Computer-Aided Design 69 (2015) 65–89

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

The status, challenges, and future of additive manufacturing in engineering

Wei Gao [a,*], Yunbo Zhang [a], Devarajan Ramanujan [a], Karthik Ramani [a,b], Yong Chen [c], Christopher B. Williams [d], Charlie C.L. Wang [e], Yung C. Shin [a], Song Zhang [a], Pablo D. Zavattieri [f]

[a] *School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA*
[b] *School of Electrical Engineering (by courtesy), Purdue University, West Lafayette, IN 47907, USA*
[c] *Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA 90089, USA*
[d] *Department of Mechanical Engineering, VirginiaTech, Blacksburg, VA 24061, USA*
[e] *Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China*
[f] *School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA*

HIGHLIGHTS

- The fundamental attributes and challenges/barriers of Additive Manufacturing (AM).
- The evolution of research on AM with a focus on engineering capabilities.
- The affordances enabled by AM such as geometry, material and tools design.
- The developments in industry, intellectual property, and education-related aspects.
- The important future trends of AM technologies.

ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Maker Movement
Topology optimization
Open-source machine
Intellectual property

ABSTRACT

Additive manufacturing (AM) is poised to bring about a revolution in the way products are designed, manufactured, and distributed to end users. This technology has gained significant academic as well as industry interest due to its ability to create complex geometries with customizable material properties. AM has also inspired the development of the maker movement by democratizing design and manufacturing. Due to the rapid proliferation of a wide variety of technologies associated with AM, there is a lack of a comprehensive set of design principles, manufacturing guidelines, and standardization of best practices. These challenges are compounded by the fact that advancements in multiple technologies (for example materials processing, topology optimization) generate a "positive feedback loop" effect in advancing AM. In order to advance research interest and investment in AM technologies, some fundamental questions and trends about the dependencies existing in these avenues need highlighting. The goal of our review paper is to organize this body of knowledge surrounding AM, and present current barriers, findings, and future trends significantly to the researchers. We also discuss fundamental attributes of AM processes, evolution of the AM industry, and the affordances enabled by the emergence of AM in a variety of areas such as geometry processing, material design, and education. We conclude our paper by pointing out future directions such as the "print-it-all" paradigm, that have the potential to re-imagine current research and spawn completely new avenues for exploration.

1. Introduction

Additive manufacturing (AM), also referred to as 3D printing, has gained popularity in media and captured the imagination of the public as well as researchers in many fields. With recent interests, this technology is continuously being redefined, reimagined and

* Corresponding author.
E-mail address: gao51@purdue.edu (W. Gao).

http://dx.doi.org/10.1016/j.cad.2015.04.001

customized to a wide application spectrum such as automotive, aerospace, engineering, medicine, biological systems, and food supply chains. A historical analysis of AM reveals its roots lie in photo sculpture (in the 1860s) and topography (in the 1890s). These early technologies led to the "Photo-glyph recording" technique (patented in 1951) that selectively exposes layers of a transparent photo emulsion while scanning cross-sections of the object to be replicated [1]. The modern day process of Stereolithography (SLA) shares a remarkable likeness to the now obsolete "Photo-glyph recording" process, and has been enabled by the advancements in computing, lasers, and photopolymers. Therefore, it is of no surprise that techniques and patents for photo sculpture are heavily referenced in current day AM literature. Modern AM techniques have their foundations in four key patents: vat photopolymerization, powder bed fusion, material extrusion, and binder jetting [2–5]. A more detailed analysis of the major milestones in AM technologies and related NSF funded awards (over $240 million) are discussed in the report by Weber et al. [6].

The significant amount of recent interest and investment towards AM technologies does not come as a surprise, as this layer-wise additive method is an elegant concept that can build complex shapes using a wide variety of materials. The reducing cost of programmable controllers, lasers, ink jet printing and computer-aided design (CAD) software has democratized the design process, allowing individuals to utilize, tinker with, and improvise these technologies. The main market driver for such systems has been consumers and industries that rely on low–medium fidelity prototyping in the early stages of product design. Several startup companies are creating innovative and low-cost 3D printers for thermoplastics. As a result, plastics-based 3D printing has captured the imagination of the general public through platforms such as Do-It-Yourself (DIY) and the Maker Movement [7]. Although this technology cannot guarantee the part quality and scalability of current production methods, we expect this gap will reduce significantly in the near future. Supply chain and retail businesses such as Staples,[1] Shapeways[2] and Sculpteo[3] are taking advantage of the popularity of such platforms and bringing commercial printing and shipping services directly to customers. These companies are also supporting hobbyist communities by providing them with simple online 3D modelers allowing them to create or tailor designs and turn them into customized products.

From the industry perspective, AM technologies have the potential for significantly impacting traditional production models in terms of industrial machinery, assembly processes, and supply chains. For example, multi-nationals such as General Electric (GE)[4] are investing in research for commercializing metal-based AM technologies for remanufacturing. If successful, such technologies can simplify their manufacturing value chain by giving them independence from third-party suppliers, improve performance, and extend useful life of their engines. AM can also positively impact smaller corporations and end-customers by changing their roles into self-sufficient "designers and manufacturers" that can develop innovative products and production systems. The rapid proliferation of AM technologies is driven by the increase in the variety of materials, low-cost machines, and potential for new application areas. This has resulted in a lack of fundamental design guidelines or standardization of best practices. For example, the same digital input (3D model) may give rise to parts that can be different in surface finish and geometric torlerance. These effects are due to differences in manufacturing techniques (material extrusion, jetting, deposition, curing, lamination, etc.), materials (thermoplastics, photopolymers, epoxy resin, metal powder, conductive composition, etc.), and the geometric positioning/orientation of the geometries. As a result, designers' often waste building and support material due to the multiple trial-and-error iterations required for fixing unqualified feature requirements, surface resolution and clearances of mechanical parts and assemblies. The use of electronics and circuits at macro- and micro-levels, both by embedding and integrating materials and sensors, is another trend that adds functionality, but threatens to complicate the design process for AM technologies.

The dependencies of AM techniques on related technologies such as material modeling, design tools, computing, and process design represent a challenge for both applied and basic research, shown in Fig. 1. In order to advance research interests and investment in AM technologies, some fundamental questions and trends in these avenues need highlighting. The goal of this review paper is to organize this body of knowledge and present challenges in the gamut of AM technologies. We believe that these technologies are at a critical stage as advancements in science and engineering are generating a "positive feedback loop" effect with regards to AM. For example, advancements in related technologies (such as a new material, or a novel topology optimization technique) can significantly affect or sometimes give rise to novel AM techniques. Similarly, advancements in AM techniques can directly affect applied and basic research providing new affordances that cannot be delivered by any other manufacturing technique. Therefore, we feel it is necessary to explore these dependencies and present significant findings to researchers who are driving these areas of interrelated research. Many roadmaps and reports have been carried out recently, including NIST roadmap [8], America Makes roadmap [9–12], CSC report [13], Wohlers reports [14–16], etc., to provide industry and business perspectives on AM technologies. In comparison to these efforts, our review paper focuses on presenting the current barriers, findings and future trends for the research community, and integrating techniques in AM-related domains towards the goal of enabling future research. These research areas span design, materials, machines, and associated technologies that all influence computer-aided design methodologies that support as well as create affordances for changing the future capabilities and expectations. This paper starts by describing fundamental attributes of AM processes in Section 2. We also present a comparative overview of AM technologies, illustrative cases, and challenges/barriers to be overcome. In Section 3, we discuss the evolution of processes and building capabilities of AM technologies with a focus on engineering capabilities for polymers, metal and ceramic powders. Next, in Section 4, we review the affordances enabled by the emergence of AM in a variety of areas such as geometry exploration and optimization, material and mechanics exploration during design, and the development of computational and fabrication tools. Section 5 summarizes developments in the industry, relevant intellectual property, and education-related perspectives of AM technologies. We conclude our discussions by outlining important future trends in Section 6.

2. The fundamentals of additive manufacturing

The fundamental attributes of Additive Manufacturing technologies are presented in this section. Additional information on AM processes can be found in prior overviews [17–20]. AM processes fabricate parts by creating successive cross-sectional layers of an object. The process begins with a three-dimensional solid model, which is initially modeled or scanned as a digital CAD file,

1 http://www.staples.com/.
2 http://www.shapeways.com/.
3 http://www.sculpteo.com/.
4 http://www.ge.com/.