METAL ADDITIVE MANUFACTURING IN THE OIL AND GAS INDUSTRY

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Abstract

Additive Manufacturing (AM) has gained increasing prominence and had the most significant commercial impact in the aerospace sector in the last few years. The adoption of AM in the oil and gas industry has been slow, although the potential economic benefits it offers are tremendous. Improving product performance, reducing costs and lead time, creating a more flexible and distributed supply chain are some of the major focus areas for the oil and gas industry today which cannot be attained through traditional manufacturing methods. A broad overview of the state of Metal AM pertaining to oil and gas applications is provided. Potential applications of AM in the oilfield are highlighted, including demonstrated examples such as components for downhole logging and drilling tools, turbomachinery, pipeline components, etc. A lack of qualification and certification methodologies, along with technical and cultural challenges that hamper AM's adoption in the industry are discussed.

Introduction

For the foreseeable future, hydrocarbons are likely to remain the largest and the most economical source of energy. To ensure a sustainable long-term growth, the oil and gas industry is pursuing technological innovations in the manufacturing sector [1]. As an emerging technology, additive manufacturing plays an important role in enabling innovative solutions to set the stage for new products and business models to drive greater organizational value.

ASTM has defined Additive Manufacturing as a "process of joining materials to make objects from 3D model data, usually layer upon layer", as opposed to subtractive manufacturing methodologies. While AM has been available for a number of years as a means of processing materials including metals, ceramics, polymers, composites and biological systems, it has only recently begun to emerge as an important commercial manufacturing technology.

AM has advanced to the stage where manufacturers can produce complex metal parts that offer advantages conventionally manufactured parts cannot. Many oilfield service companies all over the world are using AM to make metal components for a growing number of tools and equipment [2].

According to some market analysts, the ability to deliver cheaper and better parts quickly has made oil and gas industry the fastest growing user of AM. Although the parts being printed now, are limited by size and are for non-critical applications, it has not deterred the early adopters in the upstream sector who realized that AM technology is ideal for enhanced manufacturing efficiency and supply chain flexibility [3].

Additive Manufacturing in the Oil and Gas Industry

The chief drivers for adoption of AM are unlimited design flexibility, lead time reduction, and accelerated product development through faster prototype testing. Additionally, the production of replacement parts through AM is a significant advantage which enables on-demand manufacturing, and elimination of tooling and inventory costs. Within a decade, the oil and gas industry is expected to spend more than USD 1.4 billion annually on 3D printing services, mostly by service companies [2]. General Electric has been printing components for its oilfield gas turbines, and is expected to start printing parts for centrifugal pumps and artificial lift systems. Other examples for printed downhole parts include housings for sensor arrays that can be made with reduced weight and complex parts for turbines that are used to power a steerable drilling head. In other cases, AM technology is being used to reduce part count in a drilling assembly from several components to single part. Cost savings are created in one company's machine shop by printing jigs and fixtures in a few hours that took days or even weeks to machine. Due to the part consolidation and elimination of tooling (or molds) offered by AM, it is found that product development cycles are substantially shorter [2].

Although there are several AM processes that are currently available for a variety of materials, based on how the powder feedstock is supplied, the metal AM processes can be classified into powder bed and powder fed systems [3]. In the powder bed system, the metal powder is selectively fused by melting it using a heat source – laser (Direct Metal Laser Melting) or electron beam (Electron Beam Melting). Direct Metal Laser Melting (DMLM) is the most commonly used AM technology to produce metal parts using materials such as stainless steel, titanium alloys, nickel alloys, aluminum alloys and cobalt chrome. In the powder fed system, the metal powder is deposited through a nozzle (Directed Energy Deposition, Laser Metal Deposition) and is melted by either a laser or electron beam, on to a substrate. A schematic of both AM systems are shown in Figure 1.

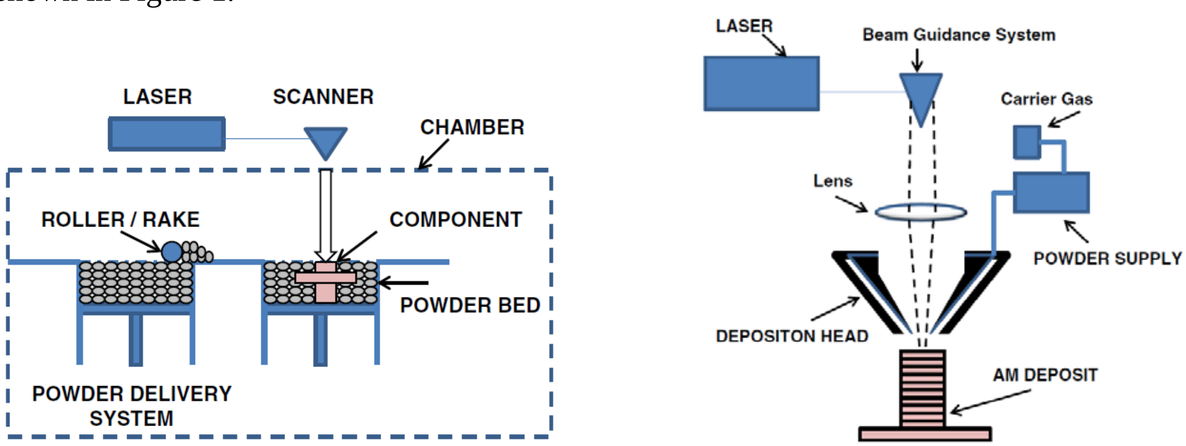


Figure 1: Schematic of (left) AM powder bed system and (right) AM powder fed system [3]

Market analysts report that global AM revenue related to the oil and gas industry is on an increasing trend for the next 10 years. A forecast model predicts that the revenue will reach $450 million by 2021 and is projected to triple to approximately $2 billion by 2027 [4]. The year-on-year growth foresees a substantial revenue increase in all segments of AM including hardware, materials, software and services, with the growth rate being very high in the near future and slowly adjusting as AM adoption becomes a consolidated practice, as shown in Figure 2. The growth is moving towards making AM a sustainable business as the technology matures. There has also been a major shift in the oil and gas industry's focus, from considering AM as a *rapid prototyping* tool to considering AM as a *rapid manufacturing* tool.

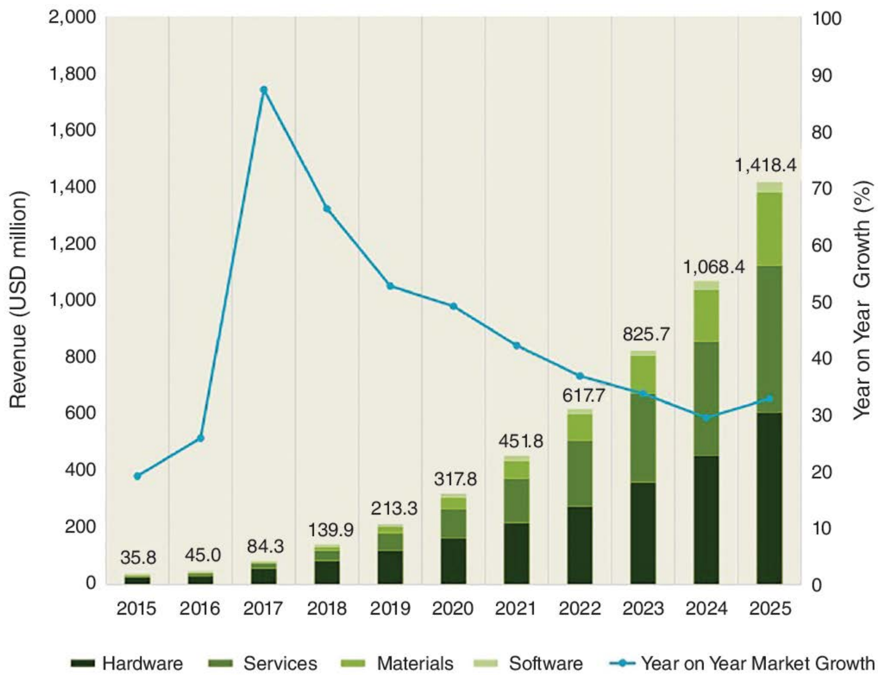


Figure 2: AM revenue forecast and Year on Year Market Growth in the oil and gas industry [2, 4]

The oil and gas industry is currently in the early stage of AM adoption, mostly using AM for rapid prototyping [5]. Some companies have progressed to the indirect AM stage where AM is used to make fully functional models and tooling to produce end use parts. The early adopter companies are at an advanced stage of utilizing AM for direct manufacturing of final parts, but these are few and far between. The real potential of AM within the oil and gas industry will be unleashed when the impact is evident on the supply chain by making it decentralized (making parts on-site or near site) and flexible (on-demand manufacturing) and by eliminating inventories for spare parts.

Applications of AM in the Oil and Gas Industry

AM as a transformative technology, has proven that it can provide significant advantages in terms of efficiency, sustainability, and cost reduction which help to streamline all phases in the supply chain [6]. The key benefits of AM are evident across the full value chain and are listed below:

1. Accelerate design innovation – AM allows for faster testing of prototypes, enables innovative thinking and design iterations to improve quality and reduce time to market for new parts.
2. Increase product performance – AM facilitates creating parts that are lighter, stronger and more efficient that are designed for functionality; enables creation of high complexity parts for function integration.

3. Reduce supply chain cost – Additive designs reduce number of total assembled parts, aids rapid manufacturing.
4. Simplify systems – AM simplifies systems by reducing part counts by part consolidation, assembly elimination and creating more robust designs.

AM parts are finding applications in many critical products such as downhole measurement, logging, and remediation tools. Any complex geometries that are impossible to build using traditional techniques can be built using AM, which can also enhance functionality and reduce cost. Compared to conventional processes, AM has proven to reduce and even eliminate several manufacturing steps, simplifying manufacturing and reducing costs [7].

The potential applications of AM within the oil and gas industry include drill bits and bit models, heat exchangers, turbine blades and sensors, acoustic and fluid filters, complex tools for directional drilling, measurement and logging systems and spare parts. The example part shown in Figure 3 demonstrates the above listed benefits. When compared with the original design, the additive design resulted in:

- 30% cost reduction
- 70% lead time reduction
- Part consolidation (7 parts → 1 part)
- Improved reliability

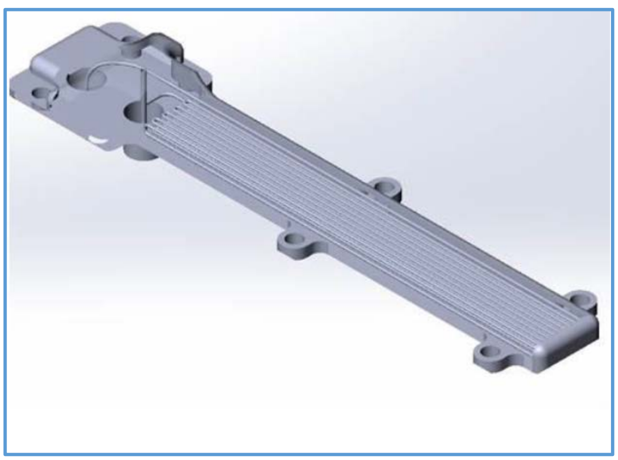
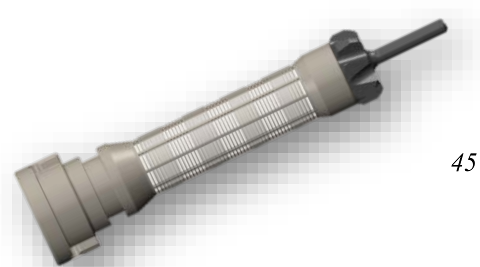


Figure 3: Modified additive design of a downhole part

In the example of a screen for a downhole tool shown in Figure 4, the conventional design had a long lead time and required machining operations such as milling, turning and wire electric discharge machining to produce the 2-part assembly. In the additive design, the part is printed and stress relieved in one step in the 3D printer, resulting in one part with increased filter area to achieve improved performance, and 80% cost out. In another example, a 2-piece component in one of the logging tools was replaced by a single piece AM part which cut the lead time by 65%.



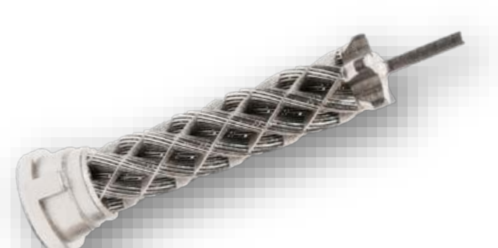


Figure 4: (left) conventional screen design; (right) additive screen design

Adoption of Additive Manufacturing in the Oil and Gas Industry

The oil and gas industry has unique challenges as the oil and gas companies sometimes operate in harsh conditions, such as high temperature and pressures (>350°F and >30,000 psi) and in corrosive environments. AM parts used in these downhole environments therefore must perform in harsh conditions with high strength, resistance to erosion and wear, and withstand fatigue. The AM process is fairly new and is not completely understood. The materials processing technology needs to be demonstrated in a relevant operational environment, since the process by which a technology is qualified for use varies. It is challenging to complete the transition from using AM for prototyping to using it in efficient production of end-use parts, which must meet robust performance and industry safety standards.

For the industry wide adoption of AM and to enable its true potential within the oil and gas industry, there are several challenges and constraints that need to be overcome. Here is a list of focus areas that need to be addressed:

- **Build speed:** Existing AM metal processes are constrained with respect to speed and size when compared to conventional manufacturing techniques. Larger, faster, and more robust AM machines with multiple sources of energy or new methods of material deposition need to be developed to enable faster build speeds, large builds and consequently rapid AM.

- **Process Modeling:** AM is a complex thermo-mechanical process where the deposited material undergoes melting, solidification cycling and solid-state phase transformations, while building up residual stresses. Enhanced modeling and simulation tools are required to develop validated models to predict the build process outcome and material properties. Predictive analytics will also help with reducing experimental trial and error and limit unsuccessful build iterations.

- **Process Control:** In-situ process monitoring systems with closed loop feedback control to detect and correct deviations in the AM process are essential for quality control and advancement of AM.

- **Material Development:** New materials with new chemistries and microstructures need to be developed specifically for AM technology. The possibility of printing multi-materials and functionally graded materials etc. that offer unique properties, needs to be explored. A good understanding of process-microstructure-property relationships is needed to help predict part performance and lifetime.

- **Qualification and Certification:** The qualification of AM process and certification of AM structural components are critical to adoption of AM. The development of industry specifications and standards for AM processes and AM processed alloys is an immediate need. Currently, there is build-to-build variability, inter-build variability, and machine-to-machine variability of AM parts that causes a significant barrier to the qualification and standardization of the process. The oil and gas industry adheres to stringent rules and standards as a means to mitigate risk. Lack of approved standards from major certification agencies is a significant barrier to the acceptance of AM. However, the process to develop and establish standards is still underway. The corrosion of AM metallic parts and application of AM to sour service are being investigated and documented by several research groups [8], [9], and [10].

- **Workforce training:** Comprehensive training of the workforce within AM, especially in design for AM is needed for deployment and adoption of AM.

Conclusion

Due to its enormous potential, AM is truly accepted as a "transformative" and "disruptive" technology and is one of the manufacturing trends that has ushered us into the Fourth Industrial Revolution. The impressive achievements of AM have already been evident in aerospace, automotive and healthcare sectors and are being recognized in other industries.

There has been a significant shift of the oil and gas industry's focus from *rapid prototyping* to *rapid manufacturing*. There's been a continued increase in world-wide AM revenue for oil and gas as reported by market analysts and a continued growth is predicted for the next decade in all segments of AM. AM has the potential to change the supply chain architecture by localizing the production of parts and could be a major disruption to the business model of suppliers in the oil and gas industry.

The significant obstacle to the widespread adoption of AM within the industry is the lack of certification and qualification standards. However, the industry is making continuous progress to develop and implement these standards to accelerate adoption of AM.

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