Verma, R., Kumar, J., Singh, N. K., Rai, S. K., Saxena, K. K., & Xu, J. (2022). Design and analysis of biomedical scaffolds using TPMS-based porous structures inspired from additive manufacturing. Coatings, 12(6), 839.
49. Alemayehu, D. B., Todoh, M., & Huang, S. J. (2024). Hybrid Biomechanical Design of Dental Implants: Integrating Solid and Gyroid TPMS Lattice Architectures for Optimized Stress Distribution.
50. Chen, Y. S., Wu, P. K., Tsai, W. C., & Lin, C. L. (2025). Enhancing bone ingrowth and mechanical bonding in 3D-printed titanium alloy implants via lattice design and growth factors. International Journal of Bioprinting, 8115.
51. Dabaja, R., Swanson, W. B., Bak, S. Y., Mendonca, G., Mishina, Y., & Banu, M. (2025). Spatially distributed and interconnected porous architectures for dental implants. International Journal of Implant Dentistry, 11(1), 30.
52. Shu, T., Shi, H., Li, M., Lin, Y. C., Li, A., & Pei, D. (2025). Microscale bone interlocking enhances osseointegration strength on the rough surface of 3D-printed titanium implants: experimental and finite element analysis. BMC Oral Health, 25, 208.
53. Suksawang, B., Chaijareenont, P., & Silthampitag, P. (2025). Effect of Unit Cell Design and Volume Fraction of 3D-Printed Lattice Structures on Compressive Response and Orthopedics Screw Pullout Strength. Materials, 18(6), 1349.
54. Binobaid, A., Guner, A., Camilleri, J., Jiménez, A., & Essa, K. (2024). A 3D printed ultra-short dental implant based on lattice structures and ZIRCONIA/Ca2SiO4 combination. Journal of the Mechanical Behavior of Biomedical Materials, 155, 106559.
55. Alemayehu, D. B., Todoh, M., & Huang, S. J. (2024). Advancing 3D Dental Implant Finite Element Analysis: Incorporating Biomimetic Trabecular Bone with Varied Pore Sizes in Voronoi Lattices. Journal of Functional Biomaterials, 15(4), 94.
56. Bari, K. (2023). Design, simulation, and mechanical testing of 3D-printed titanium lattice structures. Journal of Composites Science, 7(1), 32.
57. Gao, J., Pan, Y., Gao, Y., Pang, H., Sun, H., Cheng, L., & Liu, J. (2024). Research progress on the preparation process and material structure of 3D-printed dental implants and their clinical applications. Coatings, 14(7), 781.
58. Perween, S., Fahad, M., & Khan, M. A. (2021). Systematic experimental evaluation of function based cellular lattice structure manufactured by 3d printing. Applied Sciences, 11(21), 10489.
59. Lee, J., Li, L., Song, H. Y., Son, M. J., Lee, Y. M., & Koo, K. T. (2022). Impact of lattice versus solid structure of 3D-printed multiroot dental implants using Ti-6Al-4V: A preclinical pilot study. Journal of Periodontal & Implant Science, 52(4), 338.
60. Chung, I., Lee, J., Li, L., Seol, Y. J., Lee, Y. M., & Koo, K. T. (2023). A preclinical study comparing single- and double-root 3D-printed Ti–6Al–4V implants. *Scientific Reports*, *13*(1), 862.