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Metal 3D Printing Applications in the Oil & Gas Industry

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Abstract

Additive Manufacturing (AM) is a set of technologies that has historically found fertile applications in the aerospace and healthcare industries, while adoption in the oil and gas (O&G) sector has progressed slowly. Nonetheless, AM is reaching maturity in this industry as well, allowing for significant innovation. This paper describes how AM has been integrated within the value chain of a major oilfield supplier, highlighting specific peculiarities for each of its business segments. "Fullstream" activities of the oilfield supplier cover the entire O&G value chain, from the exploration of reservoirs and production (upstream) to the transportation and storage of hydrocarbons (midstream), as well as refining and industrial power processing (downstream). AM technologies in this company were originally deployed for rapid prototyping, but they have matured as strategic manufacturing pillars to address the maintenance of equipment of all industry segments within the company. Several manufacturing methods within the AM landscape can be deployed, depending on the technical requirements of the components and the environment in which they operate. O&G equipment end users face several challenges when dealing with spare parts management, such as performance, total cost of ownership, procurement time, inventory levels and obsolescence. From an OEM standpoint, serving a wide fleet with a variety of products and their different versions (with an unpredictable and unstable demand) is challenging. AM is the tool that enables a new way to serve such an installed fleet. The company has already experimented with several applications regarding obsolete spare parts re-introduction through AM, gaining strong benefits (50% +) in terms of cost and procurement time reduction. Consequently, it is important to continue adopting AM to deliver faster outcomes for the customer at first. This, in turn, fosters the development of sound knowledge and references that can then be used to develop further solutions and value propositions for the customers.

Introduction

The introduction of new manufacturing technologies into the oil and gas (O&G) industry is a challenge, particularly when the technology involves the manufacture of new materials. Material-forming processes such as forging and casting are well-developed and trusted, but there are limitations when it comes to the manufacturing of parts and tools from these materials. Subtractive manufacturing techniques, i.e., those used to remove material from a larger piece through standard machining processes, are the favored and conventional method for turning finished materials into finished parts. Within recent decades, however, the evolution of rapid prototyping into additive manufacturing (AM) has led to widespread investigation and adoption of some of these additive techniques, particularly within the aerospace and healthcare industries.

Additive manufacturing is a novel manufacturing process in which material is added rather than subtracted, as in traditional manufacturing methods (Kruth et al. 2012). AM techniques have existed for more than 20 years, but initial AM technologies were limited to prototype applications due to the inability of these early technologies to deliver fully-dense parts (Herzog et al. 2016). Additive manufacturing has since progressed to a production-ready technology through the transformation of a three-dimensional (3D) model into a final solid part through layer-by-layer consolidation of a base material, usually with the application of heat or force. The freeform nature of AM enables creation of complex geometries and opens the gateway for topology optimization to accommodate various loading conditions using organically based structures. AM, as a design tool, provides complexity for free, enabling designers to create structure not previously possible with conventional subtraction methods, provided the part fits inside the available build envelope, which varies depending on the AM process and machine manufacturer. In addition to providing almost unlimited design freedom - there are certain restrictions on minimum geometries and angles - the application of AM leads to shorter design cycles, time-to-market reduction, and integrated functionality in parts that would otherwise not be possible with conventional manufacturing methods. AM processes enable manufacturing of multiple parts in a single pass, reducing further assembly steps and material waste. Parts can be produced in small, customized batches as a production process, or designs can be optimized in several, short design cycles using AM as a prototype technology. The flexibility and wide applicability of AM are driven by the variety of additive technologies available on the market today. The various AM processes encompass a wide range of machine envelopes, process speeds, and material capabilities that ensure coverage of most applications. Generally, AM modalities can be broadly categorized as extrusion, granular, laminated, or light polymerized, although the feedstock for each category can vary, ranging from thermoplastics to metals to photopolymers (Camisa et al. 2014). Metals fall primarily in the granular category, and, as such, granular technologies are the focus of further discussion.

Overview of Granular Metal AM Technologies

Granular metal AM technologies, especially those with high relevance and potential for the O&G industry, primarily include selective laser melting (SLM), electron beam melting (EBM), and directed energy deposition (DED). The overarching process loop of these modalities function similarly, with all processes consisting of three main steps: 1) data preparation, 2) melting, and 3) post processing. These steps cover the entire process chain of metal AM, beginning with the computer-aided design (CAD) model.

Data preparation begins with the creation or use of an existing CAD model. The CAD model is first converted to a triangular mesh and exported from the modeling software into a preparation software used for preparing the building plate for the printing process. The software platform used is dependent on the machine manufacturer. After the part is imported into the preparation software, the designer selects the orientation and adds the support structures. Support structures are extra material added at necessary design features to help stabilize the part, depending on orientation, additionally acting as thermal sinks to remove excess heat from the part. When this is finished, the melting parameters are selected, and the part is then sliced into layers, which is then transmitted to the machine for printing. The layer thickness used is dependent on the modality selected, with EBM and DED accommodating larger layer thicknesses (e.g., 90 µm and greater) in comparison to SLM (e.g., 20 µm - 60 µm).

In the melting stage, differences between the modalities can be recognized, although the end goal (i.e., consolidation of the power to create a solid part) is the same. The SLM process utilizes a focused, high-energy laser beam to melt metal powder particles together in a layer-by-layer fashion to create a near-fully dense metal component in an inert environment (Murr et al. 2012). When the sliced part file is sent to the machine and read, the SLM manufacturing process begins with the lowering of the build plate platform a depth equal to one layer thickness. The powder is dispensed to the recoater and distributed over the surface of the build plate by the recoater blade. The laser then melts the shape of the first part slice according to the parameters selected by the user. After the part slice is melted, the build plate platform lowers another layer thickness, powder is dosed and distributed evenly across the build plate, and the process repeats, with the solid part sinking below the visible surface, until the part is finished. The SLM modality is a powder bed-based process, similar to the EBM process.

During EBM, however, the consolidation of the powder feedstock is achieved using an electron beam as the heat source rather than a laser, and the entire process is conducted under a vacuum, making it an excellent technology for the production of highly reactive metals like titanium. The manufacturing process of EBM functions similarly to the SLM process, with the exception of a pre-heating step, wherein the powder bed is pre-sintered prior to the melting of every CAD file slice. This pre-heating reduces the residual stresses during the build process due to a heated powder bed and a reduction of necessary support structures resulting from the greater support of manufactured parts due to the pre-sintered surrounding powder.

The DED process, while still manufacturing parts using the sliced CAD file, has stark differences compared to SLM and EBM. DED is capable of using either powder or wire as a feedstock and is a powder-blowing rather than a powder bed modality. DED utilizes a nozzle mounted on a multi-axial arm that projects a laser centrally through the nozzle, surrounded by the feedstock and a cover gas. The laser beam is directed towards the substrate surface, where the blown feedstock is concurrently melted and locally shielded with the inert cover gas. Similar to the SLM and EBM processes, DED manufacturing proceeds on a layered basis.

Following completion of the melting stage, excess powder surrounding the part must be removed. There are also differences between the modalities in this step. In the SLM process, the excess powder is removed in most machines via a vacuum, prior to removal of the substrate plate and parts, and the excess powder is injected back into the process for reuse. In the EBM process, the substrate plate and parts are removed together with the surrounding sintered powder, and a type of shot-peening process is applied to loosen the sintered powder and clean the finished parts. Here, the shot-peening medium is the same powder feedstock, which allows all powder following part removal to be re-sieved and recycled. In the DED process, however, the ability to recycle powder feedstock varies between machine manufacturers. In some machines, there is no method for recapture of the powder, and any powder that is over-blown is lost to the process. Some machines provide recollection of powder, which then allows recycling of the feedstock, similar to the SLM and EBM processes. When using wire as a feedstock for the DED process, however, there is no material waste. The manufactured parts, now fixed to the substrate plate, is ready to either a) be removed or b) subjected to a stress-relieving heat treatment designed to relieve residual stresses accumulated during the building process. The necessity of a stress-relieving treatment is dependent on both the process and the material used and is a direct result of the repeated heating and cooling cycles experienced by the part during additive processing (Kruth et al. 2010). If stress relieving is not a necessary step, the parts can be immediately separated from the build plate in a cutting process, and the parts are ready to receive post heat treatments and/or finish machining as needed.

For all metal AM processes, the outcome of the manufacturing step (i.e., the printed component) is subjected to many influencing parameters including machine functionality, material characteristics, and processing parameters. The interplay of all parameters involved in the printing process can often make it difficult to pinpoint issues in printed components, so it is highly recommended to have all influencing parameters as tightly controlled as possible.

Regardless of the modality used, metal AM is inarguably a game-changing technology that has captured the interest of many industries, of which the O&G industry is no exception.

AM Applications in the Oil & Gas Industry

The benefits of AM for the O&G industry, while still under exploration, have the potential for significant cost savings. Parts produced within the O&G industry, however, are often very complex, with a variety of larger product systems consisting of thousands of smaller subcomponents, and AM opportunities are not always immediately recognizable. Unlike the aerospace industry, large-scale serial production is often not necessary for parts used within the O&G industry, where unique, low-volume production is more financially viable. From this perspective, AM fits nicely into the manufacturing portfolio, providing a more cost-effective solution for both prototypes and end-use components.

A significant benefit of AM for the O&G industry is the improvement of supply chain efficiency that can be achieved with correct AM adoption and implementation. AM processes can theoretically operate on an around-the-clock basis with minimal human interaction. Parts can then be produced as needed, even outside of standard working hours, with the manufacturing process continuously running until completion. The design freedom of the AM process also helps increase supply chain efficiency, as secondary assembly procedures can be eliminated by the consolidation of parts. Assemblies can be reimagined as single parts and subsequently printed, reducing the number of manufacturing steps and ultimately saving time and money. Design freedom also has the added benefit of enhanced innovation. The free-form geometries allowed in the 3D printing process encourages designers to be more imaginative in their approach to part design, oftentimes leading to increased functionality in parts designed for the AM by the integration of multiple functions into a single design. The organic nature of the process enables the production of components that were previously impossible or prohibitively expensive to produce using conventional subtractive manufacturing techniques. The speed of AM processes, in comparison to conventional processes, can also reduce design cycle times, meaning that designers can optimize, produce, and test designs more quickly than is possible using conventional manufacturing methods. The uninterrupted manufacturing process, the reduction of assembly steps, and the design benefits gained by the usage of AM methods all contribute to the reduction of long lead times for components, improving the supply chain and ultimately leading to higher profit margins.

According to SmarTech Publishing (SmartTech Publishing 2017), the greatest benefit of AM for the O&G industry will be on-demand production of consumables or failure-prone components directly on-site or near-site. Such production could greatly reduce the cost structure and streamline supply chain efficiency, thus maximizing profitability of the exploration and production components used in the industry. Indeed, as AM technologies continue to improve in speed, form, and function, the reality of wellsite printing becomes a more likely possibility.

Despite the benefits that can be realized, however, questions still remain for complete adoption of AM into the O&G industry. One of the challenges of AM is material characteristics and their performance during day-to-day O&G operations. This challenge is especially critical in the O&G industry where downhole conditions require consistent performance at high pressures and high temperatures in corrosive environments, oftentimes under severe loading conditions. The harsh, corrosive environments to which materials are exposed in oilfield applications is largely untested with AM materials, and efforts to conduct and publish testing in these environments is slow. The decades of material data amassed for wrought and cast material performance inspires a confidence in O&G engineers and designers that is lacking for AM materials. In addition, the materials available for AM are not always useful for the oilfield. For example, development of Alloy 718 for AM has been predominantly focused on the AMS grade (Amato et al. 2012; Ardila et al. 2014; Chlebus et al. 2015; Gong et al. 2015; Lu et al. 2015; Popovich et al. 2015; Prater et al. 2015; Zhang et al. 2015; Konečná et al. 2016; Trosch et al. 2016), and little research exists for the API grade (Sarmiento Klapper et al. 2017; Sarmiento Klapper et al. 2019).

The AM process also requires a supply chain of sorts, as almost all components produced will require an amount of post processing. In most cases, this includes removal from the substrate plate on which the component is manufactured. In other cases, parts will require further treatment, including but not limited to: support removal, heat treatments, surface treatments, and finish machining. Companies considering adoption of AM should take into consideration how such a supply chain will function (i.e., internally or externally) and the time that such post-processing steps can add to overall AM part procurement.

Repeatability of the AM process can also be a challenge, even between machines from the same manufacturer. Machine hardware and software updates to the same machines can sometimes result in variations to the microstructure that may result in differences in material properties. Unfortunately, while standards are in the process of being formed, absolute methods do not publicly exist to qualify machines or to alleviate variations experienced with machines. For a company with proprietary and sensitive design data, this often means that AM implementation is largely internally located. This, in turn, can require significant amounts of time and funding to develop internal standards, operational guidelines, and material specifications that are reliable and widely accepted within the larger organization. Without standards to guide the process and extensive testing to elucidate AM material performance in comparable operating environments, AM adoption into the O&G industry will continue to be slow.

AM Applications within an Oilfield Supplier

Within a major oilfield supply company, metal AM technologies have been explored and/or implemented. In segments of the company, metal AM has successfully transitioned from a prototyping tool to a production manufacturing tool designed to accommodate a wide variety of products with a fluctuating demand. The introduction and success of metal AM has largely been focused in the upstream sector, with many successes achieved in the Drilling portion of the upstream portfolio. Metal AM began in 2012 within with the production of a flapper valve needed for a coring application. This effort was motivated by a need to reduce downtime as a result of long lead times for the conventional valve production. The valve was manufactured using a metal AM powder bed technology, and the part was procured successfully in two days rather than the three weeks it would have taken using conventional manufacturing methods. Since the flapper valve, investments into additive technologies have led an average 2.3 × increase year over year in shipments of components manufactured using metal AM.

Like many companies exploring new technologies, AM has often been used as a prototyping tool, wherein designs can be more quickly manufactured and tested, providing engineers with faster feedback on design functionality and accelerating the overall production development cycle. One such component, a mud filter, is shown in Fig. 1. The original design required round metal bars to be welded into place across the mud flow opening, resulting in turbulent flow during operation and consequential washout of the inner contour and bars due to a combination of the abrasive drilling fluid and turbulent flow pattern. The performance in the mud screen was reduced, leading to a limited lifetime and a high demand for replacement parts.

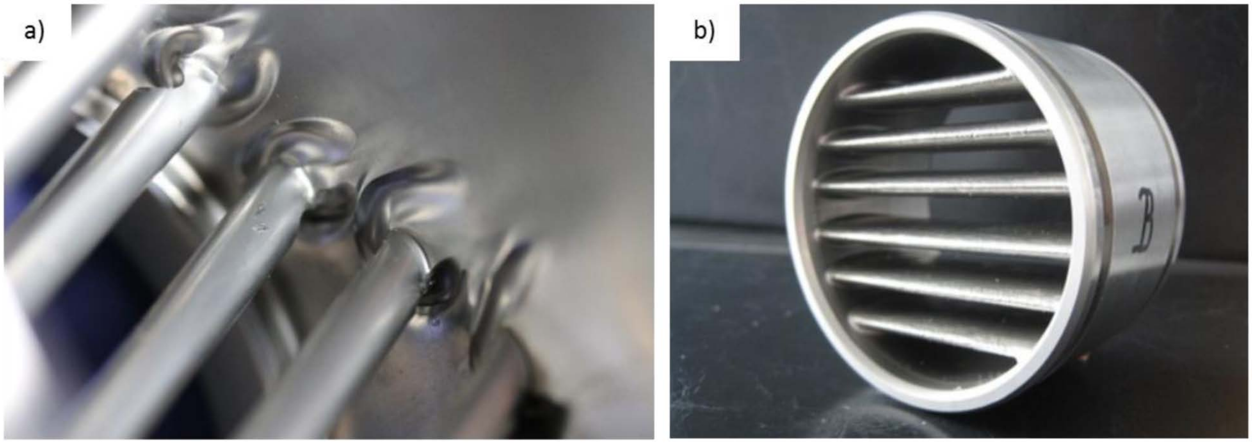

Figure 1—a) original mud screen showing close-up of washout at welded bars and b) optimized mud screen produced using AM

To improve the performance of the component, a design study was conducted to optimize the flow pattern (see Fig. 2). Using AM, the redesigns could be quickly produced and tested internally, shortening the feedback loop. Without AM, such a study would not have been possible due to the problematic nature of conventionally-manufacturing the designs on such a short time scale. The AM, flow-optimized version showed a four-fold lifetime increase as compared to the original design during testing. Additionally, the lead time was reduced by 80%. Although the re-designed component was then scheduled for manufacture using casting (due to cost savings), the optimized design gained using AM as a rapid prototyping technology greatly increased component lifetime.

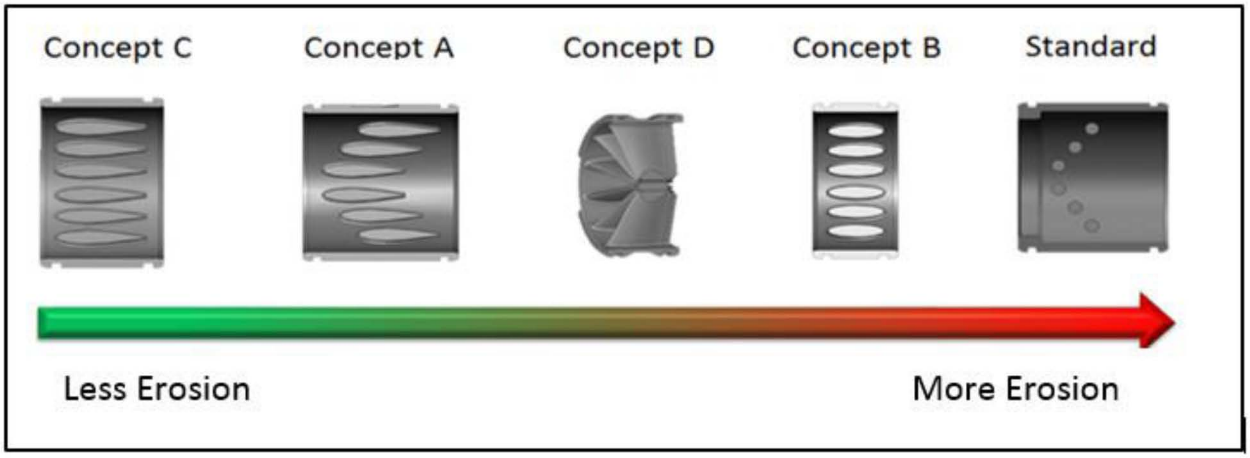

Figure 2—Design study conducted using AM as a rapid prototyping tool, arranged according to test results

AM has found success not only as a prototyping technology, but also as a tool to drive innovation by exploiting the design potential of the AM process. An exemplary component, referred to as a pad screen, that has been designed to take advantage of the free-form geometric capabilities of AM can be seen in Fig. 3. The initial driving force for the production of the component using metal AM was a need for reduced lead time. It was a critical part for a tool that was scheduled to be at a customer wellsite within a month, and the lead time for conventional production, due to its delicate features, was three months. The pad screen consists of two parts that are fitted together, and the filter element in the body of the pad screen must be manufactured using electro-discharge machining (EDM) to obtain the preciseness required for proper screen functioning. These manufacturing steps led to a long lead time and a high procurement cost. To fully realize the benefits of AM, the pad screen was re-designed to improve functionality. The two parts were consolidated to form a single part, reducing an assembly process, and the filter area was re-designed with a helix structure, resulting in an approximate 50% increase in usable filter area and a stronger mesh capable of handling variable differential pressures. The re-designed AM component made it to the wellsite on time and resulted in a more than 70% reduction of part cost compared to the conventional manufacturing method.

In addition to the obvious benefits of AM (i.e., increased freedom of design, rapid prototyping), it can also be used to decrease costs by the reduction of spare part inventories. Using AM as an on-demand manufacturing technology, it can be used to produce parts on an as-needed basis, negating the need for long-term storage of spare parts. The components can also enjoy additional benefits such as increased lifetime or enhanced functionality. Such is the case with the flow diverter, a component that is traditionally milled. Significant wear observed within a milled flow diverter led to inspection of all flow diverters in the fleet, and many were found to have severe washouts. Additionally, the average life of the milled flow diverters was 45% of the expected lifetime, with three lasting less than 25% circulating hours. For the fleet to continue operating, new flow diverters were required, but they could only be produced using metal AM on such short notice. The components were redesigned to take advantage of the AM process benefits (i.e., design freedom), manufactured, and sent out for operation. In comparison to the milled flow diverters, those produced using AM were longer-lasting, with at least five of these having over 65% of the expected lifetime with no indication of wear during the last inspection. The AM flow diverters are predicted to exceed the expected lifetime. The success of the AM flow diverters is due primarily to the greatly improved design, in which the internal chambers of the AM flow diverters are more curved and moon-shaped compared to the milled version, as shown in Fig. 4. Here, similar to the previous examples, lead time was reduced and lifetime was improved by using metal AM.

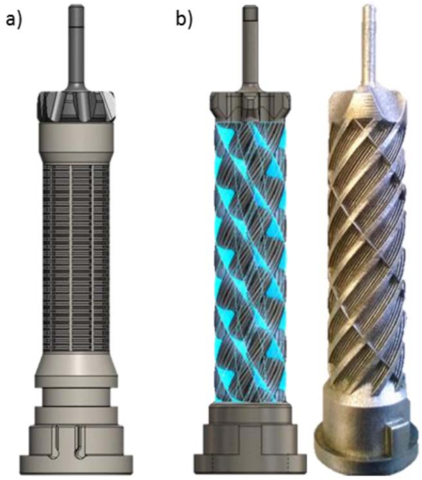

Figure 3—Pad screen improvement showing a) original CAD model and b) redesigned AM CAD model with actual part

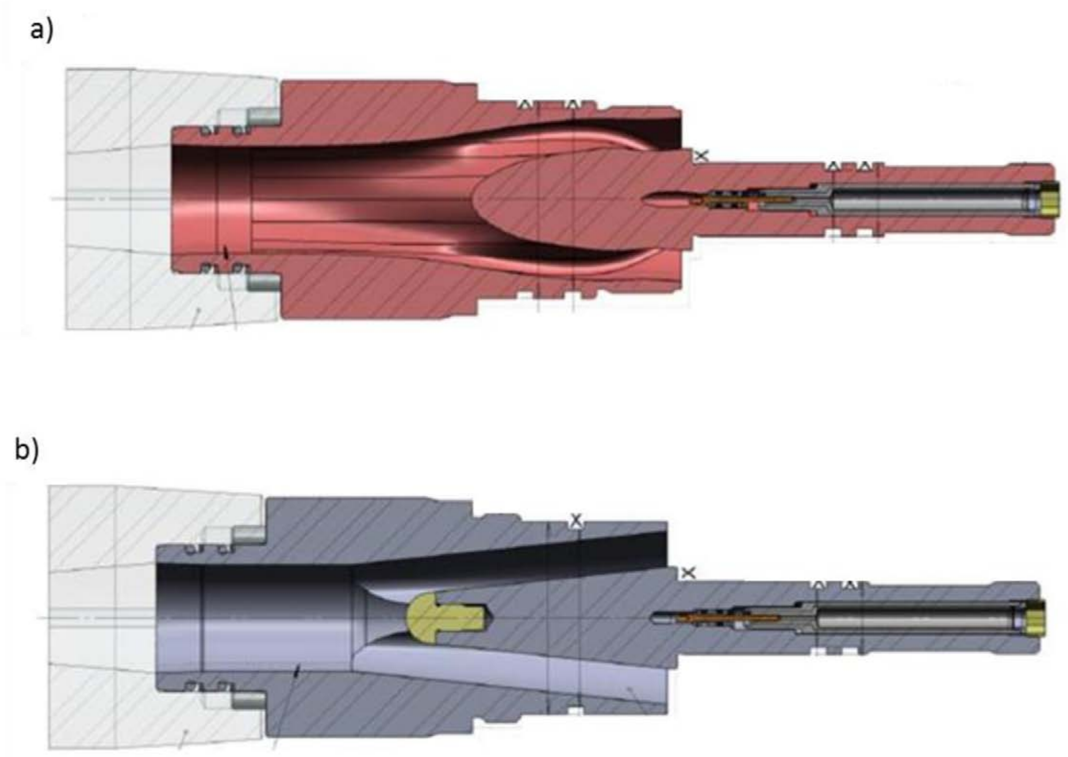

Figure 4—Comparison of flow diverter geometry showing a) redesigned AM and b) standard milled flow diverter

The Future of Metal AM in the O&G Industry

The generally-conservative nature of the O&G industry means that companies operating within the industry have been slower adopters of metal AM. Those who have begun to explore the AM space typically look first to powder bed-based technologies such as SLM and EBM, most likely due to the success of their adoption in the aerospace industry. It is predicted, however, that this dominance will begin to be challenged by other metal powder technologies (e.g., binder jetting, DED, etc.) (SmartTech Publishing 2017). Binder jetting, for example, allows more geometrical freedom than the powder bed processes and requires minimal support structures. Its speed also rivals that of DED, making it an attractive solution for large part batches or even for larger parts. Alternatively, DED equipment can often be combined with subtractive tooling to provide turnkey solutions in a single machine, with build rates that are unrivaled by current powder bed-based technologies. DED also provides the possibility for printing with multiple materials, a feat which can be accomplished with SLM technology only with significant modification to the machine. The localized cover gas of the DED process also means that the production of larger parts is more feasible than in powder bed-based machines.

Current limitations of existing powder bed metal AM processes, such as speed and maximum part size, will most likely be overcome in the near future as the technology advances and machines become more adaptable and grow to meet the needs of the consumer base. Material limitations will also be elucidated, as the research space begins to explore the behavior of AM materials in downhole environments with regards to corrosion resistance, fatigue performance, and other important material characteristics.

Integration into the supply chain is an important consideration that must be made for companies looking to adopt AM. Outsourcing AM production and research can be a way to minimize risk, allowing companies a conservative approach to examine how and if AM fits into the larger manufacturing picture and whether or not it is worth further pursuit. Cooperative research efforts can also provide a route to increasing AM knowledge quickly, but may run the risk of providing limited information or presenting results in a shared forum that may reduce competitive advantage. Unfortunately, many material qualification efforts and resulting data are not publicly shared, leading many companies to grow AM efforts in-house. Although this approach can have a longer learning curve, it can lead to a deeper knowledge of the overall process and better integration into the supply chain. Early adopters of the technology are often those who understand the process best, leading to better and earlier recognition of AM opportunities within the company. It requires, however, a higher initial financial investment in equipment and personnel that may not be required for outsourcing. Implementation of AM within O&G companies should consider all possibilities and follow the path best suited for the needs of the company.

Conclusion

AM technologies have enjoyed significant utilization within the aerospace and healthcare industries, but the O&G industry has been slower to adopt. Companies using AM technologies can enjoy benefits such as lead time reduction, increased design complexity, and enhanced functionality, all of which ultimately increase supply chain efficiency and lead to decreased costs. Integration of AM into existing supply chains requires strategic planning and careful examination, in order to avoid excess development costs. AM technologies in a major oilfield supplier have been implemented to take advantage of some of the numerous benefits of AM: rapid prototyping, innovative design generation, and spare parts production. Although there are still some unknowns, the benefits of AM for the O&G industry are clear. Adoption of AM technologies can help streamline supply chains, reducing waste and cost, and move the industry closer toward the dream of immediate, on-demand, wellsite part production.

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