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Advanced Manufacturing for Biomaterials and Biological Materials, Part II

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The development of biological materials, bioinspired materials, and biomaterials often requires advanced manufacturing and processing techniques that can realize the complex material structures and enhanced material properties that are a hallmark of these scientific fields. Research into techniques such as three-dimensional (3D) printing, freeze casting, and laser engraving can provide novel tools to enact these structures and properties. Many of these aspects are represented in this special topic Advanced Manufacturing for Biomaterials and Biological Materials. The second part of this topic addresses materials that are non-metallic, specifically ceramic, polymer, and biological materials.

Hydroxyapatite is widely used for orthopedic and dental applications. However, effective processing methods for the production of hydroxyapatite bioceramic compounds from a biological origin are of high interest for low-cost manufacturing. In the manuscript on "Low-cost hydroxyapatite powders from tilapia fish," Sales et al. have routed a relatively simple process for this purpose through calcination of tilapia bones as raw materials for hydroxyapatite, which can be applied to bioactive composites and other biomedical applications.

The manuscript "Tissue-engineered interlocking scaffold blocks for the regeneration of bone" addresses a significant problem in the repair of large bone defects using tissue-engineered scaffolds: under these circumstances, the initiation of bone growth takes far too long. Kundu et al. report a unique design of mechanically stable interlocking blocks wherein the large defect shape is filled using interlocking scaffold blocks coated with bone morphogenic proteins (BMP-2 and BMP-7). The nanocomposite scaffold blocks are made using polycaprolactone and amino acid-modified nanoclays intercalated with mineralized hydroxyapatite. On seeding with human mesenchymal stem cells (MSCs) and osteoblasts, BMP-coated scaffolds showed higher ECM (extracellular matrix) formation. Also, when assembled, accelerated tissue growth was observed compared with the similar-sized scaffold. Enhanced osteogenic differentiation of MSCs, characterized by the formation of defined fibril-like collagen, was observed at the interfaces between the blocks. The block assembly does not compromise the mechanical integrity of the macroscopic cylindrical scaffolds. Thus, a novel BMP-coated interlocking block system is presented for accelerated bone growth.

Natural materials show efficient hierarchical design strategies expanding from nano- to microscales to achieve high-performance biomechanical systems that break the trade-offs observed in man-made materials. In this regard, bioinspiration represents an innovative approach for the development of material architectures that can be tailored toward a multiplicity of applications. An example of the strategies found in nature is the use of dense architectures composed of stiff and strong building blocks joined by tough energy-dissipating interfaces offering a combination of high stiffness and high toughness. This strategy is commonly found in highly mineralized biological materials such as tooth enamel, dactyl clubs of the mantis shrimp, and seashells. In the review article "Fabrication and

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mechanics of bioinspired materials with dense architectures: current status and future perspectives" by Mirkhalaf and Zreiqat, the authors present an overview of the current status of advances in fabrication and mechanics of bioinspired architectures with dense architectures. They show that materials with dense architectures offer interesting properties such a combination of high strength and toughness, multi-hit capability, damage sensing, self-healing, and the ability to cover complex surfaces. However, despite the far more abundant material diversity and more powerful manufacturing tools available to engineers, nature is still ahead in using dense architectures to improve mechanical performance. This is primarily due to the difficulty in the development of scalable and fast fabrication technologies for the implementation of dense architectures and their associated deformation/failure mechanisms at a small scale. The authors conclude that although there has been some progress, there is still a need for the development of innovative manufacturing approaches to implement micro- and nano-architectures to enable the next generation of multifunctional materials and to expand the envelope of mechanical properties currently available.

In an effort to address some of the multiscale manufacturing challenges required to enable new bioinspired materials, in the manuscript "Control of porosity in freeze casting," Gil-Duran et al. used a combined experimental and numerical approach to evaluate the contributions from the process parameters in the final material microstructure of ceramics obtained by freeze casting. The authors found that the location, distribution, and orientation of pores in the microstructure of these ceramics are highly dependent on the geometrical and thermal properties of the mold used during processing. Therefore, a porous structure with a required morphology can be obtained by tuning the temperature gradients during freezing of the slurry through careful control of the dimensional and thermal properties of the mold.

The manuscript "3D laser engraving applied to the fabrication of tough and glass-based bioinspired materials" exploits the favorable properties of glass. In addition to being transparent, glass features durability, low electrical conductivity, and corrosion resistance; however, its brittleness still limits its range of applications. In their manuscript, Dalaq et al. explore three-dimensional laser engraving to generate 3D networks of weak interfaces within bulk glass. These interfaces deflect cracks and dissipate energy by friction, with mechanisms that are similar to those that provide fracture resistance in mollusk shells or teeth. Using confocal microscopy, the authors characterized the morphology of laser-induced microcracks in borosilicate glass and ceramic glass and measured the effective toughness of laser-engraved interfaces. They explored the effect of microcrack spacing on interface morphology, damage parameters, fracture surfaces, and fracture toughness. Dalaq et al. employed this information to fabricate architectured borosilicate glass panels that exhibited higher impact energy absorption than monolithic glass.

Nelson et al. have contributed the manuscript "Helical and Bouligand porous scaffolds fabricated by dynamic low strength magnetic field freeze casting." In this work, porous Fe_3O_4 scaffolds were fabricated while subject to a low (7.8 mT) magnetic field applied in helical and Bouligand motions using a custom-built tri-axial nested Helmholtz coil-based freeze-casting setup. This setup allowed for the control of a dynamic, uniform low-strength magnetic field to align particles during the freezing process resulting in the majority of lamellar walls aligning within $\pm$ 30° of the magnetic field direction and a decrease in porosity by up to 42%. Similar to how helical and Bouligand structures in nature promote impact resistance, these magnetic field motions produced structures with improved high-strain-rate mechanical properties. Strain at failure was increased by up to two times as cracks deflected to match the applied angles of rotation of the magnetic field.

In the review article "Peeling in biological and bioinspired adhesive systems," Skopic and Schniepp provide a comprehensive review of peeling stresses in biological materials along with discussion of bioinspired materials based on these natural systems. Two systems were primarily discussed, gecko feet and spider silk. In both cases the biological materials are capable of withstanding both significant peeling stresses and repeated peeling events, yet maintain their adhesive properties. Understanding adhesive properties is expected to be particularly important in manufactured multi-component materials, such as bioinspired hierarchical composites.

In the manuscript "Effect of low temperature plasma treatments on surface modification of polycaprolactone pellets and thermal properties of extruded filaments," Mohammed et al. demonstrate the impact of oxygen plasma on polymers common to 3D printing. Polycaprolactone polymer pellets were surface modified using oxygen plasma for a variety of durations and then formed into filaments and extruded. The structural and thermal properties of the resultant materials were examined, and it was found that the surface treatments successfully modified the hydrophobicity, but were unable to significantly alter the thermal properties. These results demonstrated the necessity for further research into the use of plasma surface modifications in polymer filaments.

To read or download any of the papers from this topic, follow the URL http://link.springer.com/journal/11837/72/4/page/1 to the Table of Contents page 193 for the April 2020 issue (vol. 72, no. 4).

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