Beyond Rapid Prototyping:

Study of prospects and challenges of 3D printing in functional part fabrication

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***Abstract*— In the recent years, the additive (layer) manufacturing technology, which emerged about three decades back, to assist design conceptualization and visualization through rapid prototyping, has created application interests beyond rapid prototyping. This transition beyond prototyping, i.e. transition to production of functional parts is driven by several other progresses including availability of advanced printing machines and materials including metal printing capabilities. Among others, the unlimited geometrical complexity, low material wastage, environmental friendly and in most cases economically viable operations of additive manufacturing are the key factors that attract diverse industrial sectors to further explore the potentials of this technology for production of fully functional parts. There even exists a sense of feeling, at many corners, that this technology will significantly change the global economy and the way business is done in the future, in a similar way the www technology and the smart phone technology did. Aimed to put a very small drop into this potentially huge future research and development area and based on existing experiences, published works and ongoing research activities, this article shades light on the prospects of the additive manufacturing technology as a production method for the future industry. Two of the most potential technologies, fused deposition modeling and selective laser melting, are described and potential challenges highlighted. In line with the national interests and international focus, the medical sector and the offshore oil and gas industry are identified as the best beneficiaries if additive manufacturing is used for functional part production.**

Keywords*— *additive manufacturing; 3D printing; fused deposition modeling; selective laser melting; medical rapid prototyping; offshore oil and gas

I. INTRODUCTION

Though not yet universally standardized, the concept of additive manufacturing (AM) is often defined as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to the conventional subtractive manufacturing methodologies" [1]. The concept is also widely referred to as additive fabrication, direct digital manufacturing, rapid prototyping, rapid manufacturing, layer manufacturing and solid freeform fabrication [2]. In this paper, AM, additive fabrication and 3D printing are synonymously used to imply the application of the technology, both for rapid prototyping and functional parts.

The original inception of AM technology in 1980s was intended to provide a prototype within a short time (thus referred to as rapid prototyping (RP) technology) and hence support design concept visualization. As a result, the traditional physical prototyping approach to validate a design is substituted by a 3D physical model, that can be of any shape, is built layer by layer by directly transforming of 3D virtual model in computer aided design (CAD) systems. Thus, the technology not only shortens the time used to develop a product, but also improves product quality through better visualization and enables construction of complex geometries at a reasonable cost. In addition, the emergence of the technology, as a prototyping tool, has highly contributed in stimulating innovation and simplifying communication among different actors of a product.

To construct the 3D physical object layer by layer, AM technology integrates other key disciplines such as laser technology, numerical control (NC) of machine tools, physical chemistry of materials and computer-aided design technologies. As such, the technology benefits a lot from the developments emerging in CAD, NC, laser and material technology.

Beyond the rapid prototyping (RP) initiatives in the 1980s, the developments of the 3D printing technology that followed in 1990s and the latter developments; including the rapid progress in each of the enabling disciplines, has led to the emergence of other RP families with new applications. Among these, rapid prototyping and manufacturing (RP&M) for direct fabrication of functional parts from plastic as well as metallic materials [3], rapid tooling (RT) for pattern work purposes [4] and bio-manufacturing (BM)/medical rapid prototyping (MRP) [5, 6] can be mentioned. Even after achieving the capability to 3D print metallic materials, researchers at the beginning of the century were skeptic stating that AM technology remains at the moment more of a goal than reality for the industry [7]. After nearly two decades of the knowledge that metal printing is possible, we observe a boom of interest both in academia and for commercial purposes. Then the natural questions that follow will be:

- Will AM technology change the way industry is making business in the near future?"
- How is the technology going to influence the society in general and what should be done to benefit from the changes that AM technology brings into the global economy?

In this short article, a state-of-the-art assessment and evaluation of additive manufacturing technology has been conducted. The article first describes the available technologies in Section II with emphasis on those having the potential to produce fully functional parts. Section III assesses the application prospects and challenges of using AM technology when used in selected sectors such as medical and offshore oil and gas industry. Finally, the summary of the study and outlooks for the technology for future applications beyond rapid prototyping is presented in Section IV.

II. BRIEF DESCRIPTION OF THE PRINTING PROCESS AND SAMPLE TECHNOLOGIES

The last three decades experienced a dynamic expansion of AM technology with a range of commercial printers with capabilities to print different materials including metals. Though almost all technologies have common characteristics in that all build the 3D object by depositing materials layer by layer and binding the layers together, the technologies are commonly categorized based on the type of material used and the way the materials are fused together. Fig. 1 shows the general category of the main technologies.

In this section, first a brief description of printing process is presented and followed by description of two typical AM machines used for production of function parts: (1) fused deposition modeling (FDM) and (2) selective laser melting (SLM).

A. Overview of the printing process

The common principle of layer manufacturing implies that the printing procedures employed by the 3D printing machines is almost identical. All of them get input data, i.e. the solid model data, in sliced or tessellated format either from a 3D CAD system or from a 3D scanner. The current standard file format for most machines is the STL-format, derived from the file format for the initial commercial rapid prototyping technology STereoLithography. STL file format is also known as a short form of Standard Tessellation Language and is currently used as an industry standard format to export geometry data from 3D CAD systems or 3D scanners to 3D printers. It represents the 3D model using information about the coordinates and outward surface normal of triangles. Using the STL algorithms, the technology integrates CAD and CAM (computer-aided manufacturing) and avoids demanding tasks of process planning and machine set up activities.

In general, the following typical steps are followed by all AM machines (depicted in Fig. 2).

- Creating a 3D solid model of the product.
- Converting the model to STL format.
- Slicing the STL file to cross-sectional layers.
- Combining the layers (building layer by layer).
- Cleaning and finishing the model

As any manufacturing process, AM process involves combined activities of information processing and physical object processing. From the material processing point of view, the technology can be regarded as a digital forming process [8]. In RP&M process, data processing is considered crucial because both the material processing and control of the overall process are dictated by the performance of the data processing.

B. Fused deposition modeling technology in brief

Fused deposition modelling technology is one of the technologies developed to transform layer manufacturing from prototyping to additive manufacturing of functional parts directly from digital model in CAD systems. FDM prints the parts from thermoplastic materials such as ABS and nylon using a print head in a similar manner as an inkjet printer. The print head is controlled by a motor and heats the plastic filament to its melting point and extrudes through the nozzles. The surrounding low temperature air then rapidly cools the deposited layer.

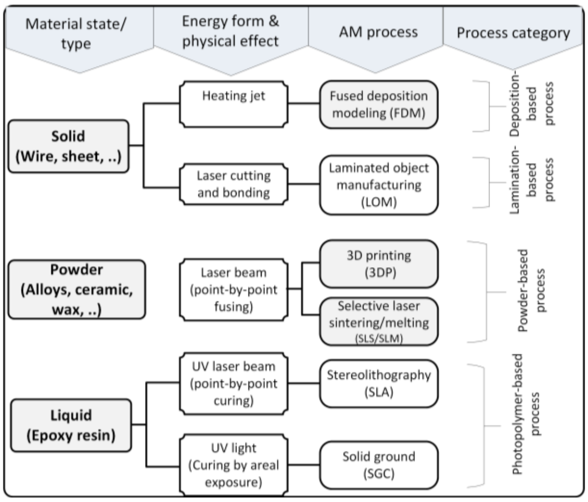

Fig. 1. Categories of main printing technologies

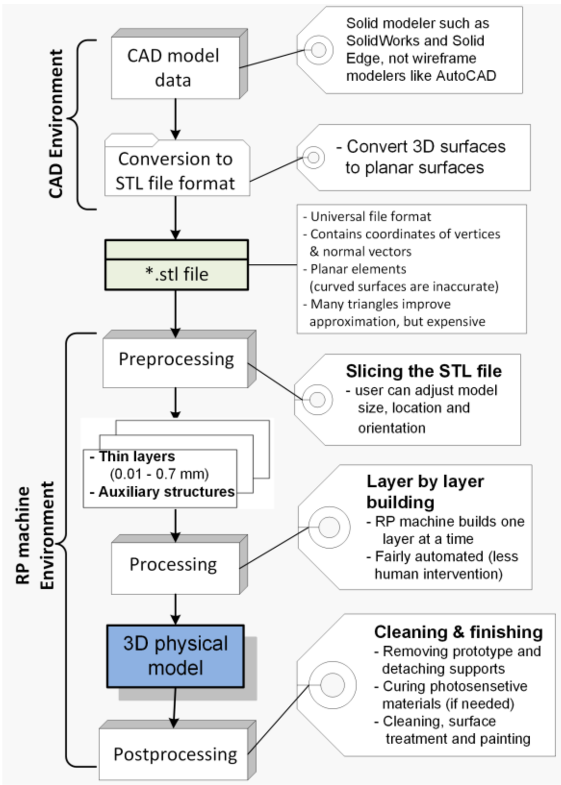

Fig. 2. Typical steps of converting a 3D CAD model to a 3D physical object

While building a component, two materials are extruded.

(1) *Model material*, i.e. the material of the component and

(2) *Support material* that provides support structure for overhanging parts of the component.

Fig. 3 illustrates the key printing components and processes of FORTUS 450 FDM machine marketed by Stratasys. This machine (also owned by the 3DP Lab. of University of Stavanger) has the following key specifications.

- Build capacity: 406 x 356 x 406 [mm]
- Accuracy/Resolution: ±0,127 mm or ±0,0015 mm/mm
- Materials used:
  - ABS (Standard material),
  - FDM Nylon and PC – ISO (Engineering materials)
  - Ultem (High performance material) .

Ultem is claimed to have excellent chemical, mechanical and thermal properties and suites critical component applications in for instance, aerospace and automotive industries as well as the medical sector. Testing these properties and potential applications for diverse functional parts including in the oil and gas industry is currently in progress in our 3DP Lab.

FDM based AM technology is considered as the most popular printing method for small-scale production of parts. The popularity can be attributed to the availability of several affordable 3D printers. This affordability combined with high material usage efficiency has put FDM as a forefront technology with great potential in several industrial sectors [9], mould fabrication [10] and design of bio-medical devices [11] and tissue engineering [12].

Though certain level of popularity, as mentioned above, has been established, FDM as an AM process for fully functional parts and mechanical systems is still far from reality. For instance, practical observations from printed parts in our 3DP Lab. indicate that the dimensional accuracy and surface finish are unpredictable and the mechanism of controlling is not straightforward. The common understanding of the process leads to the conclusion that the printing accuracy (both dimensional and geometrical) and surface finish improve with reduced layer thickness.

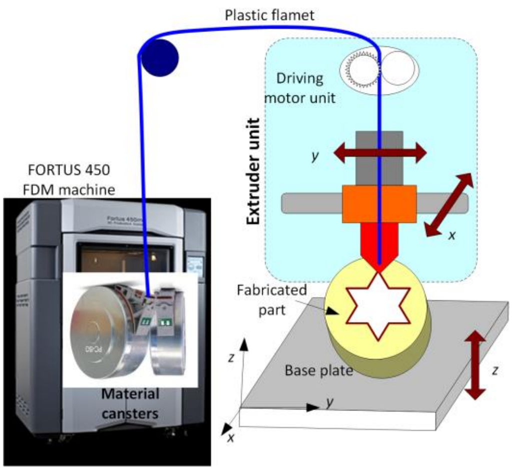

Fig. 3. Illustration of the printing process in FDM

However, reducing layer thickness has adverse effect that the fabrication time increases leading to high production costs. Furthermore, the lower limit of the layer thickness is dictated by the in-built machine parameters [13 - 16]. In this regard, further studies are required to investigate the influence of material, machine and operation specific parameters, including printing orientation and slicing software on the achievable precisions.

In summary, some of the benefits and limitations of the current FDM technology can be listed as shown in Table I.

C. *Selective laser melting in brief*

Selective laser melting (SLM) is one of the emerging and progressively growing commercial metal printers that is, by many, considered as a viable AM technology. The technology evolved from selective laser sintering (SLS) and hence is a family of powder-bed fusion technologies [17]. The advances in fibre laser technology has contributed to the transition from SLS to SLM where the latter can fully melt metal powder into dense parts by exposing the powder to the laser beam and solidify upon cooling. Contrary to SLS, SLM is claimed to be difficult to control the process [18] and hence the quality of the product. On the other hand, when compared with the conventional metal casting process, SLM not only enables fabrication of complex geometries but also enhances design flexibility and provides a fine microstructure components due to the higher cooling rate [19]. As a result, better mechanical strength is expected.

Though the emergence of SLM system was first brought to the attention of AM community in 1999, as a result of the cooperation between Fockele and Schwarze and Fraunhofer institute for laser technology in Germany [20], the real commercial product was released in 2004. Since then, it attracted attention in diverse industrial sectors particularly in aerospace, medical fields such as bio-fabrication, printing of implants, soft tissues and prosthetic knees [21, 22]. The key characteristics and advantages of this process include:

- Optimized geometry to functional requirements.
- Low-volume production.
- Customized products to individual needs.
- Low material wastage.
- Minimum need for expensive tooling.
- Etc…

TABLE I. LIST OF SELECTED BENEFITS AND LIMITATIONS OF FDM

	Benefits	Limitations
Material	• Little material waste • Easy material change	• Limited materials • Expensive materials • Cleaning difficulties of support materials
Process	• Office/environment friendly • Simple post print process (machining, painting, etc.)	• Slow process • Poor resolution • Colour printing is demanding
Product	• Strong parts • Relatively cheap	• Anisotropic behaviour • Porous sections • Poor accuracy and surface finish

The potential application of SLM the technology as a manufacturing method for functional and load carrying parts with complex geometries has also initiated a number of research works [23, 24] that shaded light on variations in mechanical properties such as hardness and strength. Most of the studies focused on how the strength and the printed microstructure are influenced by the laser power intensity while printing [25].

Closer review of the literature also shows that SLM based AM is currently a hot research issue in diverse directions. To mention a few, recent research has focused on printing parameters [24], laser scanning strategies [17, 26], mechanical and thermal behaviour, surface chemistry and characterization of different metals that can be printed by the machine.

Most of the studies conducted so far focus mainly on the printability and material chemistry of different materials. The mechanical behaviour under mechanical loads and the process capability are not sufficiently investigated and it is expected that future research can address these other issues of the process. For instance, comparative study of fatigue strength and tribological behaviours as a function of print scan strategy and other machine parameters are attractive research areas. In particular, parts produced by SLM commonly experience residual stresses due to the combined effect of high temperature forming and the need for support structure to avoid part distortion during printing. This influences the process efficiency because of the required post processing including heat treatment and post machining.

III. AM APPLICATIONS BEYOND RAPID PROTOTYPING

This section briefly explores the central industrial sectors where AM has been implemented in practice with focus on medical sector and highlights the potential benefits in the regional offshore based industry particularly the oil and gas.

A. Beyond rapid prototyping in medical sector

Closer study of the literature shows that the medical sector is one of the early users of 3D printing technology both as a rapid prototyping tool in early 1990’s and functional part production within the last 10 years. As a rapid prototyping tool, 3D printing has served the sector in surgical planning by providing 3D visualization, visualization of internal anatomy and design of individual implants and prostheses. Surgical planning that is commonly based on Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) images in 2D suffers visualization constraints where the surgeons are forced to create the 3D virtual image in their own mind. Having a 3D physical model of the patient’s anatomy obviously improves the understanding of the surgeons to devise an optimum surgical strategy and thus the quality of the surgical operation is improved.

With the goal of exploiting the above-mentioned advantages, prototype models developed using SLS method were previously applied in, for instance, in orthopaedics surgery [27], craniofacial surgery [28, 29], and analysis of vascular anatomy [30 - 32].

The recent developments in 3D printing technology has transformed the role of the technology beyond rapid prototyping, i.e. transition from prototyping to AM. The technology as AM has very important features that attract this sector for production of functional parts including:

- No constraint on geometrical complexity of, for example human implants.
- Parts can easily be customized to individual interest.
- One-of-a-kind or small batch production justifies the production cost compared with other alternatives.
- On-demand production is easier.

Among existing technologies, SLS, SLM, FDM, Polyjet and SLA (Stereolithography apparatus) are found appropriate and widely used in the sector. The last mentioned (SLA) in particular attracts the sector because of the material property (transparent and translucent) that allows viewing even internal structures. In addition, post print processing is easy because the printed model can be cut, drilled and milled using available surgical tools [33]. The colour printing options can as well contribute to better visualization of different anatomical systems. Furthermore, multi-material printing capability such as in Polyjet printing can be useful to obtain realistic combinations of bones and tissues for instance in case of prostheses printing.

Regarding selection of printing machines, their difference in product accuracy and cost can play a significant role. Qualitative comparison of the methods shows that SLA, SLS and SLM excel in achieving good accuracy, but they can be poor choices in terms of production cost. While FDM is moderate in both accuracy and cost, which puts the method in a position to compete the conventional injection moulding, multi-jet modelling can be a choice for low cost but poor accuracy products.

The key research challenges to utilize AM technology in medicine can be categorized into the following two areas:

(1) Acquisition of 3D image medical data and transforming into a printable format.

(2) Developing proper materials, including biomaterials, that behave (when printed) in identical way as the human organ or tissue.

In the first case, in particular, the acquisition is based on 3D image data (CT, MRI) that is stored in DICOM (Digital Imaging & Communications in Medicine) format. This image is normally imported into visualization tools such as MeVisLab [34] that allows manipulation and visualization of the image in 2D and 3D virtual environment. For 3D physical model reproduction, the area of interest needs to be highlighted (segmentation) and converted into a 3D CAD model data.

According to the current understanding, the 3D segmentation and conversion to a 3D CAD model (marked steps 2 and 3 in Fig. 4) remain research challenges, though some publications report success stories [35]. The following steps, i.e. storing in STL format and slicing the file into layers for printing are straightforward. Then the final step is the last challenge involving the question of material types that can be printed and properly behave.

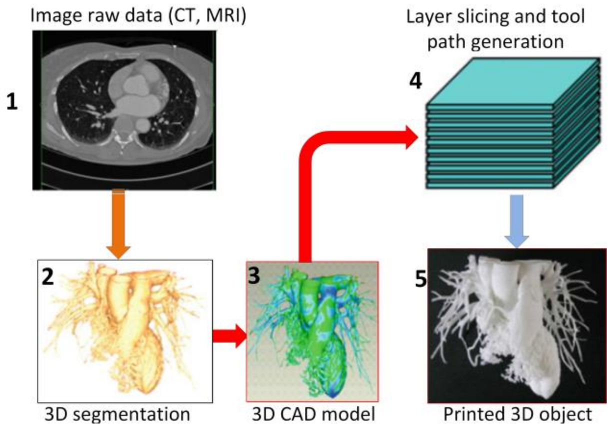

Fig. 4. Process chain to convert medical images data to a 3D physical object

B. Beyond rapid prototyping in offshore industry sector

To the best knowledge of the author, there exists no active use of AM technology on the offshore-based oil and gas industrial sector, at least on the Norwegian platforms. The attempts done by NASA to print parts on space ship, on the other hand, inspires the same for the offshore industry. The primary benefits are that 3D printing offshore (3DPO) enables on-demand production and supply of parts and tools, simplifying the offshore logistic. Instead of depending on onshore production of parts when failed, materials that can be used for almost anything and the design data are transported. This contributes to less operation downtime and hence cost effective.

It is an obvious issue that the current crises in the oil and gas industry is directly related with costs. If AM technology is utilized offshore, there are several areas where cost reduction can be achieved leading to profitable operation. Studies indicate that communication, rework and transportation costs highly contribute to costs of offshore manufacturing [36]. A recent case study and data analysis based on data collected from technology developers, suppliers and users in Sweden indicates that AM contributes to job creation at different levels including for the oil and gas industry, though there are certain barriers that hinder the full exploitation of the benefits [37].

Furthermore, there are a number of reasons, for the offshore oil and industry, which justify focus on AM of parts than the conventional manufacturing methods. The industry is continuously undergoing changes such as exploration from shallow waters to deep waters and from topside to subsea applications. In those cases, AM parts from high performance thermoplastic materials such as Ultem and composite materials will be preferred than metallic materials.

Though not at a significant large scale, few component level application of AM for offshore structures and subsea installations are reported. Arino et al. [38] reported that a subsea blowout prevention (BOP) mechanism was designed and 3D printed from thermoplastic materials to test the mechanism with several configurations and scenarios. The use of 3D printing based approach enabled to make a realistic test with reasonable costs. Oil and gas installation are composed of a large number of pipes, hoses and their joints. Some of the hoses are made of thermoplastic materials and are subject to collapse or burst particularly when used in deep water application and high internal pressure conditions. For instance, failures in umbilical cables consisting of several hoses have been recently reported [39, 40]. These and other similar studies indicate that the thermoplastic hoses are the most important causes of failure in umbilical cables. As a result, frequent replacements are needed and having AM facility offshore can best guarantee to reduce the downtime.

To sum up, the capabilities to print parts on demand with no limitation to geometrical constraints suggest that AM is the future for offshore oil and gas industries. However, there still remains research challenge to investigate the mechanical behaviour of parts (both plastic and metallic materials) accounting for the cyclic loadings, chemical, mechanical and thermal stability and the like.

IV. SUMMARY AND OUTLOOK

In this article, the potential application of additive manufacturing technology beyond rapid prototyping is described. The study identified that fused deposition modeling that prints parts from high performance thermoplastic materials and selective laser melting that can print several metallic materials have high potential to get acceptance for industrial applications. In spite of the attractive features of AM as enabler of manufacturing functional parts with no limitation for geometrical complexity, contrary to traditional material removal or forming processes, it has been observed that the technology, to be employed in production of fully functional parts in diverse sectors, suffers a number of limitations including:

- Printable material constraints.
- Conflict between precision and production rate.
- Product deformation and warpage (residual stress) due to high temperature process and material phase changes.
- Forming imprecision caused by the step effect during the layer by layer deposition of materials and which is more pronounced for curved surfaces
- Limitations of mass production.
- High manufacturing cost, which is independent of number of produced parts.

Furthermore, the status of the technology lacks focus on design procedures standardized for the process. There exists no unified convention yet how to indicate quality specifications such as dimensional and geometrical tolerances. The industrial sector adopting the technology from manufacturing point of view is also limited and can be referred to as “islands” of applications such as aerospace and some medical sectors. To raise the application to beyond pure prototyping and realize the true functional part manufacturing technology, the size and production rate limitations should be solved. The process itself should also be integrated and automated to enable cost effectiveness.

In the case of metal printing in particular, though SLM seems highly promising AM method for functional parts, it is far from being mature. The key future works ahead, in regard to limitations mentioned above, include, but not limited to, improving the production rate, devising mechanisms to reduce or eliminate part distortion caused by residual stresses, improving process monitoring, and control mechanism that leads to acceptable accuracy and surface finish.

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