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News & Views

Materials creation adds new dimensions to 3D printing

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Additive manufacturing (AM), interchangeably termed as 3D printing (3DP), has been defined as one of the key technologies in the national development strategies of a number of countries around the world. America Makes, as the National Additive Manufacturing Innovation Institute, is the nation's leading and collaborative partner in AM/3DP technology research, discovery, creation, and innovation, working efficiently to innovate and accelerate AM/3DP to increase America's global manufacturing competitiveness (https://americamakes.us). German government has launched the "High-tech Strategy for 2020" and "Industrie 4.0" which aims to lay Germany the international leader in the development and innovation of a new generation of innovative technologies including AM/3DP (http://www.plattform-i40.de/I40/Navigation/EN/Home/home.html). "Made in China 2025" plan has claimed that AM/3DP technology hopefully leads the change of manufacturing mode and promotes the transformation and upgrading of China's manufacturing industry (http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm).

Depending on the materials, objects to be built, and final application purpose, there are a number of AM/3DP processes that have been commercially available. The initially developed AM/3DP processes include stereolithography apparatus (SLA), laminated object manufacturing (LOM), fused deposition modelling (FDM), and selective laser sintering (SLS), which are typically applied for the fabrication of prototype parts made from low-melting-point plastics, polymers, and resins. To meet the requirements for AM/3DP fabrication of high-melting-point metallic and ceramic components, the typical processes in terms of direct metal laser sintering (DMLS), selective laser melting (SLM), and laser metal deposition (LMD)/laser engineered net shaping (LENS) have been developed. DMLS/SLM and LMD/LENS represent two different development directions for AM/3DP of high-melting-point components. DMLS/SLM is based on the laser powder bed approach and the parts produced by DMLS/SLM are impressive in their elaborate structures including thin walls, sound surface finish, fine configurations, and small internal channels. Contrarily, LMD/LENS is based on the laser powder feeding method, demonstrating a high capability in printing larger-sized 3D parts [1].

The most common materials used for AM/3DP are typically pure materials, from the low-melting-point plastics, polymers, and resins to the high-melting-point metals, alloys, and ceramics. Furthermore, more novel materials with unique properties, such as composite materials, multiple materials, functionally gradient materials, and even metamaterials, are currently being studied for AM/3DP and are hopeful to be applied successfully in the near future. As depicted in Fig. S1 (online), originated from the diversity of materials, there are the generalized requirements on design methodology. Besides the design of chemical compositions and physical properties of material itself, the structure of the parts to be built, the AM/3DP process, and even the preferable performance of the final parts are all

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required to be designed dedicatedly. The characteristics of a tailored AM/3DP process include high speed, high efficiency, high reliability, and attendant high precision [2]. The conventional mechanical properties, including the static properties (e.g., density, strength, and hardness) and the fatigue property, have been a long-term research issue for AM/3DP parts. Furthermore, there are a number of latest researches began to focus on the functions of AM/3DP parts, such as the chemical properties (corrosion resistance, oxidation resistance, biocompatibility, etc.) and the physical properties (microwave property, magnetic property, stealth property, hydrophilic/hydrophobic property, etc.). As a traditional routine, the performance of AM/3DP parts is implemented passively based on the determined material and process. Conversely, the future development tendency for AM/3DP lies in the following three aspects: (1) The performance-driven material design and process control; (2) the navigation of the complex material-process-structure-property relationship based on design methodology; and (3) the initiative implementation of the performance of AM/3DP parts. Behind the change of the future research strategy, the most significant research need is a more complete, fundamental understanding of the basic science behind each AM/3DP process, as highlighted in "Roadmap for Additive Manufacturing" of America [3].

It has been widely accepted that the applied material plays a fundamental role in determining the final performance of AM/3DP parts. From the viewpoint of basic research, the Mechanical Engineering Department of National Natural Science Foundation of China (NSFC) puts forward the following guidelines: Basics, Frontier, Exploration, and Innovation [4]. It accordingly prompts us to consider which materials can be used in the future for AM/3DP to broaden the advantages of this advanced manufacturing technology. If the current status of AM/3DP materials is defined as "Use Materials" (i.e., the use of the existing materials), in the next 3–5 years "Develop Materials" (i.e., the development of designed materials with elevated performance) will be a promising direction. If from a more long-term perspective of 6–10 years in the future, "Create Materials" (i.e., the creation of artificially designed materials with physically unusual properties or even unavailable properties in nature) is expected to induce the breakthrough in AM/3DP technology. The three typical stages for the future development of AM/3DP materials are illustrated in Fig. S2 (online).

Based on the perspective of "Use Materials", the production of hard-to-process materials by AM/3DP technology, especially with the integration of the advanced laser technology that can provide the high energy required for production, is regarded as a promising method to adapt to the materials and their manufacturing for extreme environments. For instance, magnesium (Mg) is not only 30 % lighter than aluminum, but it can also be used to produce resorbable implants, thus making it extremely desirable for use in lightweight construction and medical applications. However, Mg is very challenging for laser-based AM/3DP, since it is highly combustible, explosive, and has an extreme sensitivity to oxygen. Experts from Fraunhofer Institute for Laser Technology ILT (http://www.ilt.fraunhofer.de/en/press/press-releases/press-release-2016/press_release_20160301.html) have developed a SLM AM/3DP technique that now makes it possible to work on the difficult Mg material. To combat heavy smoke formation, a new process chamber featuring optimized shielding gas flow has been developed for use with Mg alloys. Implant (scaffold) with defined pore structure has been made from biodegradable Mg alloy (WE43) (Fig. S3a online) and the biocompatibility of the implant prototypes has already been demonstrated in vitro. Furthermore, SLM allows for full topology optimization to obtain lighter and stronger components, demonstrated by a topology-optimized motorcycle triple clamp (AZ91) which represents one of the world's first example of complex components made from Mg alloys (Fig. S3b online). SLM AM/3DP of hard-to-process Mg opens the door to new applications not only in lightweight construction, but also in medical technology such as custom-made surgical bone replacements. Another good example of hard-to-process materials for AM/3DP is Ni–Ti shape memory alloy, which is regarded as one kind of metallic smart materials. The pseudoplasticity (shape memory effect) or super elasticity is adjustable by choice of the suitable AM/3DP process and parameters. Also from Fraunhofer ILT (http://www.ilt.fraunhofer.de/content/dam/ilt/en/documents/annual_reports/ar15/TF3/AR15_S134.pdf), the development of micro SLM (μSLM) AM/3DP technology out of conventional SLM has demonstrated clear advantages in producing Ni–Ti medical functional parts such as endovascular stents having fine surface quality and resolution (Fig. S3c online). The successful application of Ni–Ti shape memory alloy for AM/3DP favors a large leap from 3DP to 4D printing.

In the viewpoint of "Develop Materials", AM/3DP of multiple materials to yield the elaborately designed components and properties is of significant interest. Modern technologies not only strongly rely on the unique processing methods, e.g., AM/3DP, but also urgently call for even better materials. Multiple materials and multiscale structures provide a possible route to optimizing overall properties of components [5]. A key goal of the strategy "Develop Materials" by AM/3DP technology is the realization of "Right Materials in Right Positions". The recent breakthrough in AM/3DP of the extremely high-melting-point ceramics from HRL Laboratories, USA provides an excellent demonstration of the precise development of multiple materials by AM/3DP [6]. This innovative work consists of two steps to produce polymer-derived ceramics by AM/3DP: (1) Preceramic monomers are cured with ultraviolet light in a SLA 3D printer, forming 3D polymer structures that can have complex shape and cellular architecture. (2) These polymer structures are pyrolyzed to a ceramic with uniform shrinkage and virtually no porosity. From the structural characteristics, since ceramics cannot be processed easily by conventional methods such as casting or machining, AM/3DP enables a big leap in geometrical flexibility for ceramics. In terms of properties, it reveals that silicon oxycarbide (SiOC) honeycomb cellular materials fabricated with this approach exhibit strength 10 times as high as commercially available ceramic foams of similar density and survive temperatures of 1,700 °C in air with surface oxidation, which is of interest for the core of lightweight, load-bearing ceramic sandwich panels for high-temperature applications, e.g., in hypersonic vehicles and jet engines. Taking the AM/3DP of polymer-derived ceramics as an example, a tailorable AM/3DP of multiple materials that guides the material development should consider the following criteria: (1) "Material Control": phase transformation and composition and microstructure change mechanisms of ceramics pyrolyzed from 3D printed preceramic polymer; (2) "Structure Control": mass loss and structure shrinkage mechanisms of 3D printed preceramic polymer during high-temperature pyrolysis process; (3) "Performance Control": densification behavior and mechanical properties enhancement mechanisms of polymer-derived ceramics during 3DP and subsequent pyrolysis. Therefore, the idea of "Develop Materials" by AM/3DP requires an integration of material, structure and performance, which in turn requires a trans-scale control of AM/3DP process and resultant performance from microscale (e.g., phases, microstructures, compositions) to macroscale (e.g., structures, dimensions, properties).

Originated from the idea of "Create Materials", AM/3DP of "metamaterials" containing artificially designed 3D topologies hopefully achieves the physically unusual properties or even the properties unavailable in nature. Typically, the scalable metamaterials consisted of hierarchical 3D topologies whose feature size spans seven orders of magnitude in length scale, from tens of nanometers to tens of centimeters. The fabrication of the multiscale metamaterial is enabled by a high-resolution, large-area AM/3DP technique with scalability not achievable by two-photon polymerization or traditional SLA, as revealed in recent work of Zheng et al. [7] from Virginia Tech, Lawrence Livermore National Laboratory, and Massachusetts Institute of Technology, USA. At the macroscale the 3D printed metamaterials achieve high tensile elasticity (>20 %) not found in their brittle-like metallic constituents, and a near-constant specific strength. With overall part sizes approaching tens of centimeters, these unique nanostructured metamaterials by AM/3DP might open a wide range of mechanical applications. One the other hand, the development of solutions based on biological adaptations is one of the most exciting frontiers in AM/3DP for materials creation, which is termed as "Biomimicry" or "Bio-inspired 3DP" [8]. As indicated in a comment from *Nature* entitled "Push the limits of 3D printing" [9], in nature "shape is cheap but material is expensive" and, moreover, manufacturing complex is always more costly than handling simpler, more monolithic elements. Therefore, a key challenge for 3DP designers and manufacturers is how to duplicate the finely realized shapes in nature with the right materials and processes. Materials creation helps the development of 3DP technology, like a tiger with wings added. The future AM/3DP technology highlights the creation of materials, the biomimicry of natural structures, and optimization and breakthrough of performance. For instance, spider spin intricate webs that serve as sophisticated prey-trapping architectures simultaneously exhibit high strength, elasticity and graceful failure, which has been treated as biological bionic object for a long time [10]. To determine how web mechanics are controlled by their topological design and material distribution by AM/3DP, a series of challenging scientific issues should be considered, including (1) local failure and stiffness distribution in synthetic webs; (2) asymptotic size effect on web strength; (3) spider web with scalable mechanics; and (4) optimizing the synthetic web for multiple functions [11]. Therefore, it is considered that although natural structure is easy to copy, AM/3DP manufacturing is not easy and, substantially, the underlying science is the most difficult. Therefore, science runs through the whole process of the materials creation by AM/3DP to realize the integration of material, structure, and performance.

Finally, I propose an example from our research group on laser AM/3DP of lobster eye structure, as illustrated in Fig. 1, to demonstrate the importance of materials creation on the future development and progress of AM/3DP technology. Firstly, we "borrow" the lobster eye structure from the nature to carry out the bionic design of a functional porous component which can cause the light to converge. The significant challenge for the design is how to accurately design the taper of each hole to ensure the convergence of light. Secondly, as the component will serve in an extreme environment of outer space with a considerable temperature difference between day and night, the multiple materials, i.e., the aluminum matrix composites (AMCs) reinforced with the nanoscale/in-situ formed ceramics, are prepared are to replace the conventionally used pure aluminum alloys [12–14]. The difficulties in design and preparation of AMCs lie in the complexity of in-situ reaction between ceramic reinforcement and metal matrix

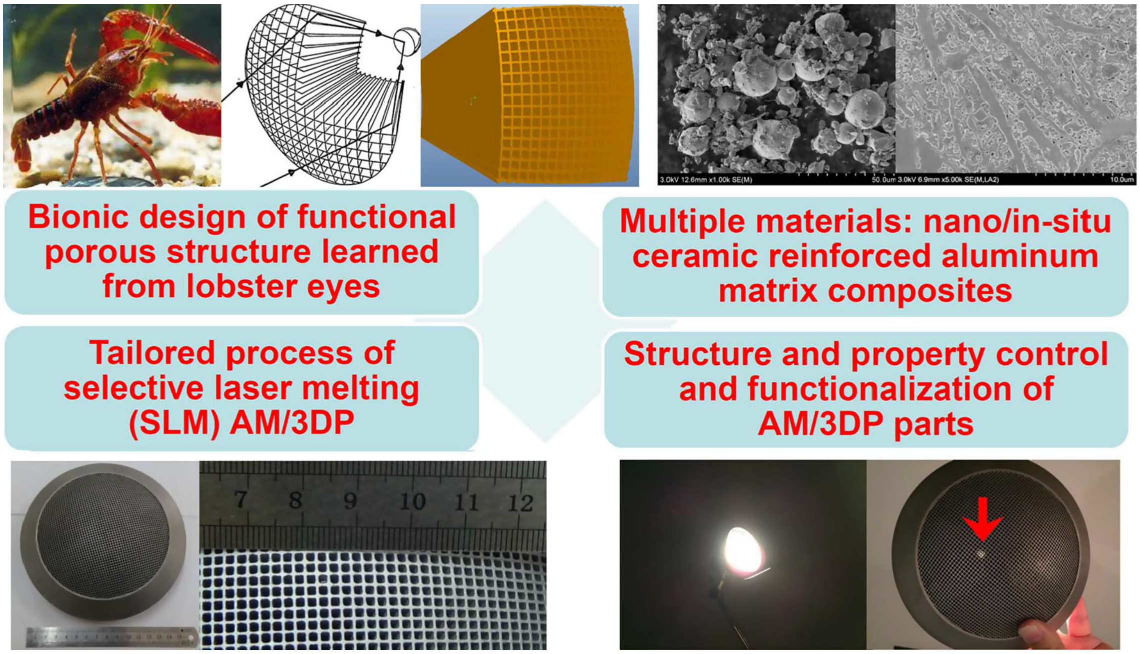

Fig. 1 (Color online) An integration of structural design, material preparation, process control, and functionalization of laser AM/3DP lobster eye structure

during laser AM/3DP as well as the regular dispersion of ceramic reinforcement with a high volume fraction. Thirdly, the as-designed lobster eye component is a typical difficult-to-process structure, which has the densely distributed hole arrays with a high height-to-width ratio. There are more than 24,000 holes within a disc diameter of 160 mm and the hole wall is only 0.2 mm. Process window for laser-based SLM AM/3DP should be carefully determined to control the SLM building process, to ensure the sound structure and property of AM/3DP component, and finally to realize the functionalization of the component.

In summary, materials are the basis of AM/3DP technology and the materials creation hopefully adds new dimensions to 3DP and extends the connotation of this advanced technology, thereby providing new opportunities for the future development of AM/3DP. The idea of “Create Materials” by AM/3DP is a step-by-step process based on the ideas of “Use Materials” and “Develop Materials”. The performance-driven materials creation and AM/3DP process control are emphasized to facilitate the initiative implementation of the performance of AM/3DP parts. The strategy of “Right Materials in Right Positions” is an important way to achieve the designed performance of AM/3DP parts. A trans-scale control of AM/3DP process from microscale to macroscale is necessary to achieve the material-structure-property integration of AM/3DP parts.

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Conflict of interest The author declares that he has no conflict of interest.

References

1. Gu DD, Meiners W, Wissenbach K et al (2012) Laser additive manufacturing of metallic components: materials, processes and mechanisms. Int Mater Rev 57:133–164
2. Tumbleston JR, Shirvanyants D, Ermoshkin N et al (2015) Continuous liquid interface production of 3D objects. Science 347:1349–1352
3. Bourell DL, Rosen DW, Leu Ming C (2014) The roadmap for additive manufacturing and its impact. 3D Print Addit Manuf 1:6–9
4. Department of Engineering and Materials Sciences, National Natural Science Foundation of China (NSFC) (2010) Mechanical engineering disciplines development strategy report (2011–2020). Science Press, Beijing
5. Lu K (2010) The future of metals. Science 328:319–320
6. Eckel ZC, Zhou CY, Martin JH et al (2016) 3D printing additive manufacturing of polymer-derived ceramics. Science 351:58–62
7. Zheng XY, Smith W, Jackson J et al (2016) Multiscale metallic metamaterials. Nat Mater 15:1100–1106

8. Gou ML, Qu X, Zhu W et al (2014) Bio-inspired detoxification using 3D-printed hydrogel nanocomposites. Nat Commun 5:3774
9. Pawlyn M (2013) Push the limits of 3D printing. Nature 494:174
10. Omenetto FG, Kaplan DL (2010) New opportunities for an ancient material. Science 329:528–531
11. Qin Z, Compton BG, Lewis JA et al (2015) Structural optimization of 3D-printed synthetic spider webs for high strength. Nat Commun 6:7038
12. Gu DD, Wang HQ, Dai DH et al (2015) Rapid fabrication of Al-based bulk-form nanocomposites with novel reinforcement and enhanced performance by selective laser melting. Scr Mater 96:25–28
13. Gu DD, Chang F, Dai DH (2015) Selective laser melting additive manufacturing of novel aluminum based composites with multiple reinforcing phases. Trans ASME J Manuf Sci Eng 137:021010
14. Dai DH, Gu DD (2016) Influence of thermodynamics within molten pool on migration and distribution state of reinforcement during selective laser melting of AlN/AlSi$_{10}$Mg composites. Int J Mach Tool Manuf 100:14–24