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Towards sustainable 3D Printing

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ABSTRACT. Additive manufacturing (AM) technologies are disrupting our society by proposing a faster and customizable way of producing parts. Along with the technological advances, the environmental, economic, and societal aspects of AM must also be addressed to create a sustainable future. In this viewpoint, I will briefly introduce three key challenges towards this goal, that are the **materials** diversity, the mechanical strength and stiffness and the use of green affordable materials. After describing our recent efforts, I will discuss forthcoming difficulties and alternatives, and stress the need for aligned research across communities.

Introduction: the disruption of additive manufacturing

Additive manufacturing (AM), also called 3D printing (3DP), is expected to disrupt the way we fabricate and conceive object and devices, creating a new future for the manufacturing industry.¹ Indeed, AM is now shifting from being used for rapid prototyping and research to mass production. The main reasons in favor of the development of 3DP technologies for large-scale fabrication are (i) the automation of the process that reduces the need of manpower in fabrication

plants, (ii) the possibility of fabricating customized parts and therefore a large range of products using one machine, (iii) the diversity and complexity of the shapes as compared to standard processes, and (iv) the reduced amount of waste as compared to subtractive fabrication methods. Furthermore, digitalization and computer-aided design allow fast knowledge transfer between fabrication sites, thereby reducing costs, transport and packaging.

To build a sustainable future embracing 3D printing, its impact on the environment, the economy, and the society cannot be ignored. The advantages of AM for reducing pollution are yet still in debate as comprehensive life cycle assessments are challenging to conduct and to compare with established fabrication routes.² The large variety of different 3D printing methods further complexifies it.³ Also, the extensive use of computational data may make 3DP appear misleadingly green. Furthermore, the main parts produced by AM should also have a long life performance and be recyclable to slow down the generation of waste and the depletion of resources. Finally, economical disruptions are to be anticipated to avoid the growing of inequalities between developing and rich countries, as it is so far predicted.⁴

Addressing chemical dependence, poor mechanics and limited inclusivity of 3DP

Three key specific issues have to be tackled to use AM for a sustainable future (**Figure 1**):

- the *materials* dependence of current 3DP methods. Current 3D printers work for selected materials compositions only. A 3D printer that can build a complex design out of titanium alloys with excellent properties may not be able to print similar pieces out of aluminum, even less out of polymer or ceramic. To expand the use of 3DP, it is desirable to have “one machine for all”, that is therefore a *materials*-independent printer.

- *the poor mechanical properties of most parts, especially ceramics.* Most 3DP ceramics contain large grains and small defects that dramatically reduce their mechanical properties. By being unreliable, those materials cannot be used in applications where lightness, temperature and corrosion resistance, or electrical insulation could significantly increase the performance.

- *the limited inclusivity of 3DP.* Although 3D printers are available to the public in many libraries, schools, etc. in rich countries, marginalized societies and developing countries have less access to the technology.^{4,5} Inclusive participation is key to build a globally sustainable future and fair society while transitioning to a larger use of AM.

Figure 1: Sustainable goals and challenges for additive manufacturing (AM), specific problems targeted and proposed research approach. B is the magnetic field, v_z and v_x printer speeds, D , d and d' the barrel, nozzle and print line diameters, respectively, l is the tip length and α the nozzle angle.

Controlling orientation in Direct-Ink-Writing

To address the current chemical dependence of 3DP, Direct-Ink-Writing (DIW) could be combined with microstructural orientation control. DIW is an extrusion-based printing method

where an ink or paste is extruded through a nozzle and deposited layer-by-layer. DIW is able to accommodate a large range of viscosities and has been used to create small microfluidic chips as well as houses. DIW relies primarily on rheology of the ink. Furthermore, when the ink contains particles, they can be manipulated using external fields to locally tune the properties in the part. Our recent efforts have demonstrated that, following the appropriate particle functionalization, low external magnetic fields can orient anisotropic particles of various dimensions and chemistries, in liquid or viscous matrices and in dilute or concentrated suspensions.⁶ We have shown that by combining slip casting and time-varying magnetic fields, we can build assemblies of platelets with local controlled orientation (**Figure 2A**).⁶ Those tools can now be combined with DIW to achieve local orientation in 3D shapes in an automated and programmable fashion.

Bio-inspiration to increase the properties

Microstructure control is one bio-inspired strategy to increase properties in ceramics and highly reinforced composites. Horizontally aligned brick-and-mortar structures, nacre-like, have been shown to increase the toughness of ceramics up to 10 times. Now, it is required to explore how microstructure impacts properties in ceramics and how the interfacial properties at the grains interface can be tuned, in dense⁷ and porous ceramics (**Figure 2B-D**).⁸ In addition, the microstructure also influences functional properties, such as morphing, conductivity, transparency, etc. As initial blueprints, taking inspiration from the microstructures found in natural hard materials can help to create enhanced ceramics and composites for applications in healthcare, aerospace and electronics.^{9,10}

Green and affordable inks for more inclusivity

Materials that perform extremely well are already present in our environment: wood, clay, latex, gelatin, etc. These materials are green, affordable, and easily available world-wide. To increase inclusivity of 3DP, inks and protocols using these materials should be available, and added value using 3DP demonstrated. For example, inks based on agricultural waste and fungi open new promises (**Figure 3A,B**).¹¹ While the fungus degrades the nutrients from the waste, it grows a tight network to yield a stiff composite that also has anti-fire and sound attenuation properties, among others. The DIW of this ink could help optimize the fungus growth and resulting properties, for applications as furniture or in housing.

Figure 2: (A) Scanning electron micrographs of a fractured cross-section of a multi-layered textured structure with alternating platelet orientation of 90° between layers. Reproduced with permission from reference 6. Copyrights 2019, the authors, published by the Royal Society of Chemistry. (B) Shrinkage after sintering as a function of the aspect ratio and alumina microplatelet orientation, (C) Relative density and porosity as a function of the diameter of the microplatelet before sintering, (D) Scanning electron micrographs of cross-sections of vertically aligned porous alumina ceramics prepared with initial microplatelets diameter of 3.6 and 6.6 μm . B-D reproduced with permission from reference 8. Copyrights 2020, Elsevier.

Figure 3: (A) Modulus- density map for mycelium- bound materials, (B) Electron micrograph of mycelium grown on bamboo fibers in presence of chitosan. A,B reproduced with permission from reference 11 under license CC BY 4.0. Copyrights 2020, the authors, published by Elsevier.

Forthcoming challenges and proposed alternatives

Anticipated difficulties for DIW with local orientation pertain to the consolidation of the prints due to local anisotropy and properties mismatch. One suggestion is to use DIW as a near-net shape process followed by infiltration or pressing. Sustainable paths using self-assembling proteins, biomineralization, or cold sintering could solve the issue. Furthermore, having a method with materials diversity, local microstructure, and 3D shaping capabilities will soon pose the challenge of selecting optimal designs. Machine learning and artificial intelligence are expected to be of great help in that direction. Design of structure and composition will be particularly critical in ceramic materials to prevent the development of flaws. Furthermore, using waste materials as ink may be hindered by our capacity to process and prepare this waste, for example by chopping, grinding, hydrolyzing, etc. Finally, although rheology plays a major role in DIW, coding skills and electrical actuation are also required to be taught effectively. It would be interesting to fabricate a printer using electrical waste and to develop further smartphone technologies for 3DP design and control, or alternatively develop 3D printers based on mechanical actuation. Evaluating the needs and benefits of 3D printing in remote rural areas will also be critical to first determine the needs and potential benefits of 3DP there.

Conclusion

As research and applications in AM advance, the development of DIW with microstructural control could better optimize the properties of stiff highly reinforced materials and allow us to establish ink compositions and protocols using green affordable materials. Aligned efforts of scientific communities and the public are expected to lead to a sustainable future and society that embraces new technologies.

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Notes

The author declares no competing financial interest.

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BIOGRAPHY

Hortense Le Ferrand received an engineering degree from ESPCI Paris, France and a master and doctoral degree in Materials Science from ETH Zürich, Switzerland. Since January 2019, she is Assistant Professor in the Schools of Mechanical and Aerospace Engineering and Materials Science and Engineering at Nanyang Technological University, Singapore. Her research focus on structural composite fabrication using bio inspired and microstructural designs to generate multifunctional properties. In 2020, she was awarded the prestigious National Research Foundation (NRF) Fellowship from NRF, Singapore, to pursue research on additive manufacturing.