Additive manufacturing technologies have enabled some of the most relevant advances in the fields of tissue engineering and biofabrication, thanks to the solid freeform fabrication opportunities they provide, which prove very adequate for achieving complex geometries capable of interacting in personalized ways with the human body. From pioneering studies dealing with the fused deposition modeling of tissue scaffolds as extracellular matrices for cells to more recent bioprinting approaches which typically use layer-by-layer fabrication techniques with living organisms and biomaterials to produce complex tissues in vitro (or use computer-aided transfer processes for patterning and assembling living and nonliving materials with a prescribed 2D or 3D organization to produce bio-engineered structures), the possibility of manipulating matter in an additive way has proven transformative. However, additional progress is needed, as there is not yet a single additive manufacturing technique (AMT) that provides the perfect compromise between achievable part size, printing resolution, dimensional operative range, structural stability, and overall biocompatibility. For instance, syringe-based bioprinting techniques are still less precise than the more traditional AMTs working with synthetic materials, which are already a mainstream trend in biomedical engineering, medical practice, and biotechnology fields (i.e., selective laser sintering or melting of metallic powders, laser stereolithography with biopolymers or lithography-based ceramic manufacturing, among others). Other biomanufacturing techniques, such as laser-assisted bioprinting has led to an improved precision level for manipulating living organisms and biomaterials, and could possibly synergize with 3D lattices, used as boundaries or structural supports. This would help to minimize hydrogel creep and

Carbon is a promising material for tissue engineering due to its excellent bioactivity, and electrical and mechanical properties. Herein, 3D microarchitected carbon structures are presented toward scaffolds for cell culturing. The 3D carbon microlattice architectures are fabricated by fabricating 3D architectures of an epoxy polymer by stereolithography, followed by pyrolysis at 900 °C in a nitrogen environment. The pyrolysis causes 64–80% shrinkage of the microlattices resulting in the formation of carbon microlattices with a minimum lattice element thickness of 103.22 ± 22.84 μm. The carbon microlattices exhibit several microstructural deformations including wavy and bent lattices, and hollow bulges along the microlattices. These hollow bulges become the weakest section of the microlattice architectures under compressive load. The microlattice architectures exhibit elastic modulus around 2.28 MPa, which is within the range of elastic modulus suitable for application in human tissue repair. Furthermore, the in vitro cytocompatibility of the carbon materials is analyzed by culturing osteoblast-like murine MC3T3-E1 cells on the carbon microlattice architecture. The results show that cells are able to adhere and survive on the carbon microlattices with high viability. These results are promising for future applicability of the carbon architectures for personalized scaffolds for tissue engineering.

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to achieve multi-scale and multi-material scaffolding structures with biomimetic functional gradients of mechanical properties. In contrast, the most precise additive manufacturing technologies, especially two-photon polymerization, which enables interactions even at single cellular level, are not still adequate in terms of throughput and the overall building volume is normally limited to less than 1 mm³. Furthermore, the materials used by most industrial AMTs, especially those relying on photopolymerization, are normally inadequate for implantation and, consequently, the achieved cell culture systems are limited to performing in vitro studies. In some cases, the use of carbon coatings (i.e., diamond-like carbon) upon laser stereolithography microsystems or the use of carbon fibers knitted to 3D-printed structures have proven adequate for enhancing cell viability upon or within tissue-engineering constructs, although with geometrical limitations and again limited to in vitro experimentation.

Carbon is indeed a promising material for tissue engineering and biofabrication, due to its interesting bioactivity, and mechanical and electrical properties that may open new horizons for self-sensing implants. In fact, a variety of carbon nanomaterials (graphene oxide, nanotubes, fullerene, carbon dots, among others) have been proposed as tissue scaffolds, although in many cases they need to be processed as additives within synthetic polymeric matrices or following procedures that lead to sponge-like structures, without externally controlled geometries, which limits design opportunities for specific tissue defects. In addition, carbon cannot be yet additively processed, without being embedded in thermoplastic filaments (i.e., acrylonitrile butadiene styrene or polyactic acid), whose biological response is less adequate than that of pure carbon. Ideally, tissue-engineering scaffolds should be biodegradable, even if both degradable and nondegradable solutions coexist, as reviewed previously, and help to further progress in the field. In some cases, degradable and nondegradable components coexist in the same tissue regeneration device, usually with a permanent structural element and a biodegradable region for enhanced biocompatibility. The fact that carbon lattices may not be biodegradable can lead to suboptimal solutions, although still showing interesting potentials in connection to the tissue engineering and biofabrication fields. In addition, the carbon lattices may also constitute a promising intermediate stage toward final biocompatible hydroxyapatite scaffolds, through subsequent carburization, oxidation, carbonation and phosphatization processes, as detailed by Tampieri et al.

To achieve pure carbon design-controlled 3D lattices or porous structures, with resolution and overall dimensions in a range needed for the tissue repair of relevant size defects, pyrolytic transformation of additively manufactured constructs may prove an interesting approach. Pyrolysis of photopolymerized 3D constructs has been reported, both at the micro and macro scale, although, to the best of our knowledge, not validated for tissue-engineering applications. In addition, pyrolysis of wood has proven interesting for tissue engineering and pyrolyzed conducting scaffolds from sugar cubes have been reported. However, features are difficult to control with these techniques, yet control over the microstructures are needed to enable personalized tissue repair.

In this communication, we report on the use of stereolithographically printed 3D carbon microlattice architectures as scaffolds for tissue engineering. We first present results toward fabrication of design-controlled 3D carbon lattice structures. Furthermore, we address the effect of microstructure of carbon microlattices on the mechanical properties of carbon microlattice architectures. We finish by demonstrating culturing of osteoblast-like murine MC3T3-E1 cells on the carbon microlattice architectures.

We fabricated the 3D carbon architectures by printing 3D architectures of an epoxy resin using stereolithography, followed by carbonization in a nitrogen environment at 900 °C. Figure 1a, b show examples of 3D-printed epoxy lattice structures before and after pyrolysis. The carbonization process was associated with geometrical shrinkage of the structures, which is due to escape of volatile by-products during thermal decomposition of the epoxy. Such shrinkage (64–80% in linear dimension) allows fabrication of carbon microlattices with dimensions much smaller than the epoxy microlattices fabricated using stereolithography alone.

To characterize the geometrical limitation of our process, we fabricated microlattices with different lattice thicknesses. The lattice element widths of both the fabricated epoxy architecture and the carbonized samples are plotted in Figure 1d. We also drew a design line as denoted by the green dash-dot line in Figure 1d. The design line represents the ideal scenario where the fabricated lattice thickness equals to the design lattice thickness. It should be noted that the fabricated lattice thicknesses were higher than the design thickness of the lattices. Such mismatch between the designed dimension and the fabricated dimension is expected due to the intrinsic characteristics of the layer-by-layer printing approach. In our fabrication process, before fabrication, the computer-aided design (CAD) geometry is “sliced” with the support of ad hoc software for generating the trajectories of the manufacturing tool, which in the case of stereolithography is a laser “drawing” lines upon a photopolymer. The slicing layers were 100 μm and the construction platform also moves in steps of 100 μm. These led the soft surface of the CAD file to a stepped shape of the manufactured parts. Furthermore, minor design modifications featuring dimensions smaller than the layer thickness might have been also modified with the slicing thickness during the slicing process, and resulted in a thicker dimension than the designed one for the fabricated structures. The smallest lattice element thickness achieved in our process was 646.67 ± 20.00 μm.

The carbon lattices featured significantly lower lattice thicknesses compared with the epoxy lattices due to the thermal shrinkage. The smallest lattice element thickness achieved here after carbonization was 103.22 ± 22.84 μm. This translates to a shrinkage of 80.26 ± 4.19% (Figure 1e). However, shrinkage for the design lattice width of 800 μm was 64.31 ± 5.14%. This means that the amount of shrinkage varies inversely with the lattice width, which can also be seen in the plot shown in Figure 1e. Shrinkage during the carbonization process occurs due to formation of volatile by-products during thermal degradation of the precursor polymers and degassing of the volatile components. These phenomena directly depend on the surface area to volume ratio (SA:V) of the lattice structures. Hence, higher degassing occurs for structures with higher SA:V. This was
confirmed when we plotted shrinkage in the lattice thickness against the SA:V in Figure 1f. However, SA:V relates to inverse of the lattice thickness ($D$) as shown in Equation (1). Hence, lattice structure with smaller thickness yielded higher shrinkage.

$$\text{SA : V} = \frac{\text{Surface area}}{\text{Volume}} = \frac{\pi DL}{0.25\pi D^2 L} = \frac{4}{D} \quad (1)$$

Although the carbonized samples retained the structure of the precursor geometry, the shrinkage of the top part of the lattice structure seemed higher than the lower part of the lattice structure, as shown in Figure 1b. We suspect that the precursor underwent a coking process during the carbonization process. As a feature of the coking process, the precursor transformed into a semisolid material at high temperature.\cite{30} Due to the semisolid state, the bottom part might have adhered to the crucible, which might have restricted the bottom part from shrinking freely. In comparison, the top part could shrink freely. Such uneven shrinkage might have resulted in such tapered cubical lattice structures. Such phenomenon is common in carbonization of epoxy structures, as described in several previous publications.\cite{29,31–34} Furthermore, the structural integrity of the carbon microlattice structure strongly depends on the lattice element design thickness and design gap between adjacent lattice elements. Too large bulky lattice elements induce larger thermal stress during the shrinkage, which eventually fails the structure resulting in cracks and breakages.\cite{31,34} In contrast, too close spatial separation of the lattice elements will result in collapsing the lattice elements onto each other during shrinkage, which also fails the structure. A detailed study will be needed to identify such fabrication limitations. However, with proper lattice thickness and spatial separation, as fabricated in this work, we speculate that scaling up the overall size of the lattice structure will not fail the structural integrity after carbonization. Such speculation originates from the successful scaling up of 3D-printed carbon microlattice architectures demonstrated by other researchers.\cite{26,27} However, validation of such successful scaling up needs to be performed for our system, especially for successful application as scaffold for tissue engineering. The systematic analysis of the scaling behavior, by manufacturing all type of geometries and spacings, is beyond the scope of this article. We plan for such thorough study for a future article.

Although the structural integrity of the lattice structures was preserved during carbonization, the carbon lattices exhibited several microstructural deformations, observed when inspected using scanning electron microscope (SEM). As shown in Figure 1c and Figure S1, Supporting Information, the lattices are wavy and bent, and feature several bulged-up sections. The formation of wavy and bent features might have occurred due to the semisolid state of the material during the coking process, which permits creep flow, and this was preserved in the final structure of the lattices. Furthermore, the bulged-up sections were suspected as formation of gaseous bubbles. During carbonization, some portion of gaseous substances generated during the thermal decomposition of the precursor might have been trapped inside the semisolid material, forming bulges along the lattice elements. This hypothesis is confirmed by the hollow cavities found inside the bulges, as indicated by the blue circle in the Figure 1c.
The carbonized material was further characterized using Raman and X-ray diffraction (XRD) studies to investigate the material uniformity and microstructural properties. The results are presented in Figure 2a,b, respectively. Two distinct peaks centering around 1343 and 1598 cm\(^{-1}\) can be observed in the Raman spectra of the samples. The peak around 1343 cm\(^{-1}\) is denoted as the D-band which represents the presence of disorder in the carbon matrix. The peak around 1598 cm\(^{-1}\) is for G-band, which corresponds to the active graphitic mode of the carbon. The intensity ratio of the D-band and G-band (I\(_D\)/I\(_G\)) for our sample was 0.95, which suggests the presence of good number of graphitic planes in our carbon samples.\(^{[35,36]}\) To further understand the degree of disorder in our carbon sample, we deconvoluted the Raman spectra using Lorentzian fit. The Lorentzian peak fit for G-band was at 1595 cm\(^{-1}\), which is left-shifted from the original G-band peak. This is possibly because of the merging of G- and D'-peaks due to high degree of disorder.\(^{[37]}\) This is further supported by the broadening of the D-peak. Furthermore, we calculated the crystallite size \(L_0\) using the Tuinstra and Koenig equation, as proposed by Cançado et al., which postulates the dependence of \(L_0\) on the laser wavelength (\(\lambda\)) and integrated area ratio (\(A_D/A_G\)) of D-band and G-band (Equation (2)).\(^{[38]}\)

\[
L_0 = (2.4 \times 10^{-10}) \lambda^4 \left(\frac{A_D}{A_G}\right)^{-1}
\]  

(2)

The \(L_0\) for our sample was \(\approx 6.70\) nm, which is similar to a turbostratic structure of carbon.\(^{[39]}\) The presence of turbostratic microstructures is further supported by the doublet structure of the 2D peak (\(\approx 2700\) cm\(^{-1}\)) along with the broadening of the 2D peak featuring a full width at half maximum of \(\approx 250\) cm\(^{-1}\).\(^{[37]}\)

The turbostratic microstructure of the carbonized sample was also supported by XRD spectroscopy. The bulge portions in the XRD spectrum that are centered around \(2\theta = 29^\circ\) and \(2\theta = 42^\circ\) represent the reflections of the (002) and the (100) plane of carbon, which are characteristics of the turbostratic microstructure of the carbon.\(^{[40,41]}\) However, peaks for antimony (Sb) were also observed in the XRD spectrum. To confirm the presence of Sb, we performed energy-dispersive X-ray (EDX) analysis of the carbon lattices. However, no peaks for Sb were found in the EDX spectrum, as shown in Figure 2c. This suggests the appearance of Sb as a contamination during sample preparation for XRD using a mortar-and-pestle. The EDX results also suggested that the composition of the carbonized sample includes 99.14\% ± 0.21\% carbon and 0.86\% ± 0.21\% oxygen, which implies formation of impurity-free carbon during pyrolysis.

One of the important aspects in tissue engineering is that the scaffold should mimic the biomechanical properties of the tissue at the site of implantation.\(^{[42,43]}\) Hence, it is important to characterize the structural properties of the scaffolds for their proper implantation. We characterized the structural properties of the carbon microlattices by characterizing the structural density and elastic modulus of the microlattice architectures, as shown in Figure 1b. The structural density was calculated using an envelope method, i.e., the ratio between mass of the microlattice architecture and its volume.\(^{[44–47]}\) As expected, the structural density increases with the microlattice thickness (Figure 3a). The structural density increases from 0.115 ± 0.018 g cm\(^{-3}\) for design lattice width of 400 \(\mu\)m to 0.184 ± 0.030 g cm\(^{-3}\) for design lattice width of 800 \(\mu\)m. The elastic modulus of the microlattice architectures was calculated from the stress–strain curve (Figure S2a, Supporting Information) obtained by performing compression tests using a 5 N load. The elastic moduli of the carbon architectures were plotted in Figure 3b. It was surprising to observe that the carbon microlattices featured an elastic modulus around 2.28 MPa irrespective of their lattice thickness. This was unlikely as we expected an increase in elastic modulus with an increase in lattice thickness; i.e., the elastic modulus should be proportional to the material density. Our initial hypothesis was that the actual volume of the carbon microlattices was significantly less than the total measured volume as occupied by the

![Figure 2. a) Raman spectra of the carbonized stereolithographically fabricated microlattice architectures. The Raman spectra was deconvoluted into D, G, 2D, and D + D' peaks for better understanding of the microstructural properties of the carbon material. b) XRD spectra of the carbonized microlattice structures suggesting formation of turbostratic carbon during carbonization process. Presence of antimony (Sb) can be also seen, which might appear during sample preparation as contamination. c) EDX of the carbonized microlattice sample showing presence of only carbon and oxygen.](image-url)
microlattice architectures, in which case the effect of the microlattice thickness might be minor. To validate the hypothesis, we performed numerical simulations using similar microlattice architectures as for the experiments. The simulation results are shown in Figure S2d–i, Supporting Information. Elastic moduli obtained from the simulation results were also plotted as shown in Figure 3b. Unlike the experimental data, the simulation results showed a strong dependence of lattice thickness on the elastic modulus, and the elastic modulus was significantly higher than the measured experimental modulus (200–900 MPa for simulation vs 2.28 MPa for experiments). From such results, our next suspicion was that the hollow bubble-like features were the cause of the experimental behavior. We inspected the microlattice structures collected after the compression tests using SEM. Figure 3c,d show the cross-sections, where brittle fracture had occurred during the compression tests. It can be noticed that the fracture occurred at the bubble-like sections as indicated by the dashed ellipses. At these sections, the carbon wall forming the bubble had a wall thickness of 2–3 μm. To confirm this new hypothesis, we performed another simulation using a hollow lattice structure and featuring a wall thickness of 3 μm, for which results are plotted as shown in Figure 4b. Using the hollow structures, the elastic modulus dropped down to 4–6 MPa, which is on the order of the experimental results. Furthermore, no dependence of the lattice thickness on the elastic modulus was observed while simulating using the hollow lattices, which agrees well with the experimental results. Although our microlattice structures are not entirely hollow, the hollow bubble-like sections were the weakest sections of the microlattices, which is sufficient for the reduction of structural modulus. Under compressive load, these weak sections became more prone to failure, resulting in mechanical failure of the entire structure. Consequently, this results in a low elastic modulus, again irrespective of the lattice thickness. Fortunately, the results are impressive in terms of potential application of the structures as scaffolds for human tissue engineering. For example, human trabecular bones feature an elastic modulus ranging from 1 MPa to 10 GPa, depending on the location and function of the bones.[48,49] This implies that the carbon microlattice structures exhibit suitable mechanical properties for tissue engineering for specific trabecular bones. The elastic modulus of the carbon microlattices can be further improved by fabrication of defect-free solid carbon microlattices as suggested by the simulation results. Such carbon microlattices can be achieved by modifying the carbonization process, which depends on the thermal degradation mechanism of the epoxy.[25] Hence, an extensive study is needed for understanding the thermal degradation of the epoxy. This will lead to define the carbonization recipe to obtain the...
defect-free solid carbon microlattices. However, the hollow bubble-like features may have some positive effects on the applicability of these materials, structures, and processes to the development of tissue-engineering scaffolds. Indeed, the bubble-like features may guide the formation of vasculature, a yet unsolved challenge in the biofabrication field, and an aspect we plan to focus on in forthcoming studies.

For preliminary assessment of the biological performance of the current framework, the in vitro cytocompatibility of the carbon materials was analyzed by culturing osteoblast-like murine MC3T3-E1 cells on the cubical carbon microlattice architecture (Figure 1b and Figure S1a, Supporting Information) with a design lattice thickness of 400 μm. Figure 4 shows a selection of the results obtained from the cell culturing experiments. These results demonstrate that the cells are able to adhere and survive on the carbon microlattices as cells can be stained in green with calcein-AM, a nonfluorescent cell-permeable dye that inside the living cells is converted to green fluorescent calcein after acetoxymethyl ester hydrolysis by intracellular esterases. This is promising and shows that the 3D carbon microlattice architectures are excellent companions for potential tissue repair strategies. In the event of tissue damage, similar cell-seeded carbon lattices may constitute functionally graded supports, which enable the permeation of nutrients and debris, promote oxygenation, enable adaptation, and provide cellular communication systems. However, additional studies can be realized using confocal microscopy facilities and performing osteochondral differentiation, which may let us provide more details about the 3D configuration of the cells within the whole constructs. Furthermore, additional assessments, both in vitro and in vivo, need to be performed.

Regarding future applications of these 3D carbon scaffolds, extracellular matrixes or cell culture niches, it is interesting to consider potentials linked to osteochondral repair, considering that the more rigid carbon lattices can be topologically designed to mimic the porous structure of bone. To this end, we plan to culture osteoblasts and chondrocytes on similar structures in the near future to analyze additional types of cell-material interactions. Furthermore, potential effects of these 3D carbon architectures on gene expression and subsequent differentiation of mesenchymal stem cells into different lineages, mainly bone and cartilage, is a relevant study we would like to tackle soon but outside of the scope of the present study. Apart from these potentials, linked to actual tissue repair and regeneration, the translation of these carbon scaffolds to in vitro testing devices and organ-on-a-chip systems for modeling disease may be even more directly achievable. The viability of cell culture processes upon these systems is already demonstrated and, with

Figure 4. Selection of cell culture results. The left column shows optical images of the osteoblast-like murine MC3T3-E1 cells on the carbon microlattices. The middle column shows the fluorescence images showing the viability of the cells adhered to the carbon structures. The last column presents the merged image of optical and fluorescence image showing cells cultured only on the carbon lattices.
some minor modifications, they can be adapted to the implementation of labs- and organs-on-chips or to the functionalization of 2D culture systems for turning them into biomimetic 4D environments.

In summary, we successfully demonstrated the fabrication of carbon microlattice architectures as scaffolds for tissue engineering. The fabrication process includes 3D printing of an epoxy architecture using stereolithography, followed by carbonization at 900 °C. During carbonization, a shrinkage of 64–80% in the microlattice thickness occurred. The smallest carbon lattice thickness achieved in our process is 103.22 ± 22.84 μm. Fabrication of smaller carbon lattices would be possible while using a stereolithography system with higher spatial resolution. The carbon obtained here features turbostratic carbon microstructures as shown by Raman and XRD spectra. Unlike the precursor, the carbon microlattice displays uneven sections, such as hollow bubble-like structures, which were the weakest point in the microlattice structure under compressive load. The elastic moduli obtained for cubic carbon architectures were around 2.8 MPa, which is within the range for implants for human tissue regeneration. Furthermore, osteoblast-like murine MC3T3-E1 cells were cultured successfully around the carbon microlattices with high viability, which proves excellent cytocompatibility of the carbon microlattices. Overall, these first results with the carbon microlattice structures represent promising candidates for future in vivo and in vitro tests for personalized scaffolds for tissue engineering.

Experimental Section

Design and Manufacturing of Lattice Structures: CAD of a set of lattice and porous structures was performed with the support of CATIA v.5 (Dassault Systèmes) and NX-8.5 (Siemens PLM Software Solutions) software packages. The geometries designed stood out for their geometrical complexity, based on interwoven elements and trusses; for covering different kinds of scaffolding geometries, as cubic, cylindrical, and toroidal lattices were used; and for providing systematic variations of truss thicknesses, as required for methodic evaluation of the pyrolysis process. To achieve the geometries of interest, a combination of extrusion, sweep features, and Boolean design operations were performed and the parametric design features of the aforementioned design software are also used.

Once obtained, the CAD models with the desired scaffolding geometries were converted into an .stl (standard tessellation language or stereolithography) file format for further processing. The master models or “green parts”, for subsequent pyrolysis, were manufactured using the SLA-3500 laser stereolithography system developed and commercialized by 3D Systems (3D Systems, USA). Epoxy resin WaterShed XC11122 (DSM Desotech BV, Netherlands), was used as prototyping material for such master prototypes or green parts. In short, the geometry stored in the .stl file was “sliced” with the help of the Lightyear software, provided with the stereolithography system, which generated the trajectories for the printer’s laser beam. The beam works layer-by-layer, activating the polymerization of the resin and generates 3D solid components and structures with complex geometries by this additive photopolymerization process. After manufacture, the master prototypes were cleaned by 2 min immersion in acetone and finally post-cured (generally to improve mechanical properties) in an UV-oven for around 10–20 min, depending on the resin’s specifications.

Pyrolysis for Obtaining Carbon Scaffolds: The structures obtained from the laser stereolithography were heat treated at 900 °C in a horizontal tube furnace (Carbolite Giro, Germany). The heat-treatment process used here was adapted from a heat-treatment recipe popularly used in the carbon microelectromechanical systems (C-MEMS) community for the conversion of carbon from polymer precursors. [47, 51–54] Our heat-treatment process was as follows: 1) heating from room temperature to 900 °C with a heating rate of 2.5 °C min⁻¹; 2) dwell at 900 °C for 1 h; and 3) cooling down to room temperature using natural cooling. Natural cooling was implemented by turning off the heater of the furnace. The entire heat-treatment process was performed under a constant nitrogen flow (flow rate 0.8 L min⁻¹) to maintain an inert atmosphere throughout the process.

Materials and Microstructural Characterization of the Carbonized Samples: The carbonized structures were characterized by SEM (Carl Zeiss AG—SUPRA 60VP SEM) for microstructural characterization. We performed Raman spectroscopy and XRD to characterize the nature of the pyrolyzed epoxy. Raman spectroscopy (Bruker Sentraa) was carried out using a diode pumped solid state laser (λ = 532 nm) at 2 mW power with a penetration depth <1 μm. XRD (Bruker D8 Advance diffractometer) was performed using Cu-Kα radiation (λ = 1.5405 Å).

Experimental Characterization and Numerical Modeling for Elastic Modulus: The compression tests were performed on a Zwick Roell testing machine using a load cell of 5 N with a compression rate of 0.5 mm min⁻¹. The experimental elastic modulus was determined from the slope of the stress–strain curve obtained from the compression test. Finite element modeling (FEM) of pyrolyzed carbon scaffolds was performed with NX-8.5 (Siemens PLM solutions), with the aim of better understanding the structural changes during shrinking and of validating the possibility of predicting their mechanical behavior. Two scenarios after carbonization were analyzed: A) an ideal shrinkage leading to reduce sized structures with completely compact trusses, and B) a more realistic shrinkage, in which size reduction leads also to hollow trusses, as experimentally understood from subsequent microscope inspections.

Starting from the original CAD models used for obtaining the “green parts” by laser stereolithography, different scales were applied, according to the measured shrinkage values. Ideal carbonized structures with cubic geometries (scenario A) were meshed with four-node 3D tetrahedral elements (NX Tetra4 of 0.1, 0.08, and 0.05 mm for the different sized structures), whereas real carbonized structures with hollow trusses (scenario B) were meshed with 2D rectangular elements (NX Quad4 of 0.02 mm) and a thickness of 2 μm obtained from microscopies. A material with properties similar to those of turbostratic carbon (Young’s modulus of 20 GPa, density of 2200 kg m⁻³, Poisson ratio of 0.3), [55, 56] was defined and applied to the structures under study.

To estimate the equivalent Young’s moduli of the different structures, the lattices were compressed by application of a normal force of 5 N on one side. The elements of the opposite side were kept fixed. Loads and boundary conditions mimicked the actual mechanical testing procedure applied to the real prototypes after pyrolysis. Structural simulation was then performed using the structural static calculation module (Sesstatic Solution 101) of NX. Post processing of results was performed with the user interface of NX, and simulations were compared with actual testing results for critical discussion purposes.

Cell Culture Experiment: To study cell adhesion to the materials and their cytocompatibility and efficiency for bone growth, MC3T3-E1 (ECACC 99072810), an osteoblast-like cell line, was chosen. MC3T3-E1 cells were seeded on carbon microlattices at 5 × 10⁶ cells mL⁻¹ in Dulbecco’s Modified Eagle Medium (DMEM) enriched with 10% fetal bovine serum (FBS), glutamine 2 mM, and 1% penicillin–streptomycin. Cells growing on carbon microlattices were maintained in a humidified atmosphere at 37 °C and 5% CO₂ for 3 days. Live cells were then stained with Calcein-AM (Molecular Probes), and cell viability was evaluated by fluorescence microscopy using an inverted Leica DM IRB microscope equipped with a digital camera, Leica DC100 (Leica, Nussloch, Germany).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest

The authors declare no conflict of interest.

Keywords

carbon microlattices, carbon scaffolds, pyrolysis, stereolithography, tissue engineering

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