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An Overview of Additive Manufacturing Technologies and Materials

Raziye Kılıç

Departmant of Industrial Engineering, Ataturk University, Erzurum, Turkey

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*Correspondence E-mail: raziyeilic@atauni.edu.tr

ABSTRACT Additive manufacturing is defined as a manufacturing method that makes it possible to produce parts layer by layer. AM encompasses a wide range of materials with cross-industry applications and a variety of processes. Various AM techniques such as VAT Photopolymerization, Material Extrusion, Binder Jetting, Powder Bed Fusion, Sheet Lamination, Directed Energy Deposition, Material Jetting are used in conjunction with different types of materials. Plastic, metal, ceramic and composite materials can be processed using these techniques. In contrast to conventional manufacturing processes, AM offers advantages such as design freedom, rapid prototyping and personalized production. This technology is considered one of the keys to industrial transformation as it offers flexibility in the production of complex structures, optimization of parts and mass production. This study looks at additive manufacturing technologies, the different materials used and the wide range of applications for this technology. The enormous potential that additive manufacturing offers can lead to revolutionary changes in all industries, and this study serves as a reference source for understanding these transformations.

Keywords: Additive Manufacturing, 3D printing, Technologies, Materials.

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1. INTRODUCTION

Additive Manufacturing (AM) or 3D printing is a manufacturing process in which physical objects are produced by gradually combining materials based on a digital data model. Unlike conventional manufacturing methods, most AM techniques focus on joining layers of materials together to form a part. These techniques are used for purposes such as prototyping, rapid production of models, rapid production of end-use parts and rapid production of vehicles for long-term mass production [1]. More recently, AM has moved beyond traditional methods and enabled the production of structures with complex geometries. This technology enables the production of functional components that can be used in many fields, from electronics to electrochemistry, from energy storage to thermal management, from automotive to aerospace, from health monitoring to the food industry, from sensors to robotics. The ability to draw specific parts using computer-aided design (CAD) increases the accessibility of this technology and opens the doors to different application areas [2]. The first step in the AM process is the 3D modeling of the object using CAD software. When a part is modeled or an existing part is scanned, this information is transferred to the software. The software then cuts the sectional planes of this model and creates a digital file (usually in STL format). During the printing phase, the object is created layer by layer on the 3D printer.

This method offers advantages such as higher material usage, lower costs, shorter lead times and mechanical improvements compared to conventional machining processes [3, 4].

AM encompasses a variety of technologies and techniques that have been developed in response to industrial needs. The main differences between these techniques lie in the variety of raw materials used, the type of material and the adhesion between the material particles [5]. When choosing additive manufacturing technology, the most suitable process should be selected taking into account the material properties and the parameters associated with the process. According to the American Society for Testing and Materials (ASTM), AM technologies are divided into seven categories, as shown in Figure 1 [1, 3, 6].

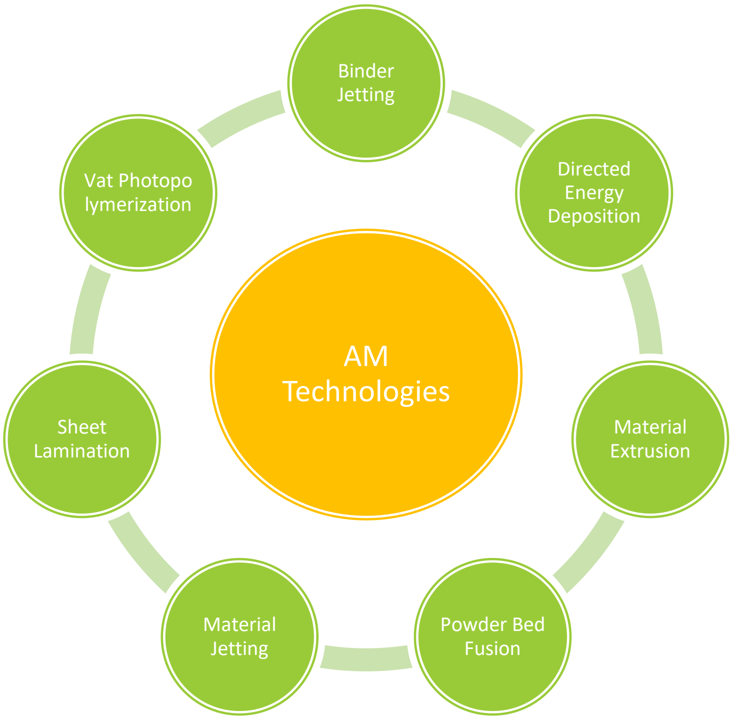

Figure 1. AM Technologies

In contrast to conventional manufacturing, the AM process enables the production of 3D macro- and microstructures by combining materials layer by layer. However, conventional AM processes may not be sufficient to meet the requirements of 3D production, especially when it comes to high-resolution, living and intelligent structures. To meet this need, various new AM processes have been developed, such as micro/nano-scale 3D printing, bioprinting and 4D printing. These next-generation AM processes are designed to produce high-resolution, complex 3D features from multiple materials or with multiple functions [7].

Additive manufacturing has several advantages. These advantages are listed below [6, 8].

- Economical and suitable for small production quantities
- The ability to change the design quickly
- The possibility to optimize the product in terms of function
- The ability to produce low-cost specialty products (one-off series)
- Possibility to reduce waste
- Potential for simpler supply chains, short delivery times and low stock levels
- Ability to produce personalized parts without additional tooling or production costs
- Functional design that enables the production of complex internal features
- Flexible and lightweight component production with hollow or lattice structures
- Components can be produced directly with minimal or no additional processing
- Potential to approach zero-waste production by maximizing material usage
- Significant reduction in overall product development and production time
- Reduced operational footprint for the production of the different parts

AM technologies enable the manufacture of products with many advantages compared to conventional manufacturing processes (milling, molding, stamping, etc.). Different manufacturing technologies and different material properties influence the results. Therefore, manufacturing technology, model orientation and material behavior should be investigated in an integrated way in the technical design [9]. At the same time, the success of AM depends on how well the manufactured object is for its intended use. Turning the possibilities of AM into truly useful products is crucial for industrial acceptance. Commercial success depends on ensuring that the materials of the desired shape or structure meet established standards while keeping production costs competitive [6].

Additive manufacturing is considered one of the cornerstones of industrial change. This method offers design freedom and enables the production of complex geometries and customized parts that are difficult or impossible with conventional manufacturing processes. It not only enables rapid prototyping, where ideas can be quickly tested and developed, but also the manufacture of products that meet individual needs and preferences with personalized production capabilities. It enables the easy production of complex structures that are difficult in conventional manufacturing processes, reduces assembly costs and enables the production of lightweight, durable parts in many areas of industrial manufacturing. For these reasons, additive manufacturing is an important technology that will contribute to even greater change in industry in the future. This study looks at the basic technologies of AM, the materials used and the different application areas. The aim of this study is to create an understanding of the future potential of AM and how it can serve as a key element for industrial change.

2. ADDITIVE MANUFACTURING TECHNOLOGIES

2.1. VAT Photopolymerization

VAT Photopolymerization is an additive manufacturing process based on the polymerization of liquid photopolymer in a tank by selective and spatial activation with light [10]. VAT Polymerization, also known as Stereolithography Apparatus (SLA), is a process in which photopolymer resins are used alongside other 3D printing processes, particularly in the production of materials with high resolution and better surface quality. In this process, the process called photopolymerization begins when the accumulated resin comes into contact with UV light. This UV light creates cross-links between the polymer chains in the resin and transforms them into a solid structure, i.e. curing occurs. In other words, under the influence of UV light, chemical bonds are formed between the polymer chains, transforming the resin from liquid or semi-solid to solid. In this way, the desired layers are created and a high level of detail and quality is achieved in the manufacture of the end product. This process is particularly preferred for the production of delicate and complex parts [11]. The disadvantages of this method include processing errors due to excessive curing, the scanned line shape and high cost of the material(s) required. The fact that the technology is based on photopolymerization makes this technology inherently limited to photopolymers [12].

2.2. Material Extrusion

The technology of Material Extrusion enables the material to move from a reservoir with the help of pressure at a certain speed and a certain cross-section. During this process, the material should be in a semi-solid state and solidify completely as it takes on the desired shape. In addition, the new extruded material must bond with the previous material to form a solid structure [13]. Material Extrusion enables the processing of a wide range of material types, from polymers to metals, composites and ceramics. Theoretically, any material that is available in liquid form at suitable temperatures can be used for material extrusion [14]. The steps of a general extrusion-based system include: loading and melting the material, moving the material through the nozzle by applying pressure, the extrusion process, pulling the material along a predetermined path, creating a consistent solid structure by bonding it to the material itself or to secondary building materials, and integrating support structures that allow for complex geometric features [10].

2.3. Binder Jetting

Binder Jetting is a process in which powdered material is arranged in layers and combined with a liquid, usually polymeric, binder. In this process, the layers of the print form a powder bed containing the binder, and over time these layers bond together, creating the desired part geometry in 3D. The resulting powder bed can then be heated if necessary to harden or stabilize the binder. The printed parts can be removed from the powder bed through a process called dust removal. At this stage, the printed parts do not yet have their final shape and are often referred to as "green". The parts must be post-processed in a final step by sintering or infiltration to obtain the desired mechanical properties [15].

2.4. Powder Bed Fusion

Powder Bed Fusion is an AM technology in which a fine material powder is applied layer by layer to the production surface through a spreader and then solidified by the thermal energy absorbed from a heat source such as a heated print head, laser or electron beam. In this process, the process is repeated layer by layer, with a new layer of the material powder being scattered over each layer. In this way, the desired 3D part is created step by step [16]. The Powder Bed Fusion process is compatible with all types of technical materials such as metals, ceramics, polymers, composites and the like. This method is widely preferred in the aerospace, energy, transportation and many other industries [17].

2.5. Sheet Lamination

Sheet Lamination is one of the oldest additive manufacturing techniques, in which clearly shaped parts are created by stacking thin sheets that are joined using various methods. These techniques include Ultrasonic Additive Manufacturing (UAM), Very High Power Ultrasonic Additive Manufacturing (VHP UAM), Laminated Object Manufacturing (LOM) and Friction Stir Additive Manufacturing (FSAM). The advantages of sheet lamination include the ability to easily create internal channels and complex geometries. The ability to combine different materials without compromising their mechanical properties is also an important advantage. On the other hand, sheet lamination avoids solidification defects such as porosity, shrinkage cavities and oxidation, which occur in processes such as Laser Powder Bed Fusion and Direct Energy Deposition [18].

2.6. Directed Energy Deposition

In Directed Energy Deposition, a stream of metal powder or metal wire is used as a starting material and applied to the substrate using energy sources such as a laser or electron beam to melt this material [19]. Lasers and electron beams are often used as directed energy sources and can bond material up to a theoretical density of 99.9%. This process produces a finer-grained structure with rapid cooling. This results in approximately 30% higher strength than cast parts. In addition, damaged parts can be selectively restored, giving this process a unique advantage when repairing parts. These processes are also characterised by the possibility of applying coatings to existing surfaces [12].

2.7. Material Jetting

Material Jetting or specifically 3D inkjet printing, is an integrated AM process in which parts can be produced by combining droplets of liquid photopolymer using piezo printheads. With this process, parts can be moulded by hardening photopolymers using UV lamps [20]. Material Jetting is an important and competitive production technology in industrial and scientific applications thanks to its cost-effectiveness, high efficiency and scalable production possibilities. Material Jetting attracts attention because it increases functionality through the possibility of multi-material printing. However, compared to other AM processes, Material Jetting can present some challenges in terms of surface finish and scale accuracy of printed parts. This technology means that it can outperform competing AM processes such as Material Extrusion, Binder Jetting or Powder Bed Fusion in some respects [21].

3. ADDITIVE MANUFACTURING MATERIALS

3.1. Polymers

Polymers are often the materials of choice for AM. Polymers are preferred due to their lower melting/curing temperatures, increased chemical stability and uniform flow properties in both molten and softened state. Polymeric materials can be processed in AM in any physical form, e.g. as liquid, powder, sheet or wire. These materials can be processed in almost any melt-based AM process with appropriate processing techniques and a compatible polymer selection. On the other hand, VAT Photopolymerization, Material Extrusion, and Material Jetting are among the three widely used AM techniques [22].

3.2. Metals and Alloys

Metal materials commonly preferred in AM include various metallic materials such as steel, aluminum alloys, titanium and its alloys, copper, nickel-based superalloys, gold, silver, brass and platinum. These metals are raw materials that are generally used in powder form in AM processes [23]. Metal ve alaşımların 3 boyutlu yazıcılar aracılığıyla üretimi giderek artmaktadır. Especially in the aerospace, automotive, biomedical and defense sectors, this material is often used for prototyping, research and small batch production. Additive manufacturing of metals and alloys makes it easier to print complex geometries compared to conventional manufacturing techniques [24].

3.3. Ceramics

Ceramic materials have an impressive thermal insulation capacity and high mechanical properties over a wide temperature range. However, the reason they are increasingly used in electronics manufacturing is their excellent electrical insulation properties. Thanks to their low coefficient of thermal expansion, they expand only minimally during temperature fluctuations, resulting in stable dimensional stability. These properties combined with high corrosion resistance, temperature resistance, wear resistance, hardness and tribological properties make them a preferred material in aerospace, automotive and industrial equipment [25].

3.4. Composites

A composite material is a new type of material that is created by combining different materials and is usually stronger and has special properties. Composite materials improve the quality of parts and ensure their durability over a long period of time. These materials are lightweight, strong and low-maintenance, making them easy to recycle. They are often preferred instead of metal and ceramics. In particular, high-strength, durable and flexible materials such as carbon fibers are often used for composites [26]. Among high-performance industrial materials, advanced composites play a crucial role in weight-sensitive applications such as aerospace, automotive and sports equipment. These types of parts are usually subject to special production processes and require a long development process [27].

3.5. Smart Materials

Smart materials are materials that change their shape, size or functional properties by responding to certain conditions (e.g. solvent, pH, temperature, electricity, light). These materials can change their properties in response to changes in their environment. The emergence of smart materials has led to the development of a new field of research called 4D printing [28]. Smart materials have a wide range of applications. Smart materials enabled by 4D printing are used in various fields such as organ and tissue engineering, biomedical devices, electronic devices, security, precision patterned surfaces for optics, soft actuators, smart valves, regenerative design, electromechanical switches and smart clothing [29].

4. CONCLUSIONS

Additive manufacturing has led to a revolutionary change in industrial production in recent years. In contrast to conventional production processes, this technology is based on the layer-by-layer application of material. AM is attracting a great deal of attention in many sectors and its areas of application are gradually expanding. It is attracting attention mainly because of the production of parts with complex geometry and the design freedom it offers. The increasing popularity of this technology has also led to an expansion of the range of materials. Various materials, from metal alloys to plastics, ceramics and biomaterials, can be used in AM processes and play an important role in industrial applications. Advantages such as less waste, lower material consumption and faster prototyping compared to conventional production methods make AM technology the first choice. However, there are also some challenges in utilising AM technology. There are still some technical and financial difficulties, especially in mass production on a large scale. Improvements still need to be made in areas such as material quality, printing speed and size accuracy. In addition, the establishment of clearer rules in the form of industry standards and regulations can pave the way for the development of the sector.

AM technology will have a major impact on manufacturing and design in the future. As it is an ever-evolving and expanding field, it encourages researchers, engineers and industrial players to make new discoveries in this area and push the boundaries of the technology. With the integration of AM into more industrial applications, a big change is expected in terms of efficiency and flexibility in manufacturing. AM is a rapidly developing field that will lead to major changes in the future. In the future, the further expansion of the material range of AM technology, the discovery of new materials and the adaptation of these materials to AM processes will increase the potential of the technology. In addition, the improvement of material properties and the development of new techniques will increase the quality and durability of parts that can be produced with AM. This will also support the expansion of AM to a wider range of applications, with advances in areas such as material sourcing, software development, design learning, safety standards and industrial compliance, as AM becomes an ecosystem rather than just a manufacturing process. AM is expected to be adopted by individual users and small businesses as well as large industrial applications.

Biographies

Raziye Kılıç received the BSc. and M.Sc. degrees in Industrial Engineering from Ataturk University in 2014 and 2019 respectively. She currently continues her PhD at the same university. She is an Res. Asst. of Computer Engineering at Ataturk University, Turkey. Her research interests include multi-criteria decision-making, logistics, production systems, simulation, information systems, artificial intelligence and machine learning.

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