International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P) Volume-8, Issue-8, August 2018

Additive Manufacturing at Industry 4.0: a Review

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Abstract — **Industry 4.0 is the recent move into intelligent technology automation. In this new era the use of modern skills of Additive Manufacturing within the context of information technology integration plays an important role in industrial economic competitiveness. This short review provides a basic understanding of the role of 3DP technology in the Industry 4.0. As can be seen, there's no doubt that 3DP technologies are leading to the next major industrial revolution. Due its versatility the Additive Manufacturing plays a key-role in the Industry 4.0, saving time and costs, being decisive for process efficiency and reducing its complexity, allowing for rapid prototyping and highly decentralized production processes. Currently, more and more industrial segments are adopting AM. The smart factories of the future have all processes interconnected by the Internet of Things, incorporating greater flexibility and individualization of manufacturing processes.**

Index Terms — **3D Printing, Industry 4.0, Production Process, Smart factory**

I. INTRODUCTION

A production chain is the process of turning raw materials into commodities. However, many steps are required to convert the available resources into products, such as design, planning, manufacturing and sales. Recently, the production chain procedure seems to have changed, since additive manufacturing (AM) technology or 3D printing (3DP) has transformed its steps. Custom products with difficult geometries can be designed and printed with the help of additive technology. Thus, markets can be supplied without requiring companies to store or produce commodities at great expense [1].

While there are still some doubts about its applicability in mass production, the use of AM in industry 4.0 is on the rise due to new advances. Being a technology in development to create precise objects with high speed of production, this one can offer a way to replace the conventional manufacturing techniques in the near future. Thanks to increased product quality, AM is currently being used in a number of industries, including aerospace, biomedical, and food [2].

Digitization and intelligentization of manufacturing process is the need for today's industry. The manufacturing industries are currently changing from mass production to customized production. The rapid advancements in manufacturing technologies and applications in the industries help in increasing productivity [3].

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The term Industry 4.0 stands for the fourth industrial revolution which is defined as a new level of organization and control over the entire value chain of the life cycle of products; it is geared towards increasingly individualized customer requirements. Industry 4.0 is still visionary but a realistic concept including: Internet of Things (IOT), Industrial Internet (II), Smart Manufacturing (SM) and Cloud-based Manufacturing (CBM). Industry 4.0 concerns the strict integration of human in the manufacturing process so as to have continuous improvement and focus on value adding activities and avoiding wastes [4]. The physical part of intelligent factories is limited by the capacity of existing manufacturing systems. This way, due to the need for mass customization in the 4.0 industry new non-traditional manufacturing methods are constantly developed. Thus AM has become a key technology for manufacturing custom products because of its ability to create sophisticated objects with advanced attributes [5]. The Figure 1 presents a comparison between the conventional industry process and 3DP process:

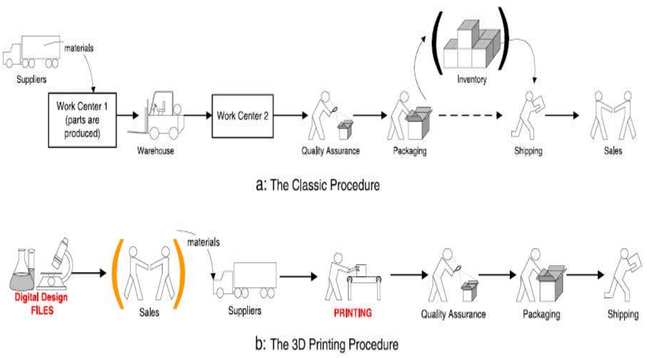

Fig. 1 Classical procedure (a) and the 3DP procedure (b) [1].

Compared to traditional manufacturing, the general advantages of additive manufacturing are the capabilities in design and development of products. Despite certain limitations, companies are using AM increasingly to use the many possible benefits like complexity-for-free manufacturing. In traditional manufacturing there exists a direct connection between complexity and manufacturing costs [6].

Designs intended for traditional manufacturing are often heavily limited by high costs in construction and tool-making. The greater freedom of design via AM makes it possible to combine an assembly of parts into one part and, therefore, to reduce the required assembly work and costs. In addition, no compromises regarding the assembly capabilities are necessary [7]. 3DP is emerging as an enabling technology for a wide range of new applications. From the point of view of the fundamentals, the available materials, speed of manufacture and resolution of the 3DP processes should be considered for each specific application [8]. Currently there are machines that allow the printing of 3D shapes by various techniques: extruder (fused filament), chemical agent (binder) or laser (sintering / fusion), this process being technically known as additive manufacture (MA), which has several advantages [9].

Industry 4.0 is the recent move into intelligent technology automation. In this new era the use of modern skills of AM within the context of information technology integration plays an important role in industrial economic competitiveness. Within this context, this short review provides a basic understanding of the fundamentals of 3DP technology into the Industry 4.0.

II. LITERATURE REVIEW

A. 3DP Materials

Freedom of design, mass customization, waste minimization and the ability to fabricate complex structures are the main benefits of additive manufacturing. The current state of 3DP material development includes the use of metal alloys, polymer composites, ceramics, wood, fibers, and composites, concrete among numerous others [10]. The 3DP technology covers a wide range of materials used in a variety of industries (including aerospace, automotive, dental, jewelry, oil and gas, orthopedics printed electronics, and tooling [11].

The Figure 2 presents an overview of the main materials most used in AM:

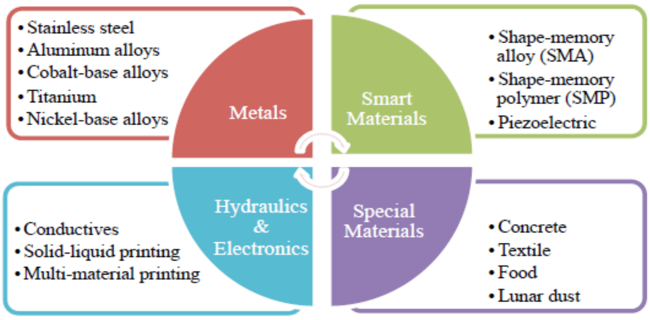

Fig. 2 General overview of current research materials for AM in the forthcoming era [12].

The components considered for driving the additive manufacturing cost are material cost, labor cost, machine cost, and energy consumption. Material cost constitutes major proportion of additive manufacturing cost for laser sintering process. Labor cost would be 2- 3% and energy consumption is less than 1% [13].

Metal AM started to gain attention in aerospace, oil and gas, marine, automobile, manufacturing tools and medical applications because of the advantages offered by this process. Every part manufactured by AM can be unique and produced in very short time which enables mass customization. AM also reduces assembly requirements by integrating number of parts required in assembly into a single part. It reduces overall weight, decreases manufacturing time, reduces number of manufacturing processes required, reduces cost and material requirements and optimizes required mechanical properties [14].

Recently, one of the actively researched areas lies in the additive manufacturing of smart materials and structures. Smart materials are those materials that have the ability to change their shape or properties under the influence of external stimuli. With the introduction of smart materials, the AM-fabricated components are able to alter their shape or properties over time (the 4th dimension) as a response to the applied external stimuli. Hence, this gives rise to a new term called 4D-printing (4DP) including structural reconfiguration over time [15].

B. 3DP Processes Technology

Recently, three-dimensional printing has been highlighted as it shows a great promise to perform almost all structural parts from computer aided drawing (CAD). Several different processes are available for 3D printing, which includes fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SL), photopolymerization (PPT) among others [16].

The Figure 3 shows the processes currently most used in AM:

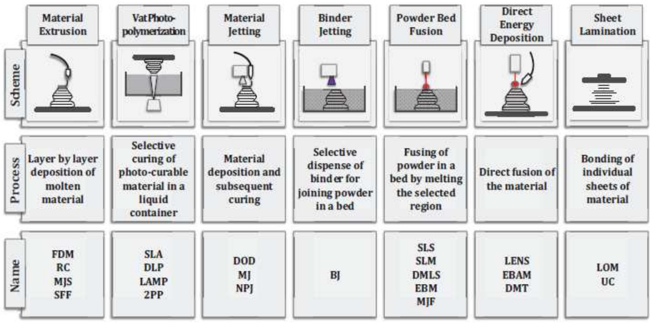

Fig. 3 Categorization of AM processes in the current state-of-the-art [12].

The basic principle of SL process is the photopolymerization, which is the process where a liquid monomer or a polymer converts into a solidified polymer by applying ultraviolet light which acts as a catalyst for the reactions; this process is also called ultraviolet curing. It is also possible to have powders suspended in the liquid like ceramics [17].

Prometal is a 3DP process to build injection tools and dies. This is a powder-based process in which stainless steel is used. The printing process occurs when a liquid binder is spurt out in jets to steel powder [18].

Already SLS is a 3DP process in which a powder is sintered or fused by the application of a carbon dioxide laser beam [19-20].

FDM is an 3DP process in which a thin filament of plastic feeds a machine where a print head melts it and extrude it in a thickness typically of 0.25 mm. Materials used in this process are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), PC-ABS blends, and PC-ISO, which is a medical grade PC. The main advantages of this process are that no chemical post-processing required, no resins to cure, less expensive machine, and materials resulting in a more cost effective process [21-22]. The disadvantages are that the resolution on the z axis is low compared to other additive manufacturing process (0.25 mm), so if a smooth surface is needed a finishing process is required and it is a slow process sometimes taking days to build large complex parts [23]. To save time some models permit two modes; a fully dense mode and a sparse mode that save time but obviously reducing the mechanical properties [24].

Electron beam melting (EBM) is a process that melts the powder using an electron laser beam powered by a high voltage, typically 30 to 60 KV. The process takes place in a high vacuum chamber to avoid oxidation issues because it is intended for building metal parts. Other than this, the process is very similar to SLS. EBM also can process a high variety of pre-alloyed metals. One of the future uses of this process is the manufacturing in outer space since it is all done in a high vacuum chamber [25-26].

Polyjet is an AM process that uses inkjet technologies to manufacture physical models. The inkjet head moves in the x and y axes depositing a photopolymer which is cured by ultraviolet lamps after each layer is finished. The layer thickness achieved in this process is 16 μm, so the produced parts have a high resolution. However, the parts produced by this process are weaker than others like stereolithography and selective laser sintering. A gel-type polymer is used for supporting the overhang features and after the process is finished this material is water jetted. With this process, parts of multiple colors can be built [27-28].

It is noteworthy that multi-material extrusion in 3DP is gaining attention due to a wide variety of possibilities offered, especially driven by the commercial availability of a wide variety of unconventional filament materials. As a result, it is possible to print models that are not limited to aesthetic purposes, but now can also provide greater functionality and therefore with mechanical performance adjusted for its purpose [29-30].

The use of AM techniques are shown to be advantageous for parts which have a high buy: fly ratio, have a complex shape, have a high cost of raw material used for machining from solid, have slow machining rates and are difficult and expensive to machine. The specific cost of material deposited by additive manufacturing systems required to give a 30% saving over conventional Machine from solid techniques is estimated for a typical aerospace-Titanium alloy over a range of buy: fly ratios [31-32].

C. Additive Manufacturing in Industry 4.0

As shown in Figure 4, the Industry 4.0 offers cybernetic and physical systems to cooperate profitably with the goal of building intelligent factories, redefining the role of human beings:

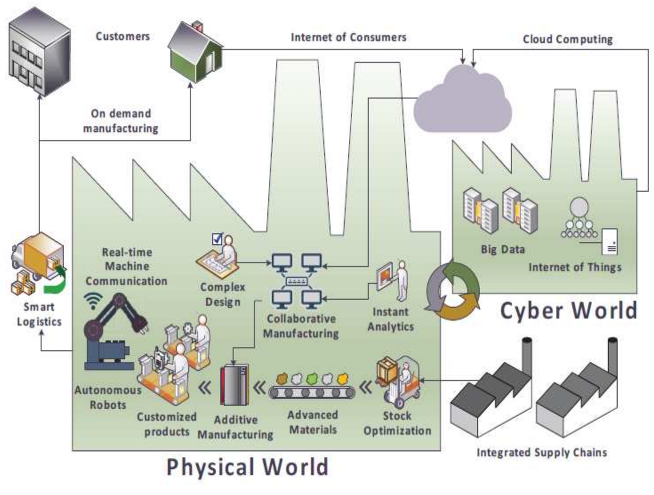

Fig. 4 Schematic of smart factories with general properties required in Industry 4.0 [12].

The term Industry 4.0 has many meanings. It seeks to describe the intelligent factory, with all processes interconnected by the Internet of Things. The first advances in this field involved the incorporation of greater flexibility and individualization of manufacturing processes [33].

The paradigm of Industry 4.0 is essentially outlined by three dimensions: (1) horizontal integration across the entire value creation network, (2) end-to-end engineering across the entire product life cycle, as well as (3) vertical integration and networked manufacturing systems [34].

The Industry 4.0 is encouraging the integration of intelligent production systems and advanced information technologies. Additive manufacturing is considered an essential ingredient in this new movement [12].

In Industry 4.0 the use of the 3DP technology will be decisive for process efficiency and reducing complexity, allowing for rapid prototyping and highly decentralized production processes: the product model could simply be off to the 'printing' site nearest to the customer, eliminating intermediate manufacturing steps, transportation and warehousing [35].

Table 1 provides an overview of the main trends and expected development for the different value creation factors in Industry 4.0:

Equipment	The manufacturing equipment will be characterized by the application of highly automated machine tools and robots. The equipment will be able to flexibly adapt to changes in the other value creation factors, e.g. the robots will be working together collaboratively with the workers on joint tasks [36].
Human	The current jobs in manufacturing are facing a high risk for being automated to a large extent. The numbers of workers will thus decrease. The remaining manufacturing jobs will contain more knowledge work as well as more short-term and hard-to-plan tasks [37]. The workers increasingly have to monitor the automated equipment, are being integrated in decentralized decision-making, and are participating in engineering activities as part of the end-to-end engineering [34].
Organization	The increasing organizational complexity in the manufacturing system cannot be managed by a central instance from a certain point on. Decision making will thus be shifted away from a central instance towards decentralized instances. The decentralized instances will autonomously consider local information for the decision making. The decision itself will be taken by the workers or by the equipment using methods from the field of artificial intelligence [34].
Process	Additive manufacturing technologies also known as 3D printing will be increasingly deployed in value creation processes, since the costs of additive manufacturing have been rapidly dropping during the last years by simultaneously increasing in terms of speed and precision. This allows designing more complex, stronger, and more lightweight geometries as well as the application of additive manufacturing to higher quantities and larger scales of the product [38].
Product	The products will be manufactured in batch size one according to the individual requirements of the customer [34].This mass customization of the product integrates the customer as early as possible in the value chain. The physical product will be also combined with new services offering functionality and access rather than product ownership to the customer as part of new business models [38].

D. Industrialization of 3DP Technology

Nowadays, industrial companies face more and more complex challenges in product development. Customers ask for innovative, individually tailored products with a high product quality for a reasonable price. In addition, the economic lifespan of products decreases which forces the companies to shorten their time to market and their development cycles [39].

Through globalization the competition in fertile markets increases. Imitators from foreign markets make it harder for the companies to maintain achieved market shares [40]. One solution to increase innovation and shorten the time to market is delivered by a new production technology, the AM [6].

At present, AM technology is gradually becoming the core technology [41] and there is a growing consensus that 3DP technologies will be one of the next major technological revolutions [42].

The Figure 5 shows the 3DP procedure future Industry 4.0:

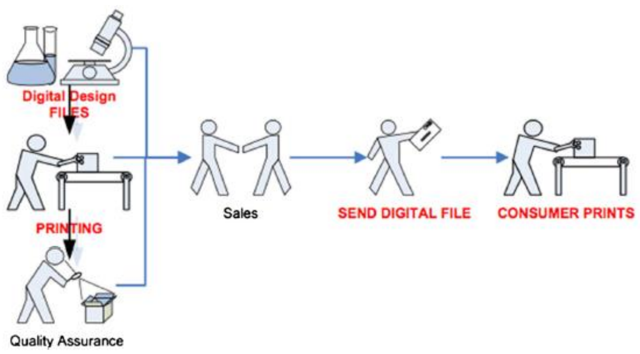

Fig. 5 The 3DP procedure in the future [1].

Some applications of 3DP technology in various industrial segments are listed below:

Pharmaceutical Industry: 3DP is expected to be a highly revolutionary technology within the 4.0 pharmaceutical industry. In particular, 3DP's key benefits lie in the production of small batches of drugs, each with custom dosages, shapes, sizes and release characteristics. In this way the manufacture of personalized medicines becomes a reality. In the short term, 3DP could be extended throughout the drug development process, from pre-clinical development and clinical trials to first-line medical care [43]. The exploration of the emerging technologies of the pharmaceutical industry 4.0 facilitates the creation of sustainable value, leads to a more agile, intelligent and personalized pharmaceutical industry and, in the long run, allows pharmaceutical companies to obtain competitive advantages. A more sustainable pharmaceutical supply chain should be implemented to combine future operations and management of pharmaceuticals throughout the entire life cycle [44].

Biomedicine: The 3DP of human organs is one of the latest advances in the medical industry of the world today. With the help of current bioprinting technology, it is possible to print human organs directly from cells. In today's world, millions of dollars have been spent on many research and education institutes to eliminate the limits of organ imprinting. The goal of the researchers is to replace a human organ successfully. In the process of organ printing, various machines and materials are searched around the world. The most printed organs with this technology are tissues of the liver, cartilage, skin, heart and bone, etc. Some of the major challenges in these technologies rely on the printing of living organs (print organ life), printing environments and post-processing (such as autoclaving). Advances in this area clearly show that researchers are very close to the future, where the replacement of the human organ by the printed organ is attainable [11]. 3D printing has already been proved viable in several medical applications including the manufacture of eyeglasses, custom prosthetic devices and dental implants [45]. Also, 3DP is becoming popular due to the ability to directly print porous scaffolds with designed shape, controlled chemistry and interconnected porosity. Some of these inorganic scaffolds are biodegradable and have proven ideal for bone tissue engineering [46]. 3D printing is emerging as a powerful tool for tissue engineering by enabling 3D cell culture within complex 3D biomimetic architectures [47].

Food Industry: In recent years 3DP of food has been widely investigated in the food industry, due to its many advantages such as customized food designs, personalized nutrition, simplified supply chain and expanding food material available. However, in order to obtain an accurate impression, three main aspects should be considered: material properties, process parameters and post-processing methods, with special attention to rheological properties, bonding mechanisms, thermodynamic properties, pretreatment methods and powders -processing. In addition, there are three main challenges in 3DP of food: 1) accuracy and accuracy of printing 2) process productivity and 3) production of multicolored, multi-flavored products [48-49].

Fashion industry: 3DP shows a number of advantages compared to traditional manufacturing processes, including an accelerated design process, less-production time, and lower costs related to inventory, warehousing, packaging, and transportation. This paper discusses the five types of 3DP methods that exhibit great potential in an application of fashion, including stereolithography, selective laser sintering, fused deposition modelling, PolyJet, and binder jetting [50].

Electrical components: 3D printing is a unique technology that potentially offers a high degree of freedom for the customization of practical products that incorporate electrical components, such as sensors in wearable applications. The availability of inexpensive, reliable, electrically conductive material will be indispensable in the fabrication of such circuits and sensors before the full potential of 3D printing for customized products incorporating electrical elements can be realized. To date, 3D printable conductive filaments with sufficiently high conductivities to fabricate practical circuits remain lacking for fused deposition modeling [51].

Casting Industry: The application of the technology of 3DP foundry moulds permits a considerable acceleration of works at prototype castings, enabling a reduction of foundry-mould printing costs. In order to reduce printing costs, a shell mould may be made and then complemented with cheaper molding material. The technology of foundry mould making in three-dimensional printing process offers huge manufacturing potential. That is why; a further research on its application for various cast elements of non-ferrous alloys is advisable [52].

So, there is a growing consensus that 3D printing technologies plays a major role in technological industrial revolution. History has shown that technological revolution without adequate business model evolution is a pitfall for many businesses. In the case of 3DP, the matter is further complicated by the fact that adoption of these technologies has occurred in four successive phases (rapid prototyping, rapid tooling, digital manufacturing, and home fabrication) that correspond to a different level of involvement of 3DP in the production process [42].

III. Conclusion

There's no doubt that 3DP technologies are leading to the next major industrial revolution. Due its versatility the Additive Manufacturing plays a key-role in the Industry 4.0, saving time and costs, being decisive for process efficiency and reducing its complexity, allowing for rapid prototyping and highly decentralized production processes. Currently, more and more industrial segments are taking advantage of AM. The smart factories of the future have all their processes interconnected by the Internet of Things, incorporating greater flexibility and individualization of manufacturing processes.

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