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THEORETICAL ANALYSIS AND PRACTICAL CASE STUDIES OF SLA, POLYJET AND FDM MANUFACTURING TECHNIQUES

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Abstract: *Among the most advanced technologies developed in recent years, Additive Manufacturing (AM) is one that meets the requirements of the Fourth Industrial Revolution. In this paper, we present some AM methods such as stereolithography (SLA), polyjet and fused deposition modeling (FDM). The AM technologies analyzed use raw material in liquid form and filament. The study is focused on three important aspects like the processing principle, the material used by each technology and the latest practical examples developed. The products exposed are from various domains such us medicine, automotive, aerospace and industry. Furthermore, we detailed the main manufacturers of AM systems, their equipments and the cost range.*

Key words: *stereolithography, polyjet, fused deposition modeling, materials.*

1. INTRODUCTION

3D Printing or Additive Manufacturing (AM) is a technology capable to process a wide range of complex structures and geometries from a virtual model. Generally, the AM technologies produce parts or assemblies by successive printing of layers that are formed one over the other, using various materials such as: plastics, metals, ceramic or composites. The AM technologies are growing very fast and promise to revolutionize the manufacturing sector through shorter production times, less material loss and the ability to print multi-materials [1]. Post-processing of parts 3D printed can include removing supports, polishing the surfaces, sintering, infiltration or heat treatments for stress relieved [2], [3]. These AM processes possess some benefits as compared to conventional technologies based on material removal. Firstly, the amount of material required is less than the traditional processing methods where the material is removed from a blank to the desired geometry [4]. In the case of AM methods, the part is made layer by layer, and the amount of material used can be controlled much better. Secondly, the AM processes are able to fabricated parts that many of the traditional methods can hardly make, such as creating multi-material parts and biomedical parts even organs. Last but not least, these technologies can reduce production times and costs [1]. Of course, in the case of the parts made by adding material, due to the method of production, layer by layer, the material has anisotropic properties [5]. Depending on the material used, the additive fabrication includes several technologies like processes that use raw materials in liquid forms, powders and filaments.

The objective of this review is to present the AM methods which use raw materials in liquid forms and filaments, and the latest developed applications. Knowing the AM methods are considered to be an essential ingredient for the latest industrial revolution (Industry 4.0), the purpose of this article is to provide some best practice for engineers, designers and other people who are interested to see how AM can be integrated in various domains like medicine, automotive, aerospace or industry.

2. STEREOLITHOGRAPHY

The stereolithography (SLA) process is the first commercialized AM technology and one of the most used [6]. This technology has a great advantage due to the flexibility of the process that can manufacture parts of various sizes and complex geometries. Also, manufacturing accuracy places this process at the leading positions of additive technologies. Moreover, SLA process has achieved remarkable success in the manufacturing of porous structures for tissue engineering [7].

At the base of SLA there is a polymerization process whereby a liquid resin is solidified with UV (Fig. 1). It uses the CAD model which is divided into layers of predetermined thickness, representing the horizontal sections of the part to be manufactured. In order to achieve the work piece, UV radiation is concentrated on the surface of the resin and solidified it by the strategy adopted for each layer. After the layer is polymerized, the machine platform descends with a distance equal to the thickness of a layer and thus a new layer of liquid resin covers the part. This procedure is repeated until the production is completed.

Once the piece has been built, it must be cleaned, fully solidified and finished. During the cleaning and finishing phase, the operator of the SLA machine will remove the supporting structures. During the completion, the operator can spend considerable time sanding the piece to ensure the desired surface quality [8].

The first US patents describing SLA resins were published in 1989 and 1990 [9], [10]. These resins were prepared from acrylates which had high reactivity but usually produced weak parts due to inaccuracies caused by shrinkage and bending [8]. The first Japan patents that prepared an epoxy composition for SLA resins appeared in 1988 [8]. Epoxy resins have produced more accurate, tougher and stronger parts than acrylic resins. While the polymerization of the acrylate compositions results in a contraction of 5-20%, the polymerisation of the epoxy compositions results in only a 1-2% contraction [11].

However, epoxy resins have disadvantages like slow photo-polymerization and fragility of manufactured parts. Addition of acrylic resins to epoxy resins is required to quickly build up partial strength so they have sufficient integrity to resist without distortion during manufacture. Acrylates are also useful to reduce the elasticity of the epoxy parts.

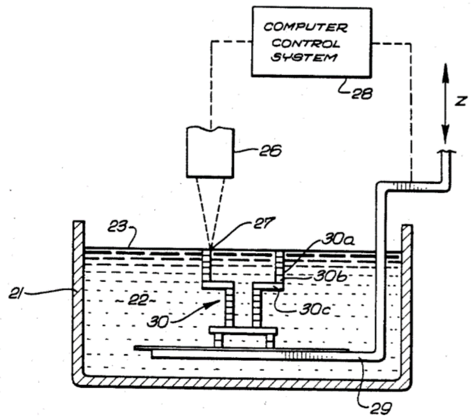


Fig. 1. Image from U.S. Patent 4575330 introduction of the term and the concept of SLA

The emergence of nano-composites has attracted great interest among researchers. Typically, nano-dispersion phases include metals [12], inorganic particles [13], [14] [15], [16], [17], graphite nano-fibres [18], clay [19], [20] and carbon nano-tubes [21], [22]. Nano-composites consisting of a polymer and silicone containing nano-materials often exhibit remarkably high properties including mechanical properties [23], [24], heat resistance [25], low gas permeability [26] and non-flammable [27]. These improved properties in nano-composites are mainly due to the stronger interaction between the polymer matrix and the silicon-containing nano-materials. Due to the special surface chemistry, silicon-containing nano-materials can be readily functional and can be easily modified and dispersed in polymers to form nano-composites.

With decreasing costs of SLA equipments, the process has been applied to different types of materials in many laboratories. Recently, intelligent materials have been printed through SLA, and they can subsequently change their form in response to various stimuli such as light, heat, water or acid [8], [28]. This property adds a fourth dimension, which is considered to change the 3D printing into 4D printing.

The leading manufacturers of SLA systems are: 3D Systems (ProX 800), EnvisionTEC (Perfect 3 DDP), Prodways (ProMaker L5000), DWS (DigitalWax 029X), Shining 3D (iSLA-650 Pro), etc. The price of such equipment varies between 35,000 - 250,000 € depending on the size of the work platform, the thickness of a layer and the accuracy obtained. An accessible desktop unit was created by FormLabs and the price is around 4000 €. The Form 2 delivers accurate parts at a fraction of the cost compared to industrial machines.

The applications of SLA process are multiple. In medical field, some authors developed a concept for a custom intervertebral fixing implant starting with the medical data of a specific patient [29]. Also, custom medical tools can be fabricated in order to assist the surgeons during some complex operations. In industry, SLA technologies can make 3D models of parts for better appreciation and inspection of them, master model for future moulds (eq. jewellery industry), in electronics as supports or cases for different circuits and sensors, decorative pieces and drones. Some of these examples are illustrated in Fig. 2.

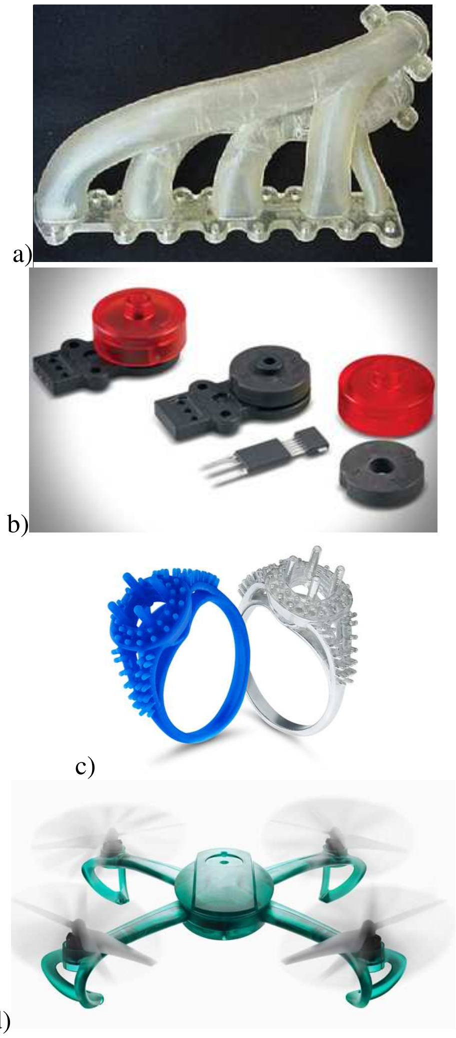


Fig. 2. SLA applications:
a) Master models for automotive industry,
b) Housing for electric sensor, www.proto3000.com,
c) Jewelry models for casting,
d) Drone www.formlabs.com

3. POLYJET PROCESS

PolyJet is a technology similar to SLA, but the difference lies in the fact that it uses a print head to deposit material. This process is also called lithographic inkjet. The material used is a photopolymer which is polymerized by means of a UV light source. The photopolymers processed by PolyJet poses different properties comparing to SLA. In the case of SLA, the raw material has a higher viscosity coefficient. Also, adding reinforcement particles to the composition of resins, composite materials can create more problems for PolyJet printing due to high viscosity.

The main manufacturers of PolyJet systems are: Stratasys (Objet500 Connex), 3D Systems (ProJet MJP 3600 MultiJet), HP (Jet Fusion 3D 4200), Solidscape (Pro), Massivit (1500 MASSIVit 3D), etc. The price of such equipment varies between 50,000 - 150,000 € depending on work platform size, precision of manufactured parts and productivity. Desktop versions were developed as low-cost equipments and the prices ranging from 10,000 to 30,000 €. The producers for desktop PolyJet systems are Stratasys (Objet30), Keyence (Agilista 3100) and Solidscape (Max²).

PolyJet technology has applications in areas such as automotive, rapid prototyping, respectively in dental medicine to manufacture mobile prostheses (Fig. 3).

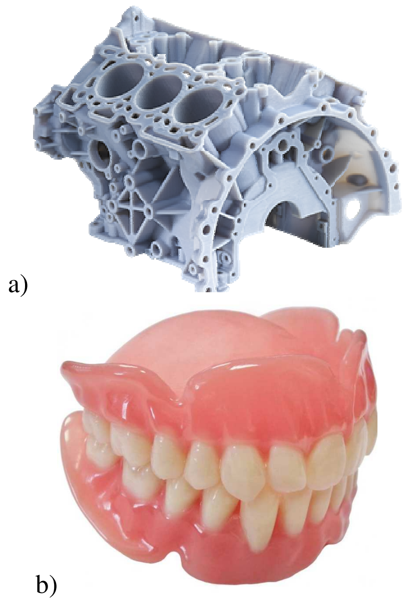


Fig. 3. PolyJet applications:
a) Automotive part www.incodemagroup.com,
b) Mobile dental prosthesis www.envisiontec.com

4. FUSED DEPOSITION MODELING

Fused Deposition Modeling (FDM) is a process that uses a nozzle or an orifice to selectively deposit a melted plastic. For 3D printers using FDM technology, a thermoplastic material thread is fed through a heated extruder that melts and extrudes the filament through the print head to a thickness that depends on program and machine settings (Fig. 4). FDM printers deposit layer-layer thermoplastic material to form the 3D piece. FDM technology use thermoplastic filaments from different plastics such as: acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polystyrene (PS) and polyamide (PA). The most common material for FDM printing is polylactic acid (PLA). All these materials are available in different colours [30].

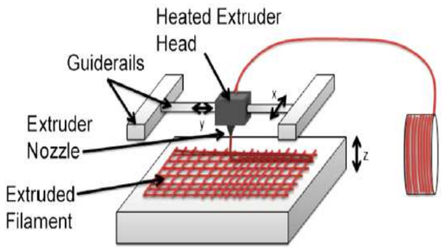


Fig. 4. FDM process [1]

The leading manufacturers of FDM systems are: Stratasy (uPrint SE), MakerGear (Makergear M2), Ultimaker (Ultimaker 2+), Prusa Research (Original Prusa i3 MK2S), Zortrax (M200), and MakerBot (Replicator 2). The price of such equipment varies between 3,000 - 15,000 € depending on the work platform size, productivity and accuracy of the manufactured parts. There are even companies which provide just the kit of a desktop systems and the end-user has to assembly the system. The products printed are just for hobby and the system posses open source software. The price for these 3D printers starts at 100 €. On the other hand, a new system is produced by Millebot in order to incorporate various features to a large 3D printer. The MILLE LE system is an industrial all-in-one FDM machine with build size 1600 x 3050 x 1600 mm. The main features include CNC milling spindle, plasma cutter, fibre laser cutter and water-jet cutter. The price for this system is around 250,000 €.

3D printing of polymers has found the possibilities of using it in many applications such as automotive, architecture, sports (Fig. 5). In dental domain, it is possible to obtain the patients' dental arches in order to allow the clinician to analyze, diagnose or to monitor the anomalies [31]. Also, customized prosthetics could be produced for new treatments resulting an improvement design and functionality of this orthopedic tools (Fig. 6). All these products are manufactured in concordance with mechanical properties of human body [32].

a) b) c) d)

Fig. 5. FDM applications:
a) Architecture www.paradigm3d.com/architecture-aec,
b) Shoes for sport, c) First 3D Printed Car Series in 2016,
d) Large scale car parts manufactured by Ford
www.compositesmanufacturingmagazine.com

a) b)

Fig. 6. 3D Printed prosthetics for:
a) Hand www.tractus3d.com, b) Leg www.art4leg.com

However, many of the parts 3D printed are used as prototypes and conceptual models, and not as functional parts, due to the fact that the PLA filament possesses low tensile strength. Such disadvantage restricts the widespread use in the industrial field of FDM-manufactured parts.

3D printing of polymeric composites partly solves the mechanical characteristics by combining matrix and reinforcements to create a system with several useful structural or functional properties that cannot be achieved by any single constituent. Incorporating reinforcements (particles, fibres or nano-materials) into polymers allows the manufacture of polyether matrix composites, characterized by high mechanical performance and good functionality. [33], [34]. The main reasons for switching to composites are due to their properties and performance comparable to conventional materials (metals, plastics and wood), keeping their advantages such as low weight, corrosion resistance and strength.

There are three configurations of FDM printers which can use composite materials. The first one has an extruder head and prints parts using a composite filament that is

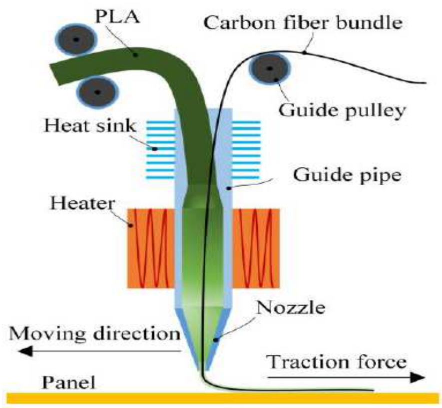


Fig. 7. 3D Printing with a single extruder head and reinforcement fibre coating inside the print head [36]

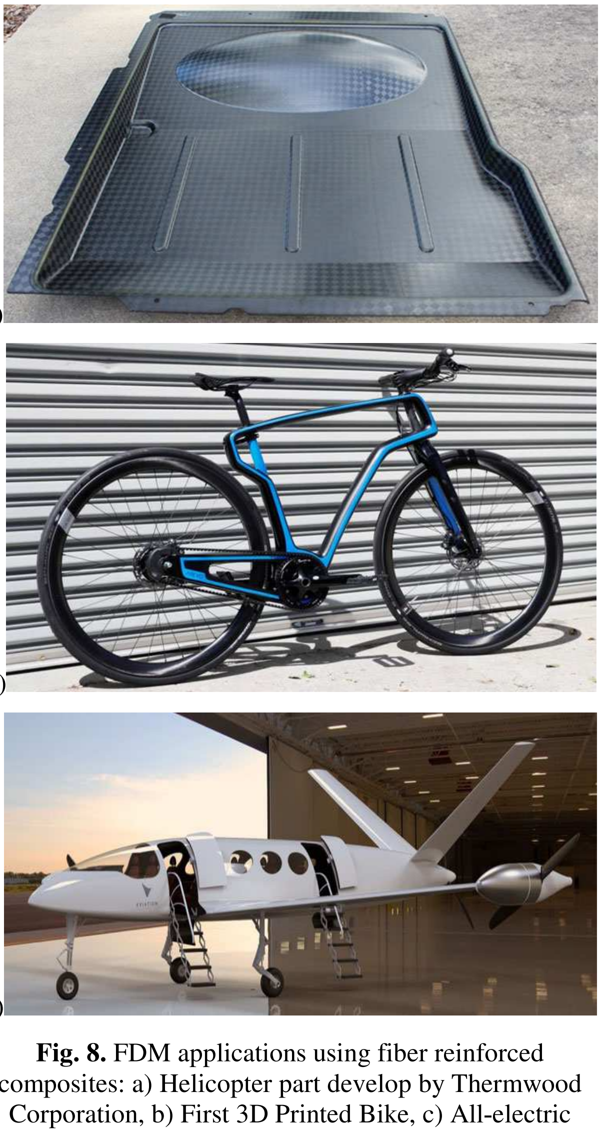
pre-extruded with the reinforcement material included therein. The second configuration has also an extrusion head, but the reinforcement process takes place inside the extruder (Fig. 7).

The reinforcing fibre is covered with a layer of thermoplastic material at the time of extrusion being passed through the material bath formed inside the print head. In this configuration one of the problems that may arise is that of the non-uniform coating of the extruded fibre [35]. The third construction of a 3D printer for composite materials possesses two deposition heads, one for the thermoplastic matrix and the other for the reinforcement fibre This construction provides a better distribution of the thermoplastic material, so a better coverage of the reinforcement fibres than that in which the combination of the two materials takes place inside the extruder head.

The most commonly used fibres as reinforcement material for composite materials are: carbon fiberglass and aramid fibres (Kevlar), and in Fig. 8 are shown some recent applications. Other reinforcing fibres can be: boron, ceramic polyethylene ceramic carbide and natural fibre or cellulose. Through FDM, both continuous reinforcement fibres (using two printheads) and composite thermoplastic filaments (Onix Markforged) that already contain short reinforcement fibres can be printed. The Onyx is a black filament, made by combining the carbon micro-fibre with nylon [37].

In this direction, the studies are ongoing, and the Project entitled “Directional Composites through Manufacturing Innovation" aims to bring together leading innovators from across Europe, to develop a new method of producing composite material parts with optimised fibre directionality (see www.dicomi.eu). The project will draw upon advanced expertise and know-how in directional fibre-reinforced polymers, processing methods and manufacturing systems design in order to develop an innovative hybrid manufacturing system capable of producing composite parts with increased accuracy, reduced cost and enhanced functionality.

The main manufacturers of 3D printers for composite materials are Cosine Additives (AM1), Markforged (X3) and Stratasys (Fortus 450mc - Nylon 12CF).



a) b) c)

Fig. 8. FDM applications using fiber reinforced composites: a) Helicopter part develop by Thermwood Corporation, b) First 3D Printed Bike, c) All-electric commuter aircraft develop by Eviation Aircraft, www.compositesmanufacturingmagazine.com

5. CONCLUSIONS

This study presents some AM techniques, focused on processing methods, materials used by each process and latest practical examples developed. Continuous progress of AM equipments and materials science leads to improved processes and quality of manufactured products. In the last years, a downward trend of prices has been observed regarding the AM systems and materials. More and more companies take the benefits of these technologies, making their production flexible. Practically, these manufacturing processes are part of Industry 4.0 and allow mass customization of parts. Innovation of AM has contributed to a vast growing of new applications fabricated in various fields such as automotive, medicine, industry or aerospace. From our point of view, AM will remain relevant and important in production of personalized goods.

6. ACKNOWLEDGMENTS

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Analiză teoretică și studii de caz practice privind tehnicile de fabricație SLA, PolyJet și FDM

Rezumat: Printre cele mai avansate tehnologii dezvoltate în ultimii ani, fabricația aditivă (Additive Manufacturing - AM) este una care îndeplinește cerințele celei de-a patra revoluții industriale. În această lucrare se prezintă câteva metode AM cum ar fi stereolitografia (SLA), polyjet și modelarea prin extrudare termoplastica (FDM). Tehnologiile AM analizate utilizează materii prime sub formă lichidă sau filament. Lucrarea este axată pe trei aspecte importante ca principiul procesări, materialul utilizat de fiecare tehnologie și cele mai recente exemple de bune practici dezvoltate. Aplicațiile expuse sunt din domenii diverse precum medicină, industria auto, aerospațială și manufacturieră. Mai mult, s-au detaliat principalii producători de sisteme AM, echipamentele fabricate de aceștia și intervalul de costuri ale acestor echipamente.

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