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Roadmap for Additive Manufacturing: Toward Intellectualization and Industrialization

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ABSTRACT

With the rapid development of Additive Manufacturing (AM) technology in the past 30 years, AM has been shifting from prototyping to advanced manufacturing of functional components in industry. Intellectualization and industrialization of AM process and equipment could be the bottlenecks to the wide industrial applications of AM technology in the future, which have been highlighted in this paper, aiming at describing the technological research roadmaps for the next 5 to 10 years. According to the data flow in the process and value chains of AM technologies, state-of-art of design methodology, material, process & equipment, smart structures, and applications in extreme scales and environments has been elaborated respectively. Some suggestions on potential challenges for research and development in AM technologies have been provided in each section, which would finally establish a critical technical platform for the future industrial innovation and entrepreneurship.

1. Introduction

Additive manufacturing (AM, also known as 3D printing) technology is a manufacturing process of joining materials (including liquid, powder, wire or sheet) to construct three-dimensional objects from digital model, usually in a layer-by-layer manner. In comparison with subtractive manufacturing, such as milling, turning, etc., and formative manufacturing, including casting, forging, etc., AM has a short technological development period since 1980s, and a great potential to promote the manufacturing technology revolution in the future. At present, in the manufacturing industry, serious lack of innovation capacity for the development of new products has become the bottleneck restricting the development of manufacturing industry. AM can quickly and efficiently realize the fabrication of new products and provide an effective approach for product research and development. Besides, AM could reduce the capital and personnel technical threshold of the manufacturing industry, which helps to promote the microenterprise in manufacturing industry, to activate social wisdom and capital resources. Additionally, AM provides great opportunities for manufacturing revolution and new product generation, which could realize the restructuring of manufacturing industry, and promote the transformation of the manufacturing industry to intelligent manufacturing [1].

The most important advantage bought by AM technology is releasing the design freedom of material selection and structural configuration, which can achieve controllable shape and customized performance. AM technology successfully realized the digitalization of design and fabrication process by creating the data flow from materials to final applications, as shown in Fig. 1. Most of engineered materials in different state could be utilized as raw materials in AM process, in which even new properties and performance could be designed and prepared by microstructure and composition design of raw materials. From microscale to meso- and macro-scales, AM technology has brought significant opportunities to the design and fabrication of complex structures with different functionalities, especially in complex curved surface, hierarchical lattice and thin-wall/hollow structures. On the basis of complex structures, functional and smart structures could also be realized by the supports of cutting-edge material science, design methods, process & equipment.

With the rapid development of AM technology in the past 30 years, AM has been shifting from prototyping to advanced manufacturing of functional components in industry. Thus, the intellectualization and in-

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Fig. 1. Schematic illustration of the roadmap for additive manufacturing.

dustrialization of process and equipment could be the bottlenecks to the wide industrial applications of AM technology in the future. Intelligent AM technology could realize unmanned, more accurate and stable manufacturing process by close-loop control. By establishing the process model of AM, the corresponding parameters could be corrected automatically by using the process database and big data analysis technology, which will be one of the most critical development directions of AM. Meanwhile, as a rapidly emerging and developing technology, AM is still far from fulfilling the requirements of the traditional industry in mass production mode of standardization and industrialization. Single part, small batch, and mass customization could be achieved in the future industrialization for AM, especially for extreme manufacturing in the aspects of environment and scale, as shown in Fig. 1.

In order to break through the challenges for AM toward intellectualization and industrialization, the state-of-art development and technological roadmap have been illustrated in this paper, according to the data flow in the process and value chain in AM technologies from design methodology, material, process & equipment, and structures to industrial applications, as shown in Fig. 1. Transformations for AM technology from digitalization to intellectualization, innovation to industrialization, have been highlighted in this paper, aiming at describing the technological research roadmaps for the future 5 to 10 years. Some recommendations have been provided in each section for the potential research and development topics of AM technologies.

2. Design Methodology

Additive manufacturing enables the intelligent design and fabrication freedom for three-dimensional structures and products. Design for AM has become the emerging research field for interdisciplinary study. A computer-aided design approach known as topology optimization (TO) is used to generate innovative and complex configuration of structures, exhibiting tunable stiffness, hierarchical features, and outstanding lightweight performance [2, 3] Part consolidation by TO is revealed as another advantageous design strategy of combining multiple parts of an assembly into a single printable component (Fig. 2(a)) [4]. Further, multidisciplinary optimization is addressed in recent, and the design structures need to meet multiple objectives and satisfy relevant constrains such as complex loading condition, high heat resistance, limited stress and displacement (Fig. 2(b) and Fig. 2(c)) [5, 6]. Integrated AM-driven design is introduced to tailored to account for typical design constrains (e.g., overhang angle in Fig. 2(d)–2(f)) [7, 8] and take advantage of the process features (e.g., anisotropy of materials, building orientation and process parameters) [9, 10]. Advanced thermo-mechanical simulation is used to predict the temperature gradient and residual stress distribution upon process, the obtained temperature or stress fields can be applied to facilitate TO eliminating structural deformation [11]. The hierarchical design of micro-lattice and macro-structure by TO exhibits outstanding lightweight and mechanical performance as compared with solid structure as illustrated in Fig. 2(h)–2(k). Further, a data-driven TO incorporating process-structure-property-performance relationship of AM is developed to achieve the concurrent optimization of multiple process parameters, building orientation and structure configuration [12, 13]. Metamaterials exhibiting extraordinary macroscopic properties based on the collective response of the periodically constructed elements rather than the individual ones [14, 15], could be established by two mainstream methods, i.e., the ad hoc method and TO [16].

To date, the following challenges still exist in the near future, as shown in the Fig. 3:

(1) **Structural and multidisciplinary TO** still face the advent of design challenges. Integrated optimization of structural design needs to consider the extreme loading conditions such as wideband vibration, material fatigue under cyclic loading, extreme high temperature and strong radiation. Multiphysics modeling of external loadings are required to be implemented to enhance and broaden the horizon of integrated optimization. The designed component maintains the necessary mechanical properties and possesses other functionalities such as optical, electromagnetic, thermal performances, etc. The multi-physics-driven volumetric design is introduced to integrate multi-scale features and multi-type of materials in digitalization to achieve function fusion of structures.

(2) **Knowledgebase-driven approach** is proposed for organize and manage the intensive data trends for AM-driven design, which is an important aspect of intelligent design and manufacturing system [20]. This knowledgebase includes material database of formulation/composition, library of functional lattice cells, combination of process parameters, etc. and their correlations. This information can be traced from the entire flow of design, manufacturing and evaluation. The relationship of material-process-structure-performance/functionality in AM need to be established by quantitative physical model or data-driven model [21]. For instance, multiphysics process simulation, artificial intelligent as well as machine learning algorithm can be utilized for quantitative relationship establishment [22]. Thereafter, knowledgebase-driven design can fully incorporate these relationships with structural topological optimization so as to bridge the gap between ideal design principle and realistic AM-fabricated structures.

(3) **Product lifecycle via cost-oriented management** will be addressed on the advanced solutions, which recommend the digital model of the part to compensate proactively for the expected warpage. The real data flow over the design, manufacturing and service-life can support the decision making and cost-oriented design. The iterative process of product design is conducted in the digital system will decrease development costs and time consumption significantly.

(4) **For metamaterial structure design**, achieving automatic design is the future trend. By taking advantages of the ad hoc method and TO method, modular design provides a novel route to create metamaterials with desired performance. It starts from structural bases that are appropriately selected based on existing knowledge, and thus could save calculation time and is less time-consuming, which balances the design performances and computational cost.

3. Materials

Materials play a key role in all AM processes due to the intrinsic character of controllable shape and performance. Material requirements are impacted by the need to create feedstock, to be processed successfully by the fabricator coupled with post processing, and to manifest

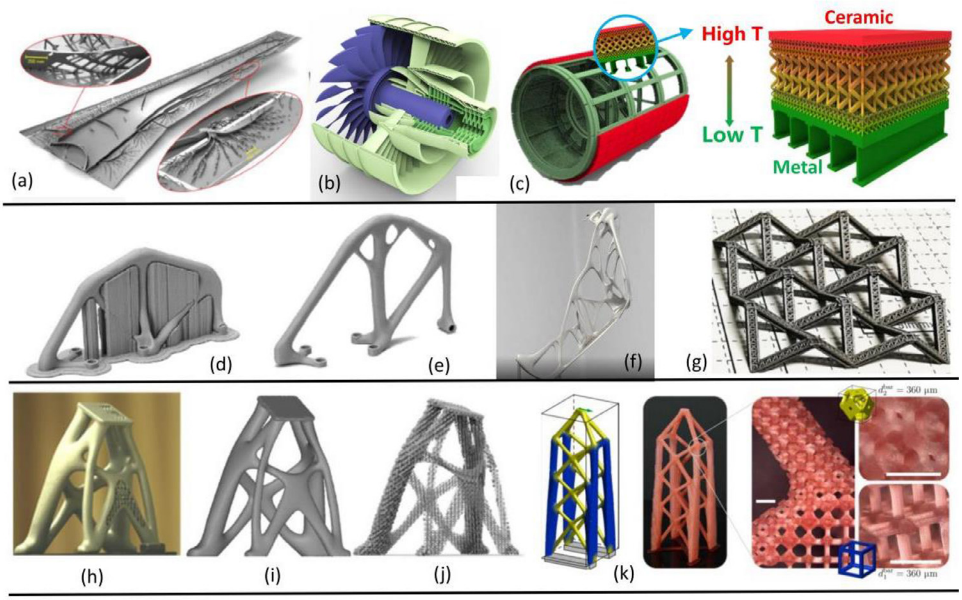

Fig. 2. (a) Aircraft wing Giga-voxel TO for AM [17]; (b) Thin-wall lattice infill for complex engine design; (c) Dual-gradient material and functional design for heat resistant structures; (d) Metallic load-bearing framework with support structure [18]; (e) and (f) Supportless design for load-bearing structure; (g) Hierarchical design of titanium alloy via SLM; (h), (i) and (j) Solid-lattice concurrent design for satellite bracket [10]; (k) Hierarchical design with continuous lattice evolution [19].

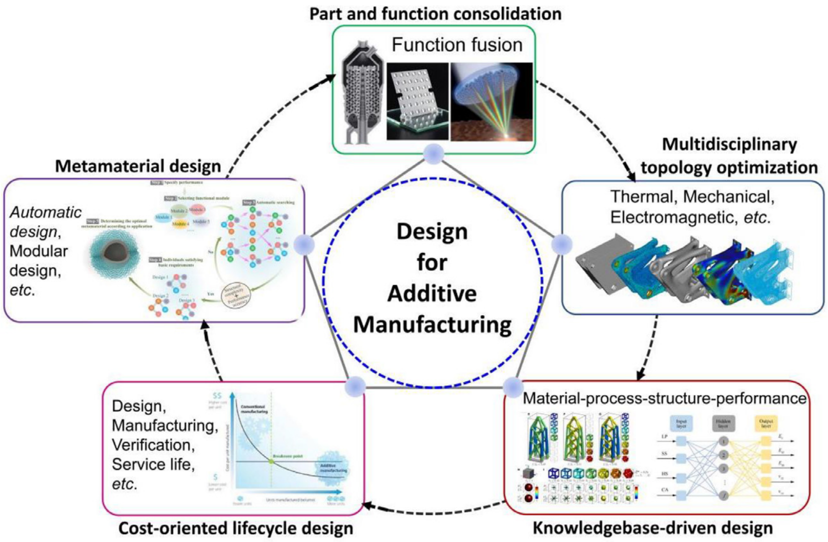

Fig. 3. Roadmap of design methodology for intelligent additive manufacturing.

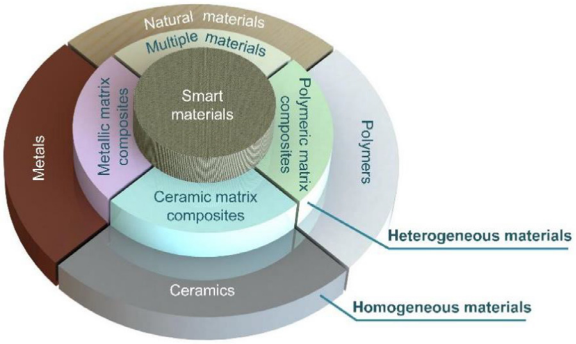

Fig. 4. Material system used in AM processes.

acceptable service properties. As shown in Fig. 4, Metal, polymer, ceramic, and natural materials have been utilized in different AM processes. Based on these homogeneous material systems, AM processes with heterogeneous materials, including all kinds of composites, and multiple materials, have been successfully established in order to obtain higher properties, more functions, even customized performance, including for example flame retardant polymers, direct metals and ceramic composites. Smart materials with certain responsive properties, such as shape memory, have also been employed in AM processes to produce shape or performance changing structures, so called 4D printing.

This diversity has resulted in a highly diverse set of materials. The grand challenge in materials and materials processing is to improve quality, process consistency, repeatability and reliability in a wider diversity of materials at a lower material, machine, processing and finishing cost. Take metallic material system as an example, as shown in Fig. 5. In the past few years, based on rapid solidification characteristics of metal-based AM, more and more new materials have been designed and expand the range of materials used in additive manufacturing. By introducing nanoparticles of nucleants to control solidification process, the large columnar grains and periodic cracks can be solved, and the prepared aluminum alloys present crack-free, equiaxed, fine-grained microstructures [23, 24]. A Fe19Ni5Ti (wt.%) steel tailor-designed for AM has been reported, where nanoprecipitation and the martensitic transformation can be controlled by cooling time [25]. To deal with the anisotropy in titanium alloys, titanium-copper alloys was designed. This

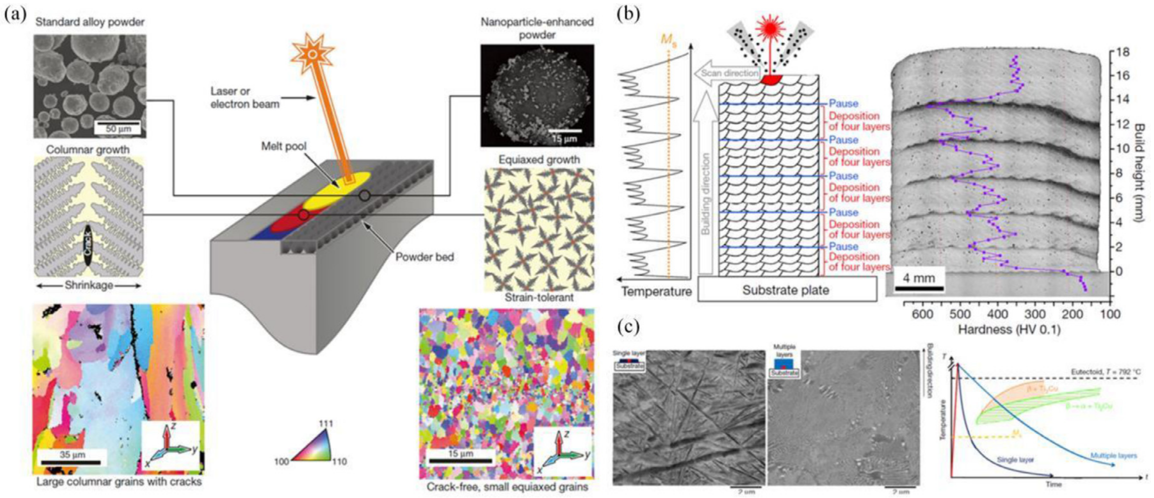

Fig. 5. (a) The schematic of AM processed 7075 alloys with nanoparticles via selective laser melting [23]; (b) Directed energy deposition produced Fe19Ni5Ti (wt%) sample [25]; (c) Scanning electron microscopy characterization of Ti–8.5Cu alloy [26].

alloy has a high constitutional supercooling capacity, which can override the negative effect of a high thermal gradient in the laser-melted region and lead to a fully equiaxed fine-grained microstructure [26]. Besides, the concentration of elements in titanium alloy can be changed by in situ design approach in AM [27].

Tremendous challenges are still faced in order to bridge the gaps between materials, processes, structure, and properties as well as various performance.

(1) **In order to improve material design theory**, it is necessary to improve the theoretical system and methodology of material design based on the process characteristics of additive manufacturing. The material genome provides new possibilities. To establish the professional database, the intelligent optimization material selection can be realized. By establish the intrinsic relationship between composition, process, microstructure and performance, the microstructure that meets the requirements according to the material's performance can be designed.
(2) **For objectives-oriented material design strategies**, the multi-level and multi-factor design of the material should be realized from the perspective of the service of the material. For structural materials, it is necessary to realize material-oriented toughening design; for intelligent material, such as shape memory polymers and alloys, it is necessary to realize controllable deformation recovery design.
(3) **For smart composite materials**, nature fabricated biological systems using natural composites in an effective patten by evolution, which provides multifunction integration and intellectualization. Biological systems that tightly integrate sensing, actuation, computation, and communication and the engineering applications that could be enabled by using composite materials that take advantage of similar principles. AM of advanced composites will provide a useful tool to realize the design and fabrication of cross-scale smart composite structure.

4. Process & Equipment

To take the lead in manufacturing, the intelligence transformation of key industries based on the digital manufacturing support systems is expected. AM with digital genes needs to improve the core competitiveness in terms of large-scale production efficiency, quality control and flexibility on the basis of maintaining the benefits of customization. As shown in Fig. 6, bringing high-end machine tools and smart industrial robots into the AM equipment architecture will greatly improve the efficiency and automation level of sensing and control during the AM process. Meanwhile, the equipment automation incorporated with digital informatization is the way to realize intelligence. The digital ecosystem based on data, software and network and combined with advanced technologies like multiscale modeling and simulation, machine learning, and artificial intelligence will connect information to physical processes more effectively, stimulating new manufacturing capabilities.

Concerning the equipment architecture, robotic-assisted AM is a promising system by providing an extra degree of freedom in design options. Multiple robots facilitate multi-material processing without size limit and in a locally-customizable manner [28]. A hybrid multi-tasking process by combing AM with subtractive or formative manufacturing makes it possible to modify internal and external features during a single processing setup [29]. Moreover, with the aid of robotic sensors or cameras, AM can realize autonomous path planning and in-situ parameters tuning through online identification and feedback [30]. Then, with regard to the AM digital ecosystem, physics- and data-driven frameworks can identify the process–structure-property (p-s-p) relationships out of trial-and-error burden [31]. Physics-driven modeling and simulation figure out the underlying physics of process and structure on multiscale [32]. Whereas data-driven approach that utilizes data-mining algorithms, machine learning and artificial intelligence, allows exploring correlations between AM input and output without explicit physical interpretation. Data-driven methods are favored in fast prediction, process optimization and especially real-time diagnosis with feedback control [33]. Alternatively, by combining physics- and data-driven approaches, a physics-informed data science is becoming attractive for both advantages of interpretability and quickness [34]. Utilizing the above digital tools creates a digital twin encompassing mechanistic, statistical and control modeling to qualify and certificate AM products in an intelligent and cost-effective way [35].

The AM intelligent transformation is still in the early exploration stage. Several future actions aligned to the industrialization of AM hardware and software include the following (Fig. 7):

(1) **Develop hybrid-AM solution under multi-robot cooperation**. Combined with the advantages of various processing techniques, hybrid manufacturing with AM as the core shows promise in multi-material, multi-structural, and multi-functional fabrication. The AM framework incorporated with additional processes or energy sources relies on the integration of process chain. The knowledge gaps concerning the influence mechanism and uncertainty of multi-physical effects on part features are worth addressing. Moreover, hybrid manufacturing requires accurately collaborative control of machine tools or robots that govern individual segments. Equipment manufactur-

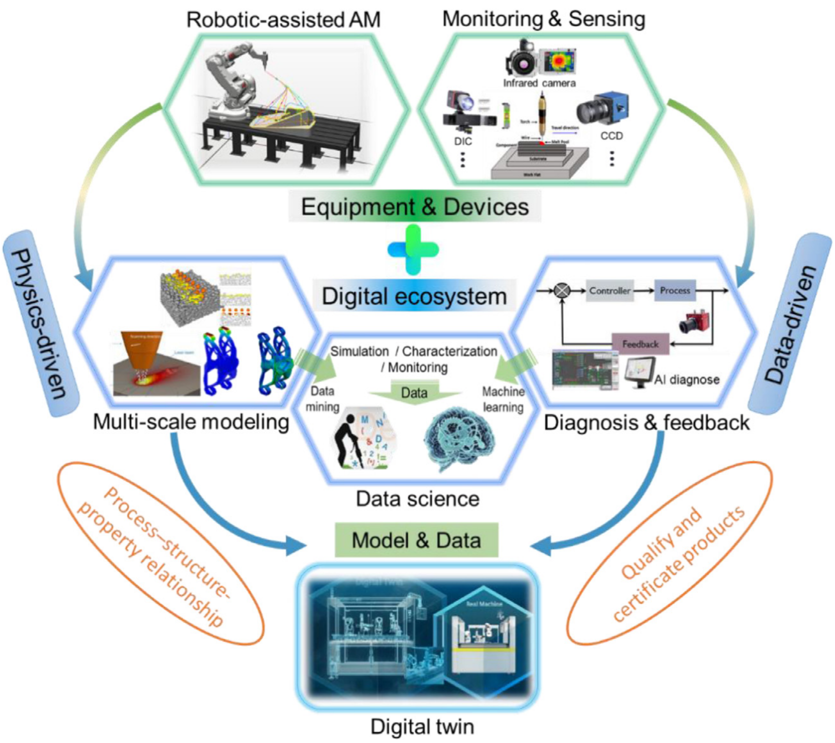

Fig. 6. Schematic illustration of the physics- and data-driven AM framework based on advanced devices and digital ecosystem.

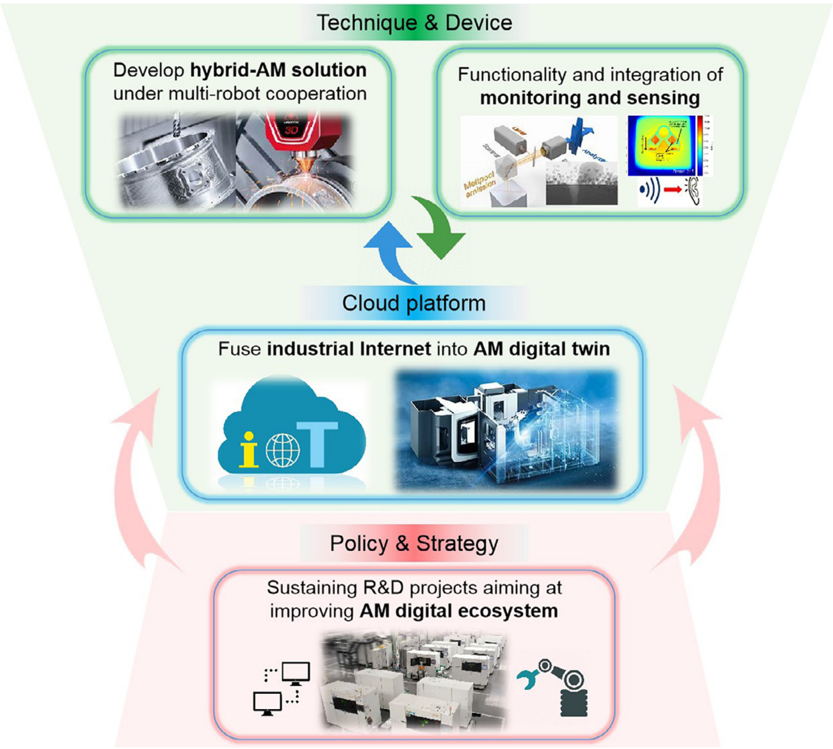

Fig. 7. Future actions aligned to the AM intelligent transformation of process and equipment.

ers should devote to proposing suitable data compilers and standards regarding the data interoperability and interflow between robotic systems and AM devices, thereby creating a feasible hybrid-AM solution.

(2) **Improve the functionality and integration of monitoring and sensing devices**. The processing signals during AM involves vision, spectrum, acoustics and thermal. The superposition of multiple sensors not only give rise to the complexity and reduced reliability of the equipment, but also brings difficulties to data processing and automatic control owing to the non-uniform structure of various data types. Therefore, the multi-functional single device will significantly improve the popularity of monitoring and sensing devices in industry; meanwhile, by coupling with the data preprocessing software, the data availability in physical modeling, process optimization and closed-loop control will be improved.

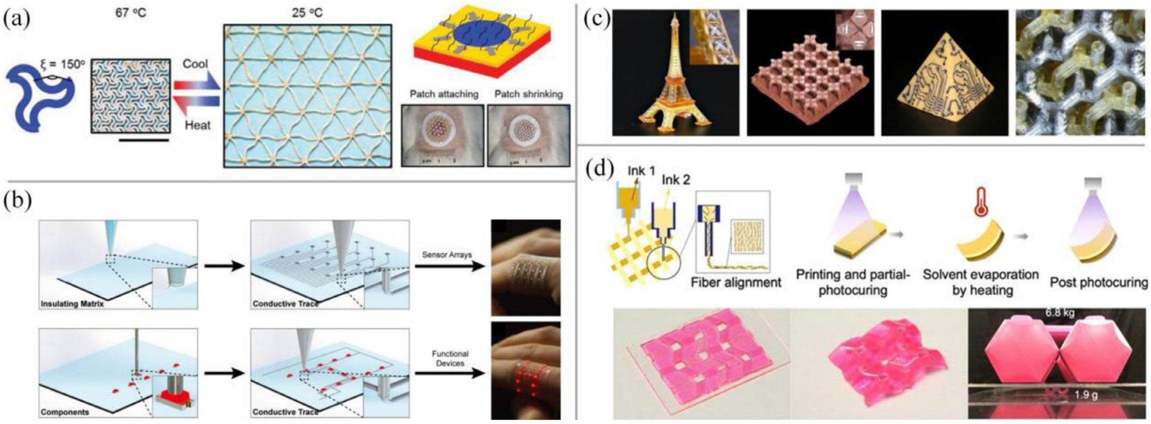

Fig. 8. Smart structures with various functionalities: (a) An artificial skin with thermal shrinkage performance [40]; (b) An AM platform combining direct ink writing of metallic ink and pick-and-place of electronic components [41]; (c) Electrical charge programmed AM of conductive and functional materials [42]; (d) 4D Printing of a shape-transformable structure [44].

(3) **Fuse industrial Internet into AM digital twin**. Intelligent AM is inseparable from the industrial Internet connecting distributed staffing, machines and materials. The core of digital twin (DT) is model and data, but for numerous AM enterprises, the construction and use of DT possess a high technology and cost threshold. Fortunately, the industrial Internet can solve the above issues, thereby sharing and analyzing data and models through a cloud DT platform. Academia and industry can acquire data and models from the cloud DT, respectively, so as to realize a normalized industry-university research cooperation mechanism.

(4) **Support the establishment and improvement of AM digital ecosystem**. Sustaining AM R&D projects aiming at integrating advanced equipment or technologies (e.g., process monitoring, information perception, machine learning artificial intelligence, database, etc.) into the AM digital manufacturing ecosystem needs policy support at the national level. Guidance jointly proposed by industry and academia will facilitate the transition to digital design and intelligent control for new AM hardware/software.

5. Smart Structures

In the past decades, we have witnessed increasing demands for smart, integrated, and multifunctional structures, which are elaborated with complex internal configurations. Therefore, the manufacturing difficulty has been one of the toughest obstacles in the industrialization process of intelligent components. AM has emerged as a powerful technology for strategically integrating sensing, actuation, computation, and communication functionalities. One example is the recent innovation on the 3D-printing of fiber-reinforced composites [36–39], which enables the integrated fabrication of hierarchical and hollowed structures with advantages of lightweight, high strength, and low cost.

Based on the AM technologies, metamaterials could be constructed and fabricated with unusual mechanical [14], optical, acoustic, or thermal performance Fig. 8(a) shows an artificial skin with negative Poisson's ratio that could greatly improve the recovery speed and decrease the painfulness of the injured area [40]. Besides, the great material compatibility of AM has promoted the industrialization of advanced materials like shape memory polymers, liquid crystal elastomers, hydrogels, and so on, which are difficult to be prototyped by traditional fabrication technologies. 3D-printed structures that transmit or process information have also been reported as novel electronics. For instance, direct ink writing of metal-based inks and pick-and-place of surface mount electronic components have been combined in a manufacturing platform of soft electronic devices (Fig. 8(b)) [41]. By manipulating electric charges, a novel approach was proposed to deposit functional materials including metals and semiconductors within arbitrary 3D layouts for creating hybrid electronic devices (Fig. 8(c)) [42]. Furthermore, AM technologies have granted structures with sensing capabilities typically based on electrical components. For example, a tissue-culture device with embedded piezoresistive strain sensors to monitor the contraction of cardiac tissues can be fabricated in a multi-material AM procedure [43]. Apart from the above-mentioned structures showing invariable performance, intelligent devices with dynamic response to environment stimulus, including reconfigurable and reprogrammable shapes (Fig. 8(d)) [44], stiffness, and optical performance could be achieved by the 4D printing process. Related applications include self-deployable devices, drug delivery, somatosensitive actuators, and so on.

Despite the rapid development of AM technologies for constructing smart structures, there are still some challenges to be overcome, as shown in Fig. 9.

(1) Beyond 3D and 4D printing, AM systems are now aiming at a fusion of different physics fields and a n-dimensional (nD) printing for complicated **multi-scale** structures with dynamic response to stimulus based on an effective combination of sensing and actuating capabilities.

(2) The library of AM-compatible materials ought to be expanded to include more unique functionalities, and smart AM process and equipment are highly desired to precisely fabricate **multi-material** structures of these materials. Developing high-precision nozzles and increasing the interfacial compatibility between different materials are key research goals.

(3) 3D-printed structures ought to be robust and adaptable in **multi-physics** fields under extreme conditions since the future working environments might include outer space, deep ocean, volcanos, and so on. Therefore, the diverse working conditions should be considered at the beginning of the structure design. By dealing with those difficulties, AM is trending towards an intelligent system which integrates in-situ diagnose, flexible controlling, full life-cycle designing and automatic prototyping.

6. Living Structures

Organs are complex structures where cells and extracellular matrices interact to develop and function. Owing to their outstanding ability to form complex structures and material compositions including cells and biomaterials, AM technologies hold great potential to imitate the sophisticated systems of organs [51]. Early studies 3D-printed prostheses and biodegradable scaffolds involving no cells, and an increasing number of studies employ live cells to 3D-print structures that grow to fulfill biofunctions. The obtained living structures may be implanted to

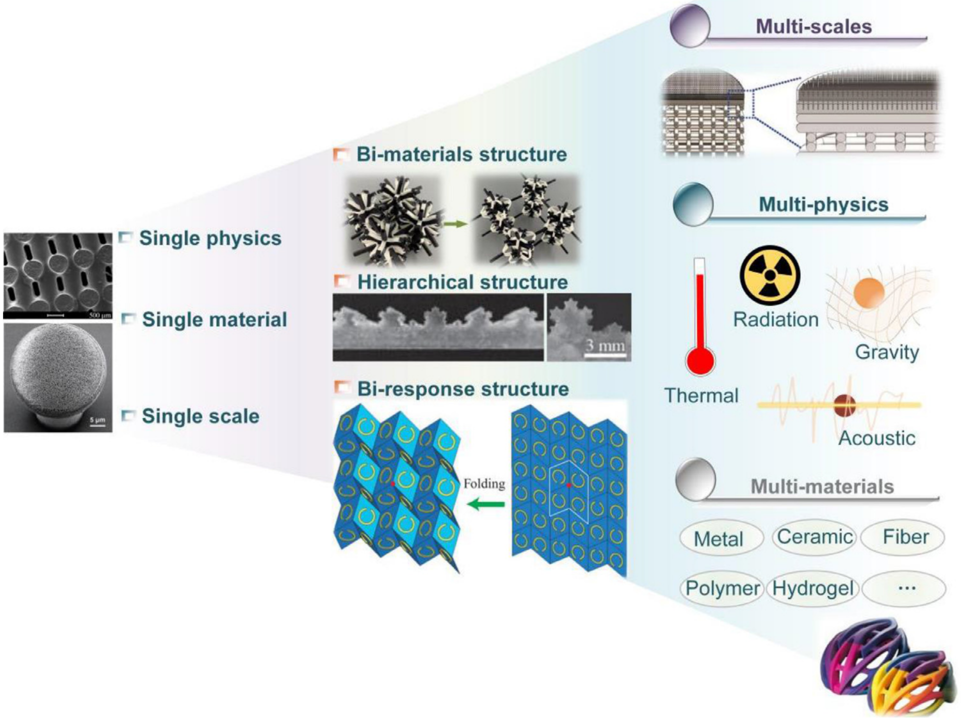

Fig. 9. Challenges encountered by AM technologies for developing smart structures [44–50].

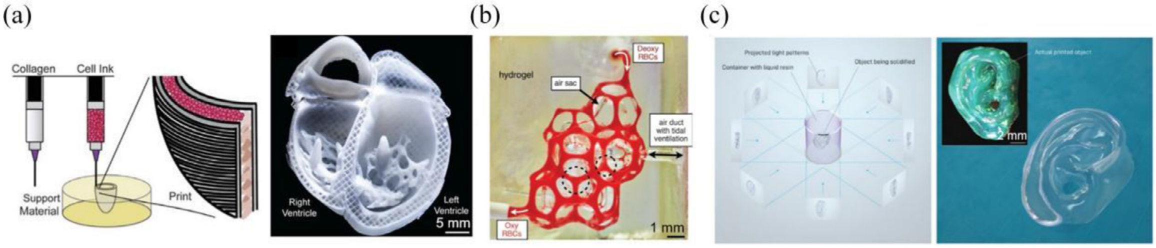

Fig. 10. Representative advances in AM technologies for living structures: (a) Extrusion-based 3D bioprinting in a suspension bath allows for the fabrication of human heart models [59]; (b) High-resolution stereolithography printing of photopolymerizable hydrogels with vascularized alveolar model topologies [60]; (c) Volumetric 3D bioprinting of cell-laden hydrogels allows for the rapid fabrication of living tissue constructs [61].

repair/replace defective tissues/organs in the human body, and they can be used as *in vitro* biological models that recapitulate physiological conditions more accurately than 2D cell culture models.

The technological advances in the aspects of materials and processing have significantly enhanced our ability to imitate organs and enrich functionalities in a more precise and efficient manner. In terms of materials, conductive biomaterials based on nanomaterials [52, 53] and polymers [54] have been developed for AM, which grant living structures with electrical activities similar to the brain and the heart. Biomaterials that respond to physical [55, 56], chemical [57], or biological [58] stimuli have also been printed to form dynamic microenvironments for cells. In terms of processing, embedded printing techniques directly deposit soft extracellular matrices and cells in a supporting buffer, which enables multiscale construction of soft extracellular matrices and cells to form complex organ models such as the heart (Fig. 10(a)) [59]. Photopolymerization-based AM techniques have also been enhanced with the use of appropriate photo-absorbers to enable the high-resolution projection stereolithography of hydrogels (Fig. 10(b)) [60] and by dynamically illuminating a rotating cell-laden photosensitive hydrogel reservoir to realize fast volumetric printing (Fig. 10(c)) [61]. For accurate single-cell printing, a manufacturing platform that combines a 3D printer and a miniaturized microfluidic sorter has been developed to deposit individual cells of interest from a cell mixture [62]. As advanced biological models, 3D-printed living structures are utilized in such products as organs-on-a-chip devices with demonstrated potential to transform biomedical research and the pharmaceutical industry. 3D-printed hepatorganoid models overperformed their 2D and 3D bulk counterparts in the expression of liver-specific transcription factors [63]. Similarly, 3D-printed multicellular bladder tumor models supported the identification of important molecular basis in tumor progression [64].

In the future, AM of living constructs can significantly improve biomedical applications and may innovate products of high-level bio-intelligence (Fig. 11). For example, AM techniques may further integrate cells with actuating and sensing materials to form living machines to move and work inside the human body for such applications as cell-based therapeutics and drug delivery. Along with the great promise, 3D-printed living constructs need to address multifaceted challenges when moving toward intellectualization and commercialization.

(1) **Technical challenges**: 3D-printed living structures are yet to fully match native organs for architectural and functional complexity. AM techniques should achieve higher spatial resolution and higher effi-

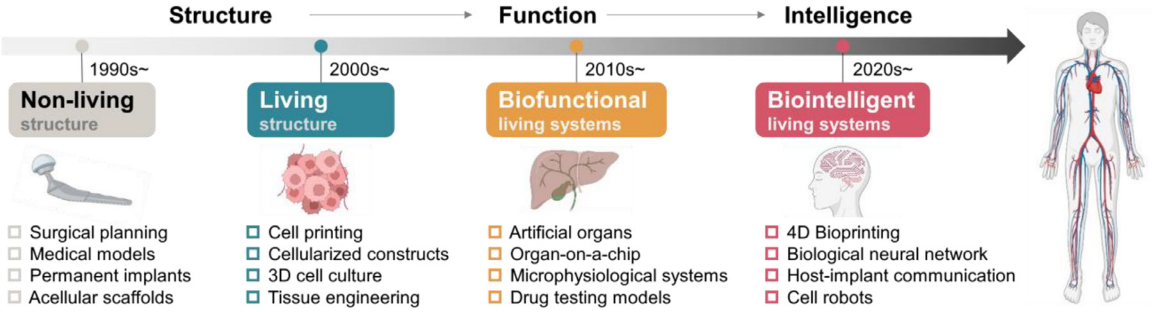

Fig. 11. Roadmap of AM technologies towards bio-intelligence (Created with BioRender.com).

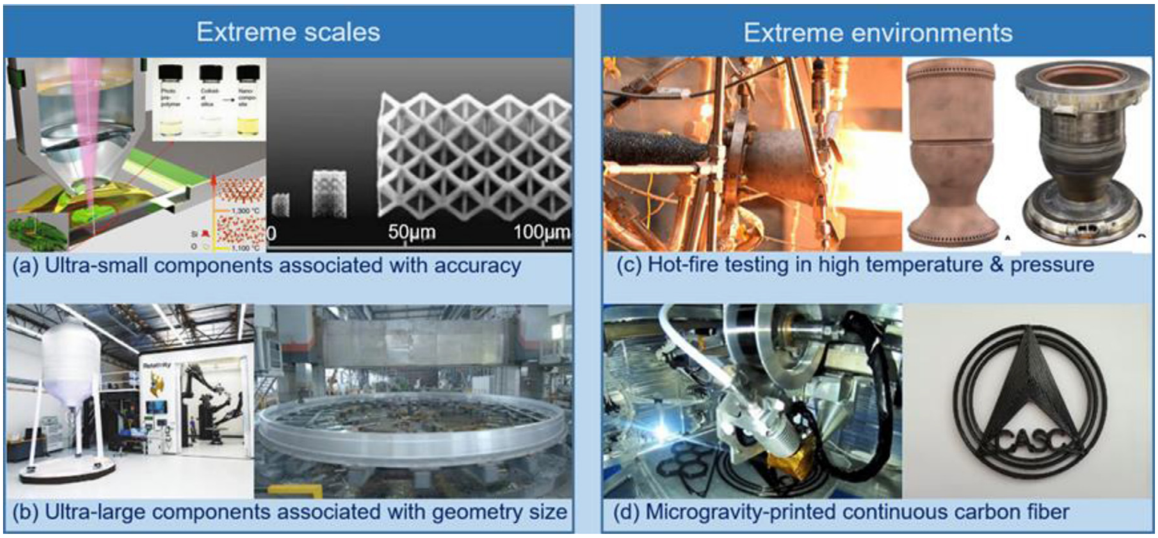

Fig. 12. Applications of 3D printing: extreme scales & extreme environments: (a) Schematic of two-photo polymerization 3D printing process and silica printed lattice crystals [65]; (b) Ultra-large metallic components printed by China and America [67, 68]; (c) Hot-fire testing of a 3D-printed bimetallic chamber [70]; (d) The world's first 3D printing of continuous carbon fiber reinforced polymer composites in space [71].

ciency in fabricating complex multiscale structures, and more functional biomaterials compatible with AM are needed.

(2) **Cross-disciplinary challenges**: Effective control of cell development within 3D-printed structures lays the foundation for successful applications. For the bio-intelligence of implanted living structures, interactions and communications between living structures and the human body ought to be further established. Accordingly, a close collaboration among mechanical engineers, bioengineers, life scientists, and clinical doctors is needed for devising fabrication strategies based on biomedical insights into specific applications.

(3) **Regulatory and ethical challenges**: 3D-printed living constructs constitute a novel group of products in biomedical industries that are highly regulated and involve ethical implications. The commercialization of 3D-printed living constructs calls for a systematic set of science-based regulations specifically designed for these products to address potential issues in medical and ethical impact.

7. Extreme Scales & Extreme Environment

AM has rich scientific and technological connotations involving machinery, materials, computations, automation control, and other advanced technologies. It has brought revolutionary applications in the aerospace, biomedical, automotive, nuclear energy, and building industries due to its characteristics of freedom of design, fast prototyping, waste minimization, and the ability to manufacture complex structures with unique performance. As a key developing industrial technology, AM will significantly promote and lead the upgrading and development of intelligent manufacturing.

The development of AM is mainly focused from two extreme scales: one is the micro/nano scale, which is to achieve fine 3D printing in micron and nanometer sizes; and the other is the macro scale, which is the realization of large-size and high-speed 3D printing, as shown in Fig. 12. The micro/nano scale 3D printing represented by two-photon polymerization is able to printing nano-structures in sub-wavelength spatial resolution owing to the overcoming of the optical limit of illumination, yielding the printing accuracy less than 100 nm [65]. This high-precision complex nanostructures greatly broaden its applications in metamaterials and optoelectronics. On the other hand, on-site printing of large-size concrete structure needs a mixture of mechanical engineering, concrete technology, data management, and construction management. The first physical demonstration that printing a large concrete structure concurrently by multiple mobile robots will extend the size of design and printing in the building and construction industry [66]. In the aerospace industry, the world's first high-strength aluminum alloy connecting ring at the level of 10 m on heavy launch vehicle has been fabricated, after printing the large and complex titanium structural parts such as main windshield window frame and central flange of the C919 aircraft [67]. These breakthroughs overcome the structural deformation and stress control of large-size structures during printing, providing technical support for the rapid development of aerospace engineering. The Relativity Space, a start-up firm in America, aims to manufacturing a nearly fully 3D-printed rocket with cooling channels to lift 1250 kg into low Earth orbit [68]. These large-scale metal-printed projects built by robot arms are disrupting 60 years of aerospace due to 100 times fewer parts, 10 times faster production time, no fixed tolling and a simple supply chain [69].

The practical applications of AM are often challenged in the following aspects:

(1) **Extreme environments** such as extreme temperature and pressure, strong radiation, and micro-gravity. In 2020, NASA completed significant material characterization and testing of 3D-printed bimetallic combustion chambers for liquid rocket engines, along with hot-fire testing, to demonstrate the multi-function and survivability of bimetallic chambers in the harsh temperature and pressure [70]. After the International Space Station (ISS) equipped with 3D printing equipment since 2014, researchers also successfully completed the first 3D printing tests in the microgravity space in 2020 [71]. This world's first in-orbit 3D printing testing of continuous carbon fiber reinforced polymer composites allows the researchers to examine the material forming process, giving a better indication of the influence of micro-gravity on the materials and structural mechanisms involved. 3D printing will not only contribute to the existing research infrastructure on-board the ISS, but also make long-time spaceflight, space exploration and colonization more convenient and sustainable. Extreme environmental conditions such as micro/zero gravity, cosmic radiation, and large temperature difference between day and night have a significant impact on the in-situ printing using lunar or Martian regolith.

(2) Another challenge to 3D printing habitat on Moon and Mars is to develop related **space robotic and automation technologies**. Excellent radiation and thermal resistance electronic devices and structural materials need to be developed to adapt such extreme environment, and multiple sensors integration and data fusion could be critical technique for future unmanned system exploration. The unique cycle of "observe-orient-decide-act" for control system is required for AM in space, so as to achieve self-adaptive control and monitoring of manufacturing process.

(3) To speed up the digitization of 3D printing, one of the most exciting frontiers in intelligent AM is the concept of **digital twins** [72]. By incorporating intelligent sensing on real-time objects, big-data statistics and analytics, and machine learning capabilities, digital twins demonstrate great potential in (i) the efficient design of new products for 3D printing, (ii) additive manufacturing production planning with respect to extreme usage scenarios and environments, and (iii) the capture, analysis, and action on 3D printing operational data and final high quality.

8. Future Perspective

Facing the future, AM technology will be further developed toward intellectualization and industrialization. AM is an extremely complex system involving multiple factors, multi-level and multi-scale, coupling materials, structures, various physical and chemical fields. It is necessary to investigate this extremely complex system in combination with big data and artificial intelligence, and to achieve a breakthrough in the principle and method of multi-functional integrated optimization design for AM. By developing intelligent AM technology with actively controllable shape, a sufficient scientific and technical foundation for the leap improvement of material, process, structural design, product quality and service efficiency could be achieved for the future AM technology. Intelligent AM equipment with self-acquisition, self-modeling, self-diagnosis, self-learning and self-decision-making capabilities is an important basis for the large-scale application of AM technology in the future. Interdisciplinary researches on AM technology with materials, software, artificial intelligence, life and medicine science, should be carried out to achieve major original technological innovation. Applications for AM should be expanded to and focused on new energy, aerospace, health, architecture, cultural creativity and other fields such as navigation and nuclear power, etc.

In the future, AM technology will be evolved toward manufacturing of four-dimensional intelligent structure, living bodies, and components with integrated material, structure and functions, which provides a new technical method for controllable shape and performance, and a technical platform for industrial innovation and entrepreneurship. Development of AM should follow the principle of "application development as the guide, technological innovation as the driving force, and industrial development as the goal" [1]. A rational AM industry standard system should be established to promote the comprehensive innovation and application of AM process and equipment in combination with emerging technologies and intelligent manufacturing systems such as cloud manufacturing, big data and the Internet of things, which will be of great significance to realize the leap forward development of manufacturing technology.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Xiaoyong Tian: Conceptualization, Writing – review & editing. **Lingling Wu:** Writing – review & editing. **Dongdong Gu:** Writing – review & editing. **Shangqin Yuan:** Writing – review & editing. **Yufan Zhao:** Writing – review & editing. **Xiao Li:** Writing – review & editing. **Liliang Ouyang:** Writing – review & editing. **Bo Song:** Writing – review & editing. **Tong Gao:** Writing – review & editing. **Jiankang He:** Writing – review & editing. **Xin Lin:** Writing – review & editing. **Feng Lin:** Writing – review & editing. **Jihong Zhu:** Writing – review & editing. **Dichen Li:** Conceptualization, Writing – review & editing.

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