



Additive Manufacturing Technologies and its Future in Industrial Applications

Osman İyibilgin^{1,2*}, Engin Gepek^{1,2,3,4}

¹Mechanical Engineering Department,
Sakarya University, Sakarya, TURKEY

²BIOENAMS, (Biomaterials, Energy, Photocatalysis, Enzyme Technology, Nano and Advanced Materials, Additive Manufacturing, Environmental Applications and Sustainability Research and Development group),
Sakarya University, Sakarya, TURKEY

³BİMAS-RC, (Biomedical, Magnetic and Semiconductor Materials Application and Research Center),
Sakarya University, Sakarya, TURKEY

⁴Turkish-German University, Mechanical Engineering Department, Istanbul, TURKEY

*Corresponding author

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Abstract: Additive manufacturing technologies have developed rapidly in the last ten years and have become a technology with significant advantages compared to traditional manufacturing. Depending on discovering new materials and techniques, additive manufacturing technologies also develop and become more economical and sustainable technology. The widespread use of this technology in industrial areas has accelerated development and contributed to increased product quality. However, to ensure the development and continuity of this technology, it is necessary to reduce the production costs, increase the quality and accelerate the production processes. These processes also trigger competition and accelerate the development of technology. The areas that additive manufacturing technologies are mostly applied can be grouped as aerospace, biomedical, smart technologies, and other industrial applications. The fact that these areas are popular research areas also accelerates the development of additive manufacturing technologies. In this review, additive manufacturing technologies from past to present, advantages and disadvantages of these technologies, aspects that need to be developed, and industrial applications are examined and explained. When the studies on additive manufacturing technologies and industrial applications are examined, it is seen that this technology has a wide usage area. With the use of additive manufacturing technologies, previously encountered in prototypes and special applications, in automotive, biomedical, and smart technologies, it is seen that they have begun to take place more in people's daily lives.

Keywords: Additive manufacturing, industrial applications, aerospace, biomedical, automotive.

1. Introduction

Additive Manufacturing is the general name of production technologies in which materials are deposited in layers and 3D objects are produced. With this technology, parts with different structures and complex geometries can be produced using a large number of materials such as polymer, ceramic, metal, composite, etc. from three-dimensional (3D) model data. Today, different names are used for Additive Manufacturing Method such as "Solid Freeform", "Rapid Tooling", "Rapid Casting", "Rapid Prototyping", "3D Printing", "Indirect Additive Manufacturing". Additive

*Corresponding author: ibilgin@sakarya.edu.tr

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manufacturing (AM) technology was invented first in the 1980s by Charles Hull as a Stereolithography (SLA) process [1]. Thereafter, Additive Manufacturing Technologies is called fused deposition modeling (FDM), three-dimensional printing (3DP), selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM) according to the material type used in manufacturing and joining technique used in the following years [2–6].

The general advantages of the additive manufacturing method compared to traditional techniques are the high precision production of parts with complex geometry, the customization of production, less material waste, flexibility in design, and short production time in small numbers of productions. In this method, combining the layers of part production allows production with precision and control, which is not possible with traditional production methods [7]. The ability to produce parts directly from the CAD model without using molds in additive manufacturing techniques provides significant advantages in terms of cost and production time in the production of parts designed and modified according to the person/desired specifications [6]. Contrary to traditional machining methods, manufacturing by combining powder, filament and resin and reusing unused material minimizes material waste [8]. In additive manufacturing, it has design flexibility in part production since there is no need for a separate model for each part with different geometry. Different geometry parts can be produced directly on the 3D printer in one go, which significantly reduces production time and cost

2. Basic Additive Manufacturing Techniques

The principle of AM lies in adding material instead of removing it. The part whose 3D model is created is produced directly with a 3d printer. Today, 3D printers are used to manufacture end-use products with various materials such as polymers, ceramics, metals, and composites. Additive manufacturing technologies take different names according to the method of combining materials. Schematic diagram of classification of additive manufacturing methods are shown in shown in Figure1 [9,10].

2.1. Fused Deposition Modeling (FDM)

FDM is one of the additive manufacturing techniques in which three-dimensional parts are produced by melting the thermoplastic material and combining it layer by layer according to a certain model. One of the most common additive manufacturing techniques, it was first developed by Scott Crump [11–14]. The scheme of the production system with FDM is shown in Figure 2 [15]. Polylactic acid (PLA), polycaprolactone (PCL), polypropylene (PP), polyethylene (PE), polybutylene terephthalate (PBT), Acryloyl-butadiene styrene (ABS), wood, nylon, metals, carbon fiber, graphene-added PLA used in the FDM method materials [16–20]. FDM method has many application areas such as rapid prototyping, mold production, personalized auto parts, toys and parts, design components, model production [21–23].

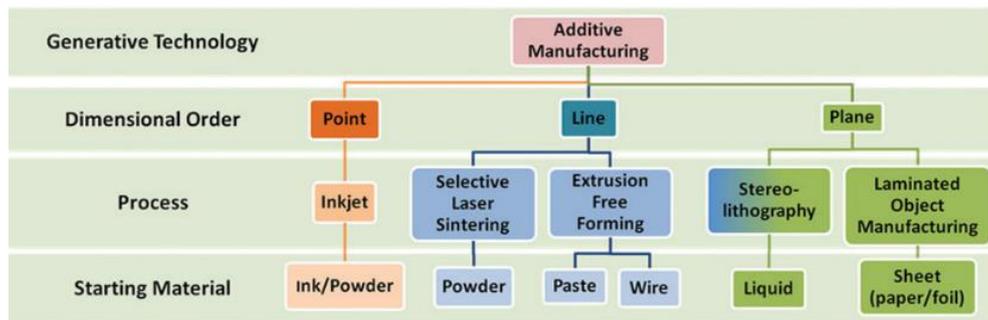


Fig. 1 - Classification of additive manufacturing methods [9,10]

2.2. Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is an AM method in which three-dimensional parts are produced by combining particles and layers by laser sintering [24]. The SLS 3D printer scheme is shown in Figure 3 [25]. In this method, the regions that make up the powder material model laid on the production platform are selectively scanned with laser and combined. Powder material that is not used after the production process can be reused. The SLS method, it can use a wide range of materials including polymers, metals, and composites [13,26,27]. SLS is used in industrial applications such as military, aviation, biomedical, electronic equipment, automobiles [6,25,28,29]. The high cost of laser and other equipment in SLS production is not suitable for personal and home applications.

2.3. Selective Laser Melting (SLM)

Production is performed by combining it with laser similar to the selective laser melting SLS method [30]. In this method, the desired part is completed by selectively scanning the powder material laid on the platform and melting it

with a laser and solidifying this melt region [30,31]. In SLM, the end-user product is directly obtained without applying additional processes such as binder removal and heat treatment. In addition, this production technique has advantages such as material savings, high dimensional accuracy and the ability to produce functional products with personalized geometry [24,32].

2.4. Binder Jetting

The Binder Jetting (BJ) method is produced by combining the powders by selectively spraying the powder material laid in the production pool according to the desired part shape [33]. Figure 4 shows the schematic of the Binder Jetting production system. In this method, when the powder material is kept together with only the binder, the mechanical properties of the raw part are low. After production, the raw parts are given strength by applying heat treatment. Mold production, biomedical and aviation, decorative parts and prototype production are the usage areas of Binder Jetting method. With the Binder Jetting method, direct production is carried out with many materials such as polymer, ceramic, metal and composite without the need for molds.

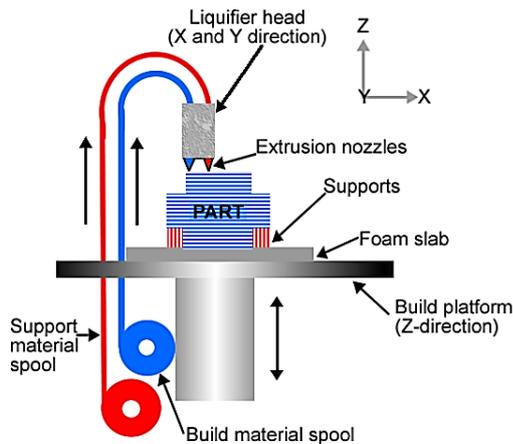


Fig. 2 - Schematic representation FDM 3D printing [15]

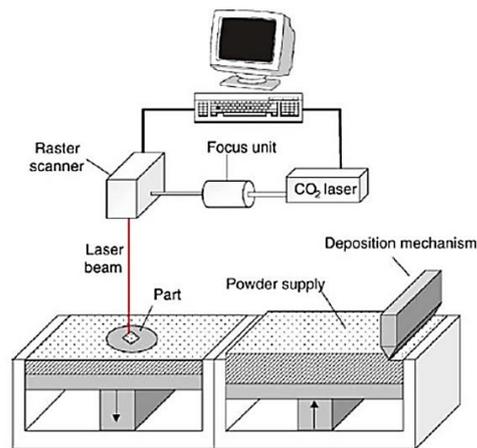


Fig. 3 - Scheme of SLS 3D printing [25]

2.5 Stereolithography (SLA)

SLA is an additive manufacturing technology in which the production is carried out by curing the polymer resin material with ultraviolet light [1,34]. Production is carried out by creating new layers on the first layer after certain areas of the liquid photopolymer resin layer are cured with a laser beam [6,35]. Resins with different properties are used according to the application areas. Its main areas of use are jewelry, dental models, biomedical applications, and the production of industrial prototypes [35].

3. Industrial Applications of Additive Manufacturing

Today, additive manufacturing technologies are encountered in many sectors such as automotive, biomedical, construction machinery, aviation, defense, rapid prototype production and user products. Figure 6 shows the distribution of additive manufacturing technologies by industrial areas as of 2018 [36]. When we look at the industrial distribution of IR technologies, automotive, industrial machinery and aviation applications come to the fore. The main reason for this is that the final products such as engines, spare parts, other interior and exterior parts can be applied more easily than other sectors. Figure 7 shows the estimated annual market share of Additive Manufacturing technologies from 2013 to the present and until 2027 [37,38]. When the market share of EM technologies is analyzed by years, it is seen that there is a growth in the range of 12-17%. The market share, which was approximately 4.5 billion dollars in 2013, is expected to be 44.6 billion dollars by the end of 2027 [38]. Polymers are one of the most widely used materials in additive manufacturing technologies [39,40]. The polymer material can be easily shaped, recycled and its costs are low, providing convenience in accessing and using polymers [41]. Thermoset polymers are preferred for structural applications due to their superior mechanical properties and thermal resistance [42,43]. Figure 8 shows the market value of the polymer material used in additive manufacturing technologies [38]. Considering the market value on an annual basis, the use of polymers is increasing regularly every year. Polymers are used in many industrial applications such as prototype production, automotive, biomedical, aerospace [36,44,45]. The use of metals other than polymers in additive manufacturing technologies is increasing day by day. More resistant parts can be produced with metals materials compared to polymer materials. The market shares of the techniques used in shaping metal materials is shown in Figure 9 [36]. It is seen that PDF is the most widely used shaping method in forming metals.

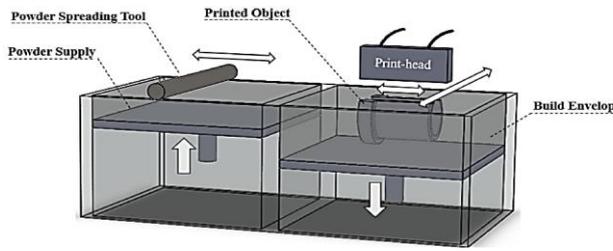


Fig. 4 - Schematic representation of Binder jetting system [33]

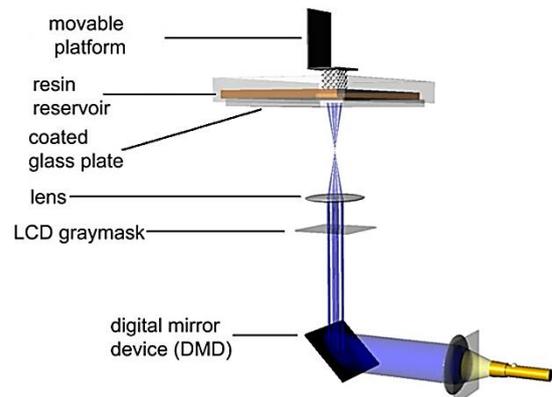


Fig. 5 - Schemes of stereolithography 3D printer setups [35]

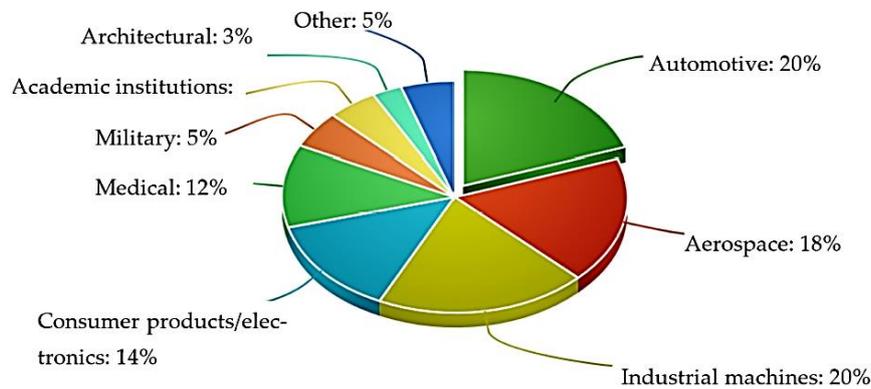


Fig. 6 - Industrial Adoption of additive manufacturing (AM) in 2018 [36]

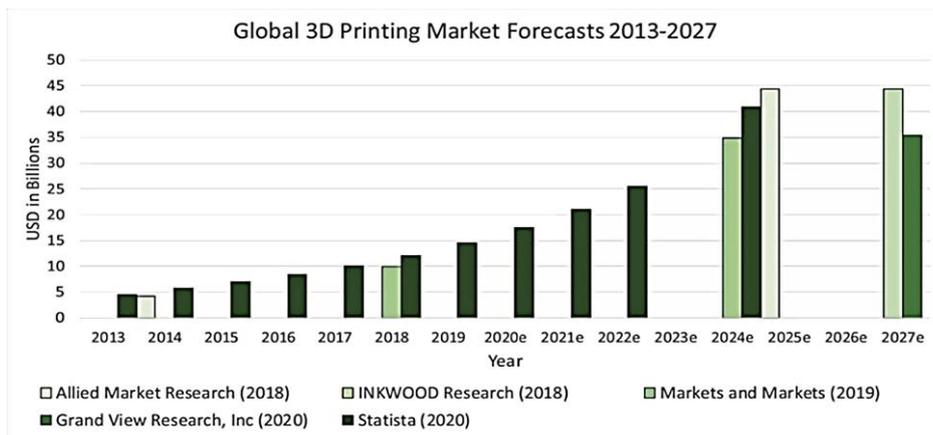


Fig. 7 - Estimated market share of additive manufacturing Technologies [38]

3.1 Aerospace Applications

Additive manufacturing technologies enable the production of parts with higher strength, lighter and more complex designs compared to parts produced by traditional methods in the aviation industry. Thanks to the absence of design constraints in this method, complex and lighter parts designed with topological optimization studies can be produced. The use of lightweight materials in aircraft provides savings in material costs used in production and fuel consumption in these vehicles. A large proportion of costly raw material is wasted in the production made by traditional methods such as machining [46]. With additive manufacturing, the loss of raw material is minimized as powder materials that are not

used during production can be reused. The parts used in air vehicles are not suitable for mass production due to their high safety coefficients and their long service life. Additive manufacturing methods are more advantageous in the production of spare parts that are needed in small numbers and may be needed in the long term. In additive manufacturing methods, it can be produced directly on the 3D printer without the need for molds, which significantly reduces time and cost. The main applications of Additive Manufacturing technologies in the aviation industry include rapid prototyping, prototyping and testing of end-use parts, and repair of damaged parts. In these applications, many production studies are carried out with polymer, metal, ceramic and composite materials. In Figure 10, the Leap Engine Fuel Nozzle produced by EOS metal powder bed fusion machine and cobalt-chrome by GE aviation company is shown[46,47]. This nozzle, which is produced by welding about 20 parts together in the traditional method, was produced as a single piece, 25% lighter and with the DMLS method (GE).

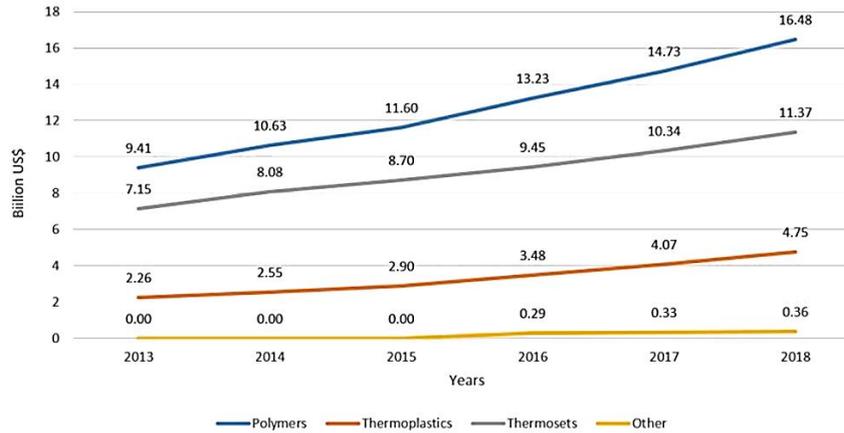


Fig. 8 - Market share of polymers in additive manufacturing Technologies [38]

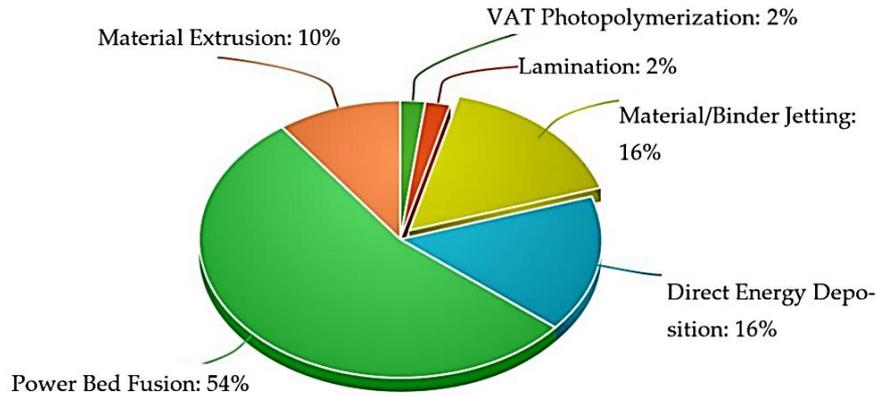


Fig. 9 - Market share of metal additive manufacturing [36]



Fig. 20 - Leap Engine Fuel Nozzle manufactured by using direct metal laser melting[46]

Fig. 31 - Cabin bracket connector used in Airbus A350 XWB produced using additive manufacturing [46]

Concept Laser manufactured a "bionic" design bracket used in the Airbus A350 XWB using the Laser CUSING system (Figure 11). This piece, which was previously produced from aluminum, was produced from titanium with a bone-like porous structure and its weight was reduced by 30%. While 95% of waste material is generated by the milling method, the waste amount is 5% in the Laser Causing method [46]. In addition, with the SLM method, the development/production time of this part has decreased from 6 months to 1 month [48]. Airbus has contracted with Stratasy to fabricate non-structural parts such as the bracket shown in Figure 12 on FDM 3D printers using ULTEM™ 9085 material (Stratasy). This project, it is aimed to use less material and avoid waste.

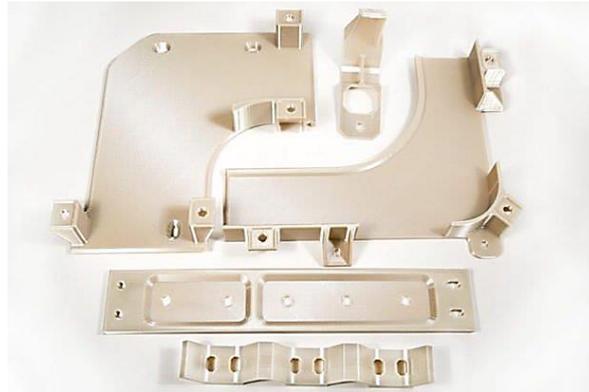


Fig. 42 - FDM Printed internal brackets for Airbus [48]

In another study conducted with the FDM method, polycarbonate cable channels shown in Figure 13 were produced to be used in Bell Helicopter. While the production of approximately 42 models with small variations in this method takes 2 and a half days, it takes approximately 6 weeks to produce them in aluminum molds [48]. NASA used the SLM type printer for the production of the metal rocket injector part shown in Figure 14 for the next-generation Space Launch System (SLS) J-2X engines. While this injector consists of 115 parts in the production made by traditional methods, it consists of two parts in the SLM method. The fact that the rocket injector can be produced as a whole in the 3D printer ensures that its strength is higher and the production time is significantly reduced. In addition, in bilateral cooperation with NASA Stratasy, 70 of the parts that make up the Mars Rover (Mars Rover) vehicle were directly produced with 3D printers[48,49].

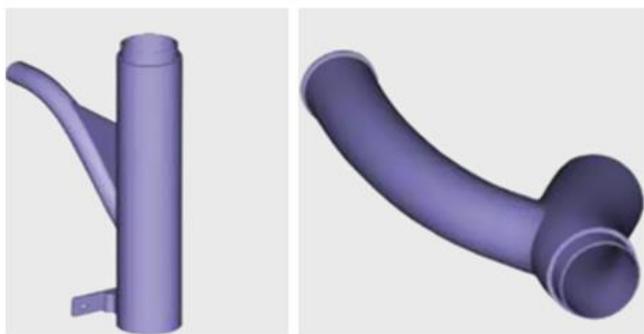


Fig. 53 - Polycarbonate wiring conduits made by fused deposition modeling. Courtesy Stratasy and Bell helicopter [48]



Fig. 64 - Metal rocket injector part for their next-generation Space Launch System (SLS) J-2X engine [49]

3.2 Biomedical Applications

Another area where additive manufacturing technologies are widely used in biomedical applications. There are many applications in biomedical applications such as hip, knee or joint fittings/prosthesis, artificial bone and tissue applications (Singh and Ramakrishna, 2017). Additive manufacturing methods enable more economical production of specialized biomedical parts with complex geometry compared to other methods in a limited number of productions. Production

costs and production time are reduced because there are no additional processes such as molding, milling and grinding in the production of a limited number of biomedical products directly with a 3D printer. Another important advantage of additive manufacturing technologies in biomedical applications is that products can be designed and modified according to the needs of the patient. One of the most common uses of additive manufacturing technologies is that the models obtained by 3D scanning are produced in a printer and used in surgical planning and medical training. By making use of the models produced with a 3D printer, it enables better planning of surgical operations and enables more successful and more appropriate use of medical products [50]. Surgeons can achieve more successful results in complex cases thanks to training made with 3D printing. Figure 15 shows the 3D visual and 3D printing of a patient's aorta. Figure 16 shows the MRT image dataset and 3D print of the ventricular system of a child with Dandy-Walker malformation [51]. As seen in Figure 1 and Figure 2, 3D printing helps clinicians fully understand the nature of anatomical abnormalities in humans [52]. In another study in the biomedical field, Additive manufacturing technologies were used in liver transplantation performed by surgeon Maki Sugitom at Kobe University Hospital in Japan [53]. In this study, using 3D printing models of the patient's organs, it was planned to cut the liver taken from the donor with the least tissue loss (Figure 17). Meyer et al developed UV-sensitive poly (tetrahydrofuran ether diacrylate) (PTHFDA) resin and produced micro-sized pipes used in blood supply systems with SLA 3D printer [54,55]. Figure 18 shows micro pipes produced with an SLA 3D printer. Production in micro sizes with additive manufacturing technologies allows the production of tissues in capillary sizes.

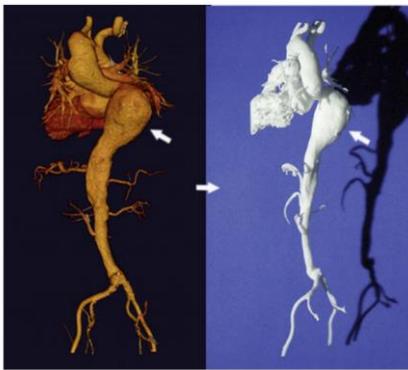


Fig. 75 - 3D visualization and 3D rapid prototyping of the aorta [52]

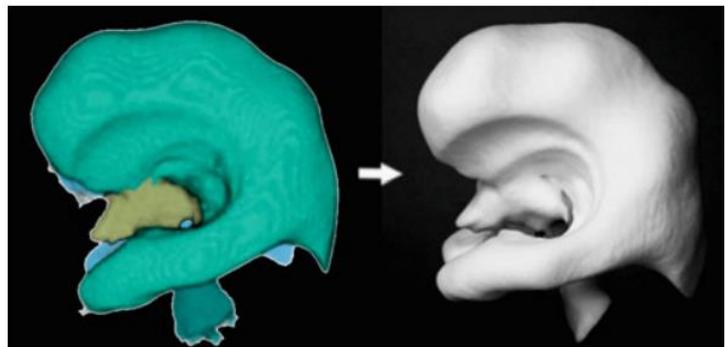


Fig. 86 - MRT image data and 3D printing of a child's ventricular system [51, 52]



Fig. 97- 3D printed model of liver[53]

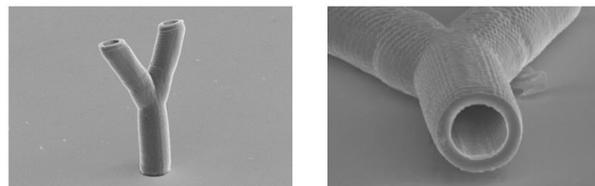


Fig. 10 - Scanning electron micrographs of branched tubular structure manufactured with SLA 3D printer (The height of the tubular structure is approximately 160 μm , the inner diameter and wall thickness are approximately 18 μm and 3 μm . [54])

Additive manufacturing technologies are a suitable method for the production of custom permanent implants other than the printing of anatomical models and surgical guides. The use of patient-specific implants increases the success rate of implants and shortens the duration of surgical procedures and patient hospitalization. In the production of metal implants, many different techniques such as SLM, SLS, EBM and Binder Jetting are used [56–58]. With additive manufacturing technologies, implants are produced using various metals such as stainless steels (316L), Co-Cr-Mo alloy, titanium (Ti) alloys, pure titanium and tantalum [57,59,60]. Figure 19 shows the patient-specific screw acetabulum implant. Being able to produce patient-specific by optimizing the position of the prosthesis can minimize tissue loss and prolong the life of the prosthesis[61,62].

3.3 Automobile Applications

In the automotive industry, additive manufacturing technologies are used in developing a new product, prototyping, production of lightweight optimized parts and spare parts [63]. Due to the short production costs and production time in the production of a small number of parts in additive manufacturing technologies, it can shorten the development cycle and reduce manufacturing and product costs [6]. In addition, the problem in the supply of spare parts in old model vehicles can be solved with additive manufacturing technologies.

In research about the automotive industry, the reasons for companies' inclination to additive manufacturing include the decrease in production costs, high material wastage, freedom in design, rapid response to market needs and less assembly process [64]. In Figure 20, the report published on motor vehicle and motorcycle manufacturers in EU countries shows that more than 60% of companies adopt AM technologies at any stage of the production process [65]. When the results of the report are examined, the most adopted applications of IR technologies are product visualization and prototyping applications, while the least adopted applications are tooling. French car manufacturer Bugatti produced the 2.9 kg brake caliper shown in Figure 21a from Ti6Al4V using SLM 500 Multilaser 3D printer [36]. consisting of 2213 layers and manufactured in 45 hours on a 3D printer, this bracket caliper is 40% lighter than the original Aluminum bracket, which weighs approximately 4.9 kg. Figure 21b shows the steering knuckle produced with a 3D printer [66]. This steering knuckle was made 35% lighter than the existing casting with the EOS DMLS 3D printer. Figure 21c shows the production of rarely requested water connectors for the 3D printer Audi W12 engine [67].

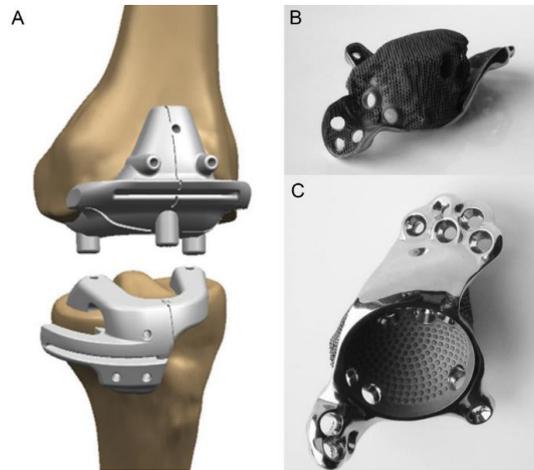


Fig. 119 - Custom-made titanium acetabulum implant with screw [62]

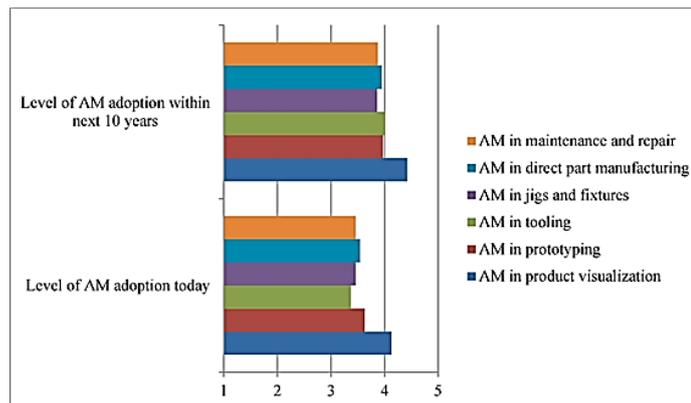


Fig. 20 - Distribution of additive manufacturing adoptions across product lifecycle stages [65]

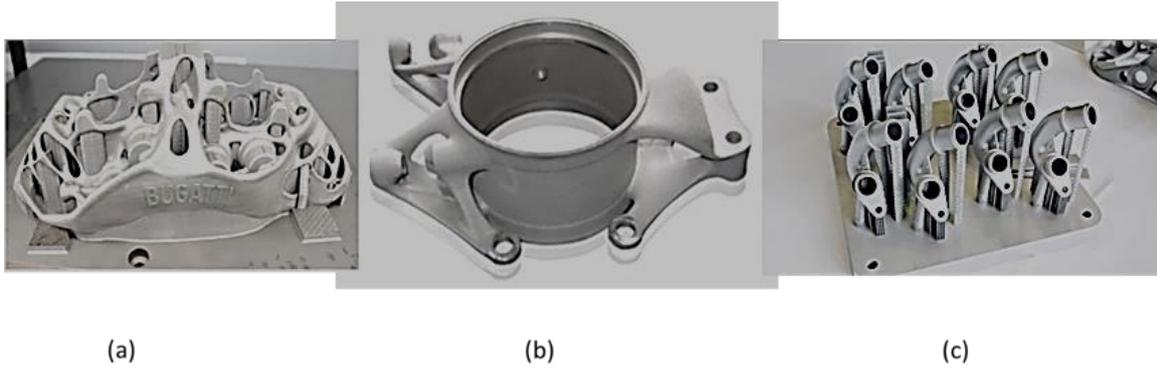


Fig. 212 - Automotive products manufactured with 3D printer; a) Bugatti Brake caliper [36], b) Steering knuckle [66] c) Audi W12 engine water connectors [67]

3.4 Other Industrial Applications of AM

Other application areas of additive manufacturing technologies are 4D Printing (3D printing of Smart materials), eyewear industry, electronic hardware, energy storage, food industry, sensors and robotics applications [68–71]. The 3D printing of smart materials such as shape memory and self-healing is called 4D printing [71]. Smart materials are defined as materials that change shape when stimulated by an external stimulus such as heat, light, chemical, electric and magnetic fields. Figure 22 shows the 3D printed models with shape-memory materials. As seen in Figure 22b, the stent produced with a 3D printer is shown [72]. The stent is programmed into a smaller diameter temporary shape before application. After the stent is heated, it returns to its original shape with a larger diameter. Another application area of additive manufacturing technology is construction applications. The use of additive manufacturing technologies in the construction industry can reduce labour costs, material waste and help to produce customized complex parts that are difficult to produce with traditional methods thanks to its low cost of prototyping and unlimited design ability [73,74]. In Figure 23, the Arup group produced the construction node, obtained as a result of the topological optimization, with a 3D printer [74]. As a result of the work done, the weight of the part has decreased by 75% and the weight of the whole structure can be reduced by approximately 40%.

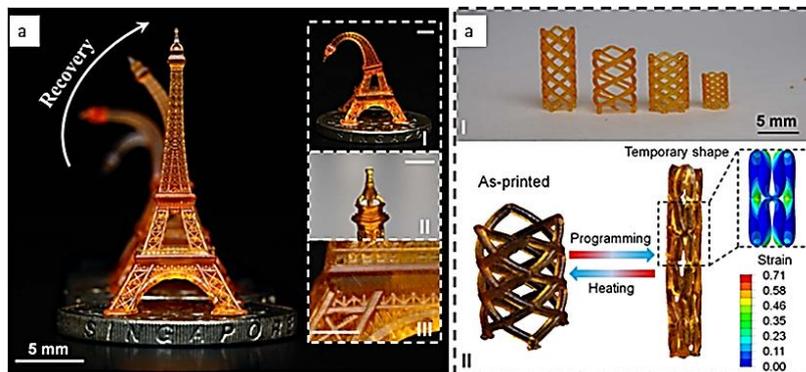


Fig. 22 - 3D printed shape memory (SM) structures (a) 3D SM Eiffel tower, (b) SM stents [72].

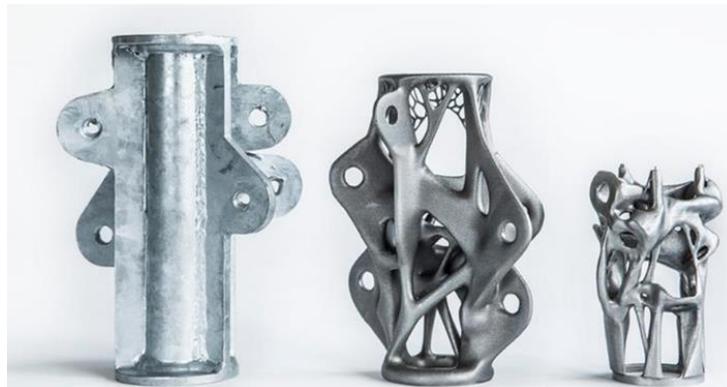


Fig. 23 - Arup group's optimized node produced with AM [74]

4. Conclusions

Additive Manufacturing is the general name of production technologies in which materials are deposited in layers and 3D objects are produced. With this technology, parts with different structures and complex geometries can be produced using many materials such as polymer, ceramic, metal, composite, etc. from three-dimensional (3D) model data. The general advantages of the additive manufacturing method over traditional techniques are the high precision of complex geometry parts, customization of production, less material waste, flexibility in design, and short production time in a small number of productions. The combination of layers of part production in this method allows precise and controlled product that is not possible with traditional production methods. The following conclusions can be drawn from the current study:

- a. Today, 3D printers are used to produce many types of materials such as polymer, ceramic, metal and composite. Additive manufacturing techniques include fused deposition modeling (FDM), selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), as well as inkjet printing, stereolithography. It is classified as direct energy deposition (DED) and laminated object manufacturing (LOM).
- b. Currently, additive manufacturing technologies are encountered in many sectors such as automotive, biomedical, construction machinery, aviation, defense, rapid prototype production and user products.
- c. Additive manufacturing technologies enable the production of parts with higher strength, lighter and more complex designs compared to parts produced by traditional methods in the aviation industry. Thanks to the absence of design constraints in this method, complex and lighter parts designed with topological optimization studies can be produced.
- d. Another area where additive manufacturing technologies are widely used is biomedical applications. There are many applications in biomedical applications such as hip, knee or joint placement/prosthesis, artificial bone and tissue applications. Additive manufacturing methods enable the production of special biomedical parts with complex geometry more economically compared to other methods in a limited number of productions.
- e. In the automotive industry, additive manufacturing technologies are used in the development of a new product, prototyping, lightweight optimized parts and spare parts production. In additive manufacturing technologies, the production of a small number of parts can shorten the development cycle and reduce production and product costs due to the short production costs and production time. Recently, companies have turned to additive manufacturing due to lower production costs, high material waste, freedom of design, quick response to market needs and less assembly time.
- f. Other application areas of additive manufacturing technologies are 4D Printing (3D printing of smart materials), eyewear industry, electronic hardware, energy storage, food industry, sensors and robotics applications. Smart materials are defined as materials that change shape when excited by an external stimulus such as heat, light, chemical, electric and magnetic fields. The stent, produced with a 3D printer, is programmed into a smaller temporary shape before application. After the stent is heated, it returns to its original shape with a larger diameter.
- g. Another application area of additive manufacturing technology is construction applications. The use of additive manufacturing technologies in the construction industry can reduce labor costs, material waste, and help produce customized complex parts that are difficult to produce with traditional methods, thanks to low prototyping costs and unlimited design capabilities. As a result of the work done, the weight of the entire structure can be reduced by 40%.

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