3D PRINTING OF BIOMATERIALS

This special issue of the Journal of Materials Research contains articles that were accepted in response to an invitation for manuscripts.

Introduction

Guest Editors:

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The concept of 3D printing (3DP) started in mid-1980s with stereolithography where plastic parts could be directly manufactured from curing monomers using ultraviolet light layer-by-layer. This idea of direct printing was very exciting particularly for rapidly prototyping concept models or show-and-tell pieces, but not functional parts. All first generation 3DP processes were focused on polymeric materials and mimicking the size and the shape of a design rather than functional properties. However, from the mid-1990s, 3DP processes started to evolve to manufacturing functional components. Three decades later, 3DP has revolutionized most manufacturing sectors by significantly reducing time to produce elements and minimizing cost related to manufacturing parts with higher complexity.[1] The focus is no longer on low-quality plastic parts that are primarily used for 'touch and feel' or design validation, but on functional components of metals, ceramics, polymers, and composites that are now routinely manufactured using 3DP and used in almost all sectors from space to toys to biomedical devices. 3DP-related businesses have grown to multi-billion dollar enterprises around the world, and the growth rate continues to rise for most manufacturing sectors worldwide. However, application of 3DP in biomedical devices is still relatively new and only recently have regulatory bodies in different countries begun to approve 3D-printed devices for human use.[2,3]

Application of 3DP in biomaterials is being realized in many areas. Polymer-based 3DP technology is the most mature, where manufacturing biopolymer-based parts via 3DP is a growing area of research. These polymers could be bioresorbable for tissue engineering applications or non-resorbable for various functional devices or surgical tools. Following polymers, metals are the next group of materials for which commercial 3DP technologies are mature enough to produce functional devices.

Traditionally, metallic devices are manufactured via casting or forging, followed by final machining or surface modification and finished with sterilization. Use of 3DP can reduce the number of steps needed to manufacture such devices, particularly those where a porous coating can be beneficial, thus reducing the cost of production significantly while increasing the yield. Other salient advantages of 3DP for manufacturing these products lies with smaller footprints for manufacturing operations, on-demand manufacturing as opposed to projection-based manufacturing, and ease of manufacturing patient-matched devices. Using 3DP, complete functional device manufacturing can be done with one or two machines that are not sensitive to design changes. This idea also helps to protect intellectual property at the early stages of product development because even small companies can establish a 3DP facility for design iterations and new product development. Moreover, in the past most biomedical devices were produced based on market prediction or a projection-based systems. If an event changed projections, device manufacturers struggled to meet altered market demand quickly or sat with a large inventory without customers. 3DP technology now allows on-demand manufacturing for shorter lead time to produce parts with different designs and compositions. Finally, there is always demand for patient-matched biomedical devices due to complex fractures, unique anatomy, or concerns related to allergies, just to name a few. Use of 3DP can produce patient-matched devices easily and directly without any design-specific tooling. Such devices can be tailored for specific patient needs without significant addition to manufacturing costs.

3DP of ceramics is still mostly at the research stage due to concerns related to reproducibility and reliability in mechanical properties. However, there is significant interest in 3DP of porous ceramic scaffolds for bone tissue engineering, as these scaffolds can be tailored for their bioresorption ability for different clinical needs.[4,5] Apart from porous scaffolds, 3DP is also being explored to modify surface chemistry via ceramic coatings. 3DP technology for ceramic polymer composites is widely studied for a variety of biomedical device applications. In general, 3DP of ceramics is still in its infancy and expected to grow in the coming years.[6]

Since early 2000, 3DP research is growing toward the new field of bioprinting. The concept of bioprinting is simple. Instead of printing acellular materials, live cell-laden materials are printed along with acellular materials

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with a ultimate goal of organ-tissue engineering. Even in its early stages, bioprinting is being used to create a variety of cell lines for organ tissue engineering using different polymers as a substrate material. Though very exciting, cell viability for larger tissues and their three-dimensional growth remains a challenge.

Current challenges and future trends

3DP of biomaterials is a rapidly growing, inherently interdisciplinary field in which both biological science and expertise in engineering sciences are often needed along with clinicians' perspectives. While expectations are rising in equal measure, the most important challenge for 3D-printed biomaterials is to prove that they can perform at the same level as conventionally processed materials, and with reliable reproducibility.

Since 3DP components are produced in a layer-by-layer manner, chances of defect accumulation during processing are much higher than with conventional manufacturing. Processing defect-free 3D-printed biomaterials requires in-depth understanding of process-property relationships as well as in situ imaging during manufacturing to identify defects as they happen. Most 3DP processes are not capable of such a high level of quality control, which is an inherent challenge that must be overcome. For large part manufacturing, local temperature fluctuations during part building dependent on the specific tool path is also of concern. Inherent surface roughness can be beneficial in some applications for 3D parts, but for many applications, such surface finish is not acceptable. Therefore, some finishing operation may be necessary for the final product.[7]

For 3D-printed ceramic elements, process optimization and reproducibility are still primary challenges. Similarly, for 3D-printed metal parts, loosely bound powders can be of serious concern in vivo. Not only is removal of those powders challenging, but predicting where those powders may be located can also be very difficult. Mechanical properties of 3D-printed metal components usually show better performance than those conventionally processed under uniaxial loading. However, under fatigue loading, 3DP parts often show lower performance than conventionally processed ones. At present, many surgical tools are manufactured via 3DP. Maintaining a clean work environment, minimizing part-to-part variation, and establishing appropriate sterilization process for 3D-printed biomedical devices will continue to evolve further in the coming days. Moreover, manufacturing products with multiple materials is poised for significant growth using 3DP. The main idea behind multi-material 3DP is not only to match the size and shape of the parts but also to add functionality at selected locations by varying compositions in one manufacturing operation. Demand for such multi-material 3DP certainly will grow in the future.

We sincerely appreciate contributions from different areas of the world from authors with expertise in engineering sciences, physical sciences, biological sciences, and medicine. We have received manuscripts related to processing, applications, and modeling of 3D printing involving ceramic, composites, metals, bioprinting, and coatings or surface modification. These papers highlight current research trends in biomaterials and biomedical devices using 3DP.

ON THE COVER:

Cover image came from the W. M. Keck Biomedical Materials Research Lab at Washington State University. Front image is of a calcium phosphate scaffold manufactured using an ExOne binder jetting 3D printer. The background color image is from the same group showing bone-tissue integration after implantation in critical sized defect in rabbit tibia.

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