Trabecular-Like Structure based on Triply Periodic Minimal Surfaces 3D-Printed by low-cost LCD-Printing via two-stage curing.

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Abstract

Bone scaffolds based on Triply Periodic Minimal Surfaces (TPMS) represent a cutting-edge approach to creating structures with properties that significantly promote osteointegration. The use of TPMS geometry allows researchers to precisely manipulate parameters such as relative porosity, pore size, and pore shape, all of which influence the mechanical properties of the scaffold and the rate of bone healing. These scaffolds also have the benefits of an interconnected porous network, which is a critical feature for bone regeneration and for additive manufacturing. TPMS scaffolds also enable the generation and control of architectural gradients, including variations in relative density and TPMS geometry. This feature is a major asset for modeling both cortical and trabecular bone in the same scaffold. Cortical bone, with its high density and mechanical strength, contrasts with trabecular bone, which is more porous and flexible. Using data from CT-scans, cortical and trabecular regions can be identified based on mean Bone Mineral Density (BMD) and morphological parameters. This gradient design can effectively replicate the natural structure of bone, optimizing both mechanical stability and biological compatibility. Various 3D printing methods can be used to produce TPMS-based scaffolds, including Stereolithography (SLA), Fused Deposition Modeling (FDM) or Electron Beam Melting (EBM). However, these techniques are often expensive and limited in resolution, constraining the potential for designing really small pore sizes and geometries that can be obtained with TPMS structures. The emergence of consumer-grade Digital Light Processing (DLP) and Liquid Crystal Display (LCD) 3D printers offers a cost-effective alternative. These printers can achieve higher resolutions compared to FDM and EBM and similar resolution to SLA. However, post-curing the printed parts with UV light is a crucial step for ensuring complete polymerization but shows one major flaw. UV penetration depth is limited due to its short wavelength, leading to inhomogeneous polymerization within the scaffold and uncontrolled mechanical properties, especially in its inner regions.

In order to address this limitation, a novel low-cost two-stage curing method has been developed. The initial stage of polymerization occurs during the 3D printing process, with the application of UV light. The photoinitiators present in the commercial resin, when irradiated with 405 nm light, generate free radicals which initiate the polymerization of each layer in accordance with the desired geometry. Following the printing process, the scaffold

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is cleaned in an isopropanol bath in order to remove any unpolymerized resin.The second stage consist of thermal polymerization. In this approach, thermal initiators, such as azobisisobutyronitrile (AIBN), are incorporated into the resin prior to printing. Using a 1% by mass concentration of AIBN, the scaffold is thermally treated at 80$\circ$C for 24 hours. This process releases additional free radicals, which facilitate the completion of the polymerization process in a uniform manner across the structure.

A series of tests were conducted to evaluate the homogeneity of the polymerization and mechanical properties of the 3D-printed scaffolds. The test samples were 3D-printed encapsulated within TPMS cubes of varying relative densities in order to analyze the properties within the scaffold. The samples were subjected to three-point bending tests and nanoindentation experiments, while Fourier-transform infrared (FT-IR) spectroscopy was employed to evaluate the degree of polymerization along the depth of penetration within the structure. The results were compared between samples with and without the addition of AIBN and those subjected to conventional UV post-curing.

The findings demonstrate that the two-stage curing process achieves a homogeneous polymerization rate and consistent mechanical properties throughout the structure. This outcome is unattainable with traditional UV post-curing methods alone, which often result in non-uniform properties due to incomplete inner polymerization. The use of ceramic particle-loaded resins enables the further tailoring of the mechanical properties of the scaffolds. For instance, the incorporation of ceramic particles enables the scaffold's compressive Young's modulus to approach that of cortical bone. This adaptability ensures that the cortical regions of the scaffold, which exhibit higher density and stiffness, can provide the requisite mechanical strength. Concurrently, the trabecular regions, which exhibit a lower density and greater porosity, retain the desired elasticity and permeability for cell infiltration and nutrient transport.
Bone scaffolds based on TPMS geometries represent a transformative step in biomaterials engineering. Their ability to precisely mimic the structural and mechanical characteristics of natural bone enhances their potential for osteointegration and effective bone regeneration. By integrating ceramic-loaded resins and gradient density designs, TPMS scaffolds can provide customized solutions that meet the diverse mechanical and biological demands of bone repair. The development of a cost-effective two-stage curing process using consumer-grade 3D printers marks a significant advance, addressing previous challenges associated with incomplete polymerization and high production costs.