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Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints

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ABSTRACT

The past few decades have seen substantial growth in Additive Manufacturing (AM) technologies. However, this growth has mainly been process-driven. The evolution of engineering design to take advantage of the possibilities afforded by AM and to manage the constraints associated with the technology has lagged behind. This paper presents the major opportunities, constraints, and economic considerations for Design for Additive Manufacturing. It explores issues related to design and redesign for direct and indirect AM production. It also highlights key industrial applications, outlines future challenges, and identifies promising directions for research and the exploitation of AM's full potential in industry.

1. Introduction

The evolution of Additive Manufacturing (AM) over the past three decades has been nothing less than extraordinary. AM has experienced double-digit growth for 18 of the past 27 years, taking it from a promising set of uncommercialized technologies in the early 1980s to a market that was worth over $4 billion in 2014. The AM market is expected to grow to more than $21 billion by 2020 [354,355]. This growth has been made possible by improvements in AM materials and technologies and is being driven by the market factors that necessitate its use such as shorter product development cycles, increasing demand for customized and personalized products, increased focus and regulations on sustainability, reduced manufacturing cost and lead times, and the introduction of new business models [13,354,355].

During the past 30 years, the use of AM technology has also undergone a transformation. Early AM applications focused on models and prototypes [178,179]. As the technology matured, AM played a major role in producing rapid and soft tooling (e.g. vacuum and silicone casting molds) [187]. Today it is also used for the production of end use parts and products. It is estimated that the market for AM end use parts was worth $1.748 billion in 2014 – up 66% from the previous year. Strong double-digit growth in this area is expected to continue for the next several years [355]. Leveraging the geometric and material freedoms of AM for end use parts creates a world of opportunity. However, not all parts are possible or cost effective to produce using AM. This necessitates a better understanding of when, why, and how to (re)design for the opportunities and constraints associated with these technologies.

The CIRP community has previously reported on advances in AM processes [152,178,179,181,187], their role in rapid product development [42], and how they have been used in the biomedical [36] and turbomachinery [176] industries. This paper explores the opportunities, constraints, and economic considerations related to Design for Additive Manufacturing (DfAM). It begins with a brief overview of Additive Manufacturing, Design for Manufacturing, and the need for DfAM. It presents the main design opportunities, considerations and constraints related to AM technologies, including production time and cost. It presents DfAM success stories from a number of industries. Finally, it identifies promising directions for research and

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development that will enable Design for Additive Manufacturing to reach its full potential in industry.

2. Additive Manufacturing

Additive Manufacturing processes produce physical objects from digital information piece-by-piece, line-by-line, surface-by-surface, or layer-by-layer [130,178]. This simultaneously defines the object's geometry and determines its material properties. AM processes place, bond, and/or transform volumetric primitives or elements (voxels) of raw material to build the final part. Each voxel's shape and size and the strength of the bonds between the voxels are determined by the raw material(s), the manufacturing equipment (e.g. the build platform precision, nozzle geometry, light or laser beam wavelength, etc.), and the process parameters (e.g. the nozzle temperature, light or beam intensity, traverse speed, etc.). The overall part geometry is determined by tool paths, projection patterns (digital masks), or a combination of the two. This allows AM technologies to fabricate parts without the need for intermediate shaping tools [155].

AM processes are characterized by increasing workpiece mass. They represent one of three major classes of manufacturing technologies, along with subtractive processes where the workpiece mass is reduced and formative processes where the workpiece mass is conserved [26,125]. Additive Manufacturing processes are also distinct from chemical and thermal processes such as etching, plating, oxidation, and heat treatment, which act on all exposed (reactive) surfaces and traditional processes to create composite materials.

2.1. History of Additive Manufacturing

The foundations of Additive Manufacturing go back almost 150 years, with proposals to build freeform topographical maps and photosculptures from two-dimensional (2D) layers [40,48,256]. Research efforts in the 1960s and 70s provided proof of concept and patents for the first modern AM processes including photopolymerization in the late 1960s [356], powder fusion in 1972 [72], and sheet lamination in 1979 [243]. This work was enabled by the invention of the computer in the late 1940s, the development of photopolymer resins by DuPont in the 1950s, and commercial availability of lasers in the 1960s. It followed advances in computer aided design (CAD) and manufacturing (CAM), including the development of numerical control machine tools in the early 1950s, computer graphics and CAD tools in the early 1960s, CAD/CAM systems in the late 1960s, and the availability of low cost computer monitors starting in early 1970s [71,258,356]. However, the technology was in its infancy with no commercial market and little support for research and development activities.

The 1980s and early 1990s saw an increase in patents and academic publications; the development of new technologies such as MIT's 3D printing process in 1989 [130] and laser beam melting (LBM) processes in the early 1990s [287]; and the successful commercialization of process technologies including stereolithography (SL) in 1988, fused deposition modeling (FDM), solid ground curing, and laminated object manufacturing in 1991 [356], and laser sintering in 1992 [287]. These advances were made possible, in part, by improvements in geometric modeling capabilities [71] and the development of programmable logic controllers [130] during the 1960s and 1970s, the development of ink jet printing technology in the late 1970s [130], and by the decreased cost and improved capabilities and availability of computers and CAD/CAM systems in the 1980s [256]. However, the high cost, limited material choices, and low dimensional accuracy of these machines limited their industrial application to rapid prototyping and model making.

The 1990s and 2000s were a period of growth for AM. New processes such as electron beam melting (EBM) [22] were commercialized, existing technologies were improved, and attention began to shift to developing AM related software. AM-specific file formats such as STL (StereoLithography), CLI (Common Layer Interface), LEAF (Layer Exchange ASCII Format), and LMI (Layer Manufacturing Interface) [256] were introduced. AM-specific software programs, such as Clemson's CIDES (1990) and Materialise's Magics (1992) were developed. New generations of commercial systems offered new and improved features. Quality improved to the point that Additive Manufacturing technologies could be used to produce patterns, tooling, and final parts. The terms 'Rapid Tooling', 'Rapid Casting', and 'Rapid Manufacturing' were created to highlight the ability to use Additive Manufacturing technologies for production. Cheap, powerful computers helped to make new generations of AM machines smaller and more affordable [131]. Advances in solid modeling software made it easy and inexpensive for students and professionals to design and model 3D objects. Finally, the Internet made knowledge sharing easy and supported the development of open-source hardware and software. This led to the development of the first hobby AM machines from the RepRap project in 2005.

The late 2000s saw the commoditization of the AM processes that were commercialized in the 1980s and were a period of growth for the younger metal-based AM processes. The expiration of key patents for a number of older AM processes opened the market to competition. This, combined with a growing AM hobby community, spurred innovation, leading to a major expansion of market supply and demand. Today, AM products and services support a wide range of activities including manufacturing, energy, transportation, art, architecture, education, hobbies, space exploration, and the military. Wide scale adoption of AM for the direct manufacture of final parts has occurred in the medical, dental, and aerospace industries. Meanwhile, commercial hobby printers and entry-level professional machines have made AM technology available to the masses.

If the current trends continue, we will soon enter a new stage of evolution where Additive Manufacturing becomes a design paradigm in addition to a means of production.

2.2. Digital workflow for Additive Manufacturing

Additive Manufacturing processes have a digital dataflow that generates the instructions for the AM machine followed by a physical workflow that transforms the raw materials into final parts (Fig. 1). The process usually begins with a product idea, a 2D image such as a photograph, a set of 2D images like those derived from Computed Tomography (CT) scans, or a physical 3D object like a prototype or a part for reverse engineering. These are transformed into digital models (e.g. volume models or facet models) using solid modeling, metrology, or image reconstruction software. Next, the data is checked for errors, the errors are corrected, and support structures are added if needed. This is often done with AM-specific software such as Magics from Materialise NV. Finally, the model is sliced or otherwise discretized to create instructions for the machine. This is often done using machine-specific software.

New software formats have been developed and standardized to support AM data preparation and digital workflow. For example, the AMF format, which has native support for color, materials, lattices, and constellations, has been standardized and is intended to replace the STL format. Other formats such as STEP, STEP-NC, and 3MF have integrated AM concepts to compete with AM-specific formats. Kim et al. [174] recently proposed a systems approach for data flow structuring and decomposition in several steps, clarifying the need for data generation and transformation along the AM digital chain.

2.3. Additive Manufacturing processes and physical workflow

The physical workflow begins with one of the seven currently recognized groups of AM technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder