Adoption of metal additive manufacturing in nnpc limited: current state and challenges

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Abstract. Metal additive manufacturing has emerged as a promising technology with vast potential in the oil and gas industry. The Nigerian National Petroleum Company (NNPC) Limited recognizes the significance of this technology and has initiated efforts to adopt metal additive manufacturing within its operations. This paper aims to provide an overview of the current state of metal additive manufacturing in the NNPC and highlight the challenges faced during its adoption process. The study goes on further to suggest strategies and future directions to ensure successful company-wide and industry-wide adoption and acceptance.

Keywords: direct metal laser melting (DMLM), metal additive manufacturing (MAM), oil and gas, spare parts manufacturing.

1. Introduction

In the oil and gas industry, having enough spare parts when needed is crucial for both keeping operations running smoothly and managing costs effectively. The main goal is to ensure a steady supply of spare parts while also making sure it makes financial sense [1]. To achieve this, the system that manages spare parts needs to be able to quickly respond to unexpected demands and find the right balance between costs, how much is kept in stock, and how quickly items can be delivered [2]. Unexpected downtime in the oil and gas sector can lead to significant revenue losses, and the combination of aging equipment with supply chain disruptions only amplifies this potential for loss.

Additive Manufacturing (AM) is a process whereby a part can be created from three-dimensional (3D) model data in a layer-wise fashion as opposed to a subtractive or formative process. Additive manufacturing has gained increasing importance in several sectors 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 substantial. 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 [3].

The Nigerian National Petroleum Company (NNPC) Limited holds a paramount position within the global oil and gas landscape as the state-owned entity responsible for operating Nigeria's vast hydrocarbon resources. Established in 1977, NNPC operates as the focal point of Nigeria's upstream and downstream petroleum activities, responsible for the exploration, production, refining, marketing and distribution of oil and gas resources. Its multifaceted functions encompass joint ventures, partnerships, and collaborations with international oil companies, making NNPC a linchpin of Nigeria's economy and a key player on the global energy stage. This ensures that Nigeria maximizes its petroleum reserves and benefits from the revenue generated through the export of oil and gas. NNPC Limited also ensures the availability and affordability of petroleum products to meet the energy needs of Nigerians. The company overseas the distribution network, storage facilities, and retail outlets, ensuring the smooth supply of petroleum products across the country.

The NNPC Limited, a key player in the global oil and gas domain, acknowledges the potential of additive manufacturing and has embarked on explorations to harness its benefits. The oil and gas industry, known for its intricate supply chains, demanding operational conditions, and critical reliance on spare parts availability, is set to benefit from the disruptive potential of additive manufacturing. NNPC stands to be among the early majority with capabilities for non-hobbyist industrial 3D printing in Nigeria and West Africa with the development of capabilities in Additive Manufacturing in its Research, Technology, and Innovation (RTI) Division. The NNPC's strategic interest in the adoption of metal additive manufacturing presents an opportune moment to evaluate its current state, challenges, and the pathways towards successful integration.

This paper endeavours to present a comprehensive analysis of the current state of additive manufacturing within the NNPC and the unique challenges it encounters during its adoption journey. By examining the organisation's efforts, successes, and barriers, this study aims to shed light on the feasibility and prospects of implementing 3D printing technologies in a dynamic and critical industry. Additionally, the paper will explore potential strategies to address the identified challenges, thereby offering insights into fostering a conducive environment for additive manufacturing to thrive.

Ultimately, this study aspires to contribute to the discourse on technological innovation within the oil and gas sector, with a particular focus on the prospects and challenges of adopting metal additive manufacturing in Africa from a Nigerian context. As industries worldwide evolve to meet the demands of the 21st century, the marriage of metal additive manufacturing and the oil and gas sector could potentially redefine operational paradigms and position the NNPC at the forefront of innovative excellence.

2. Literature review

2.1. Additive manufacturing

Determining the many AM methods that can help the oil and gas industry produce useful parts is of utmost importance. Thus, understanding the various AM technologies and their uses is a fundamental step to successful adoption. As shown in the figure 1, the American Society for Testing and Materials (ASTM) has classified AM into seven different technologies. By understanding the strengths, weaknesses and applications of each, one can decide which is a suitable technology for further time and financial investment.

One of the earliest AM techniques was stereolithography, which Chuck Hull introduced in the 1980s [5]. The cornerstone for stereolithography (SLA) and its associated processes is the vat photopolymerization principle. A brief description of the various additive manufacturing processes as well as applicable material types and applications is shown in Table 1.

The technologies that were applicable for manufacturing metal components were researched and discussed further in the following section.

2.2. Additive manufacturing techniques for metals used in the oil and gas industry

Due to the extreme stress placed on the part and occasionally the need for the part to endure corrosive environments, AM manufactured parts in the oil and gas industry are typically composed of metals and their alloys. Because of this, the majority of parts are created using metal additive manufacturing, however 3D prototypes are created using non-metal AM processed. The most common metals and alloys used in the oil and gas industry are stainless steel, aluminium, titanium, cobalt chrome, nickel-based alloys (like Inconel), and other alloys like super-duplex stainless steel [3]. The following section highlights the various technologies that utilise these and other materials to manufacture metallic components.

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Table 1. Additive manufacturing technologies

Technology	Definition	Materials	Application
Vat Polymerization (SLA, DLP, CLIP, DPP)	An AM method whereby light-activated polymerization selectively cures liquid photopolymer in a vat	Photopolymers	Prototypes Jewellery industry
Material Extrusion (FDM, FFF)	A method of AM in which material is dispersed selectively through an aperture or nozzle	Polymers Metals	Prototypes Tooling Consumer goods
Material Jetting (MJ, NPJ, DOD)	An AM method in which build material droplets are deposited selectively	Polymers Biomaterials Waxes	Prototypes Jewellery industry Molds for casting
Binder Jetting	An AM procedure that uses selective deposition of a liquid bonding agent to bind powder materials	Polymers Gypsum Metals Foundry sand	Prototypes Creative industries Metal final parts Casting patterns
Power Bed Fusion (SLS, DMLM, EBM)	A method for AM in which a powder bed's individual powder particles are fused using thermal energy	Polymers Metals	Prototypes Tooling Final parts Refurbishment
Directed Energy Deposition (LENS, WAAM, LMD)	An AM method that uses concentrated heat energy to melt the components as they are deposited, fusing them together	Metals	Final parts Repair Refurbishment
Sheet Lamination	An AM procedure where material sheets are bonded together to create an item	Paper Metals	Prototypes Metal final parts Tooling

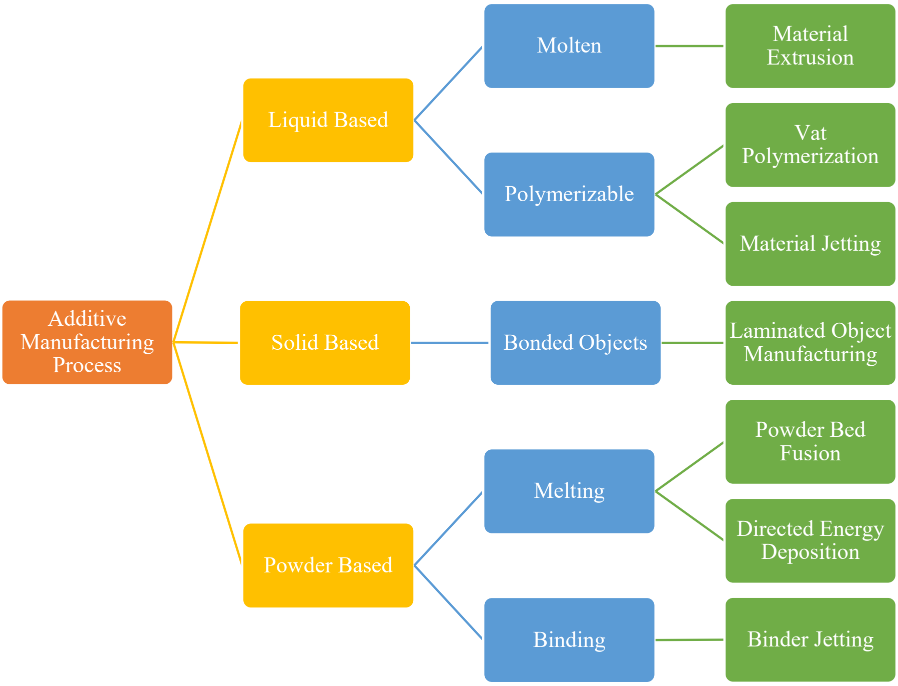

Fig. 1. AM processes classification (ASTM) [4]

2.3. Direct metal laser melting (DMLM)

Using very thin layers of metal powder, Direct Metal Laser Melting (DMLM), builds up the structure layer by layer until it is complete. Titanium, aluminium, cobalt-chrome, stainless steel, Inconel 625, and Inconel 718 are some of the materials that can be used in the DMLM process. DMLM encompasses several distinctive features, notably layer-by-layer material deposition, cross-sectional area laser melting, a seamlessly automated net-shape process, minimal shrinkage, and the absence of high-temperature post-processing solidification [6]. To increase the part's wear resistance and temperature resistance, some surface treatments must be applied after the product is manufactured. In order to achieve desired surface roughness and hardness on the finished parts once the DMLM process is complete, further post processing can be performed on the components. Post processing steps include, stress relieving in a furnace, peening with steel shot to increase the hardness of the surface, tumbling or blasting with a media to improve the surface finish. Additionally, one can manually grind and polish surfaces to enhance their quality further [6]. A schematic of the DMLM process can be observed in Fig. 2.

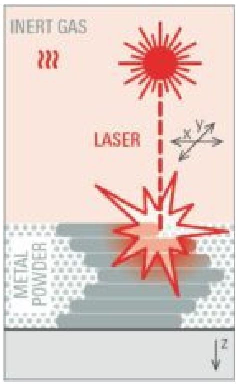

Fig. 2. Schematic of direct metal laser melting additive manufacturing [7]

2.4. Laser metal deposition (LMD)

Directed energy deposition (DED) has been used to create high-performance superalloys. DED works by melting a feeding material (powder or wire) while simultaneously focusing a power source (laser or electron beam) on a small area of the substrate. There are various DED system types, but the most used metal DED technology is the powder-based laser metal deposition (LMD) approach. It uses a laser beam to generate heat and melt the material in process. Wire Arc Additive Manufacturing (WAAM) processes offer a decreased resolution than laser-beam and powder-based DED methods, but a higher deposition rate and the ability to produce larger parts [8]. DED is not typically used to manufacture complex components as the process has less precision (0.25 mm) in comparison to DMLM technologies. It also has poorer surface roughness. DED is therefore typically used for large, straightforward components. DED provides superior mechanical properties and lowers production lead times and costs.

The LMD process is mostly used to create new parts, repair or rebuild worn or damaged ones, and apply wear- and corrosion-resistant coatings. From CAD data (.stl), LMD can create fully dense functioning parts by layering metal powder or wire with laser melting. LMD combines five widely used technologies: sensors, computer-aided manufacturing (CAM), computer-aided design (CAD), lasers, and powder metallurgy. In this method, a workpiece is targeted by a laser beam controlled by CNC/robotics, creating a melt pool into which a small quantity of powder or wire metal is introduced to build up the part in thin (typically 1 mm) layers. Based on CAD geometry, the beam traces out the part layer by layer before moving on to the next layer. Therefore, by coating the components in this method, it can be used to repair damaged parts in the oil and gas industry and to make them anti-corrosive [9]. When compared to conventional machining, this method has a number of advantages, including:

1) The molten pool cools and solidifies quickly, producing parts of superior quality and strength with no material waste.

2) A wide range of metallic materials can be used and, in some cases, both wire or metal feedstock can be utilised.

3) The parts made have a uniform fine microstructure with superior strength and quality.

4) Metallic composition can be changed using this method by injecting various types of metal powders into the melt pool.

A schematic of the LMD process can be observed in Fig. 3.

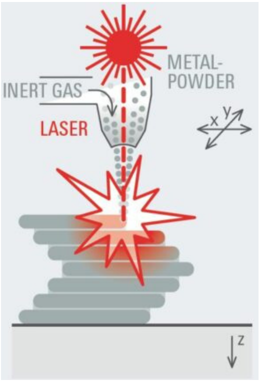

Fig. 3. Schematic of laser metal deposition additive manufacturing [7]

2.5. Material extrusion

In this method, a material is heated and continuously flowed through a nozzle at a constant pressure before being deposited layer by layer. As a part is created layer by layer, both the part platform and the nozzle move within the cartesian plane. This method is relatively inexpensive, and most desktop hobby machines are of the material extrusion type. Materials like plastics and polymers are mostly used in this technique. Numerous aspects may have an impact on the final product's quality, but if everything is done under control, high-quality goods can be produced [9]. Material extrusion technology such as fused filament fabrication (FFF) can also be utilised to manufacture metal components through Sinter Based Additive Manufacturing (SBAM). The parts are printed from plastic or organic filament fused with metal powders that requires a post sintering step to solidify the component. During this process the plastic or binder evaporates, and the part shrinks while the metallic powder particles sinter and bond together.

2.6. Electron beam melting (EBM)

High-power electron beams are used in the EBM process to produce the energy required for high melting capacity and high productivity. The vacuum process ensures a clean and controlled environment, while the hot process enables parts to be produced with less residual stress than other powder bed fusion (PBF) technologies. This process is appropriate for producing dense, lightweight, and long-lasting metal end products. The oil and gas, aerospace, medical, and defence industries are where the technology is most commonly used. The build plate is covered with a layer of metal powder, which is then warmed and selectively melted by a high energy electron beam in the areas indicated by the digital CAD model. The beam melts and fuses layers together and then a next layer is deposited until the part has its desired final shape, this recoating and melting process is repeated numerous times. After production, in order to acquire the necessary material properties, post-processing is performed on the component [10]. EBM has the following advantages:

1) The electron beam used in the EBM process has a higher energy density than a laser source, allowing for faster printing.

2) The preheating procedure and high temperature required during printing gives EBM parts strong mechanical qualities as well as high density (over 99 %).

3) When compared to the traditional casting procedure, EBM can make metal parts of high quality and unique features.

4) This technique creates little waste because most of the wasted powder may be recycled for use in the future.

Some of the drawbacks include:

1) This method can only be used for specific industry applications due to the high cost of the material and the hardware.

2) It demands high-quality materials that must first undergo extensive testing, the material choices utilised in EBM is constrained in comparison to other PBF technologies.

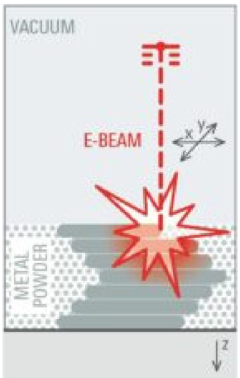

Fig. 4. Schematic of electron beam melting additive manufacturing [7]

2.7. Laminated object manufacturing (LOM)

LOM also known as ultrasonic additive manufacturing (UAM), commonly referred to as sheet lamination, is a step in the fabrication of laminated objects. Ultrasonic welding is used to join metal sheets or ribbons together in the UAM process. This technique involves ultrasonic welding to secure a sheet of material over the top of the layer before the layer is cut into the desired form and the subsequent layer is attached. Up until the desired 3D shape is achieved, these processes are repeated again. Additional CNC machining may be necessary to remove unbound metal that developed during the welding process from the finished product produced through this process. Aluminium, copper, titanium, stainless steel, and other metals are used by UAM. This low-temperature method is often suitable for generating interior geometries. Given that the metal is not being melted here, this technique can combine various elements and uses relatively little energy [9]. A schematic of the paper-based LOM process can be observed in Fig. 5.

Recently, work has been done regarding developing a framework for various aspect of AM. For example, the authors in [11] developed a framework to formalise the production planning problem in AM at the operational level which can be used to can be used as a reference to focus on and address these AM-related problems for efficient production planning. The study performed in [12] addressed the need of the industrial sector for structured and organized expertise training for the fruitful exploitation of AM, paving the road for its wider application. The authors developed an AM training framework and set guidelines for an industrial-oriented AM training curriculum. Also, the authors in [13] made propositions on industrial marketing for AM. Their findings Through the adoption of AM technologies, suggests that firms can improve their level of servitization through customized products, offer more sustainable value propositions and

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empower their customers through the sale of digital files, which can be considered as levers to strengthen relationships with customers.

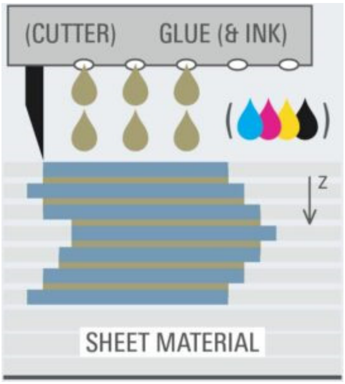


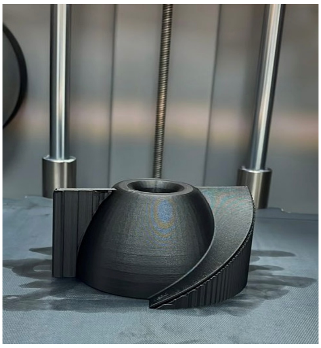
Fig. 5. Schematic of laminated object manufacturing additive manufacturing [7]

3. Metal additive manufacturing in NNPC

3.1. Current state of additive manufacturing at the NNPC

Currently the NNPC has undertaken to adopt metal additive manufacturing technologies at the research, technology, and innovation nexus (RTI). This strategic initiative signifies a progressive step towards embracing the transformative potential of AM within the organisation. Initial ventures into this technology have laid the foundation for a broader exploration of its applications, with a focus on enhancing operational efficiency and unlocking unique solutions. Pilot projects within the NNPC RTI have demonstrated the feasibility of using metal additive manufacturing for rapid manufacturing and localised production of critical spare parts. These initial endeavours serve as promising indicators of the NNPC's commitment to leveraging cutting-edge technology to address industry-specific challenges and make a significant contribution to localisation of spare part manufacturing on Nigerian soil.

A pilot project with stakeholders from the various NNPC departments and streams was performed whereby subject matter experts were invited to workshops and online training around 3D scanning and additive manufacturing. A Markforged X7 FFF printer was procured alongside an Artec Leo 3D scanner to demonstrate the potentials of the technologies to assist with spare part production. Use cases were then developed with the assistance and buy-in from the subject matter experts and the various NNPC departments. Several prototypes were printed using the Markforged X7 at the RTI, NNPC Limited with few examples shown in Fig. 6.



a)

b)

Fig. 6. a) Prototypes of an impeller and b) turbine impeller printed in RTI, NNPC Limited [14]

With the aid of the subject matter experts, several high impact use cases were developed to test the various additive manufacturing technologies. A multi-criteria decision analysis was performed on several parts to identify the parts with a high return on investment (ROI) and best suited to manufacture with the various AM technologies. The main criteria used were size of parts, material properties, design complexity, post-processing requirements, time to manufacture, and price. The current price and lead time to order were then linked to the ROI. Those with high prices and lead times were weighted more favourably against those that were readily available from the original equipment manufacturers.

Several components were identified with high ROI and ease of manufacturing with the specific AM technologies in the scope of the adoption project. These parts can be observed in Table 2.

Table 2. Additive manufacturing use case development results

Part name	Use	Material	AM Technology
Shaft coupling	To connect the rotating pump shaft with the drive shaft of the motor	Rubber	Material extrusion or vat polymerisation
Shrouded impeller	Pumping specific liquids	Brass, stainless steel,	Powder bed fusion
Unshrouded impeller	Pumping specific liquids	Stainless steel, peek	Powder bed fusion, directed energy deposition, or material extrusion
Control valve trims	Control the flow of liquid and gas through a valve	Stainless steel	Powder bed fusion
Choke cage valves	Throttle the flow of liquid in a valve	Stainless steel	Powder bed fusion or directed energy deposition
Burner plugs	To plug an access hole in a burner	Inconel	Powder bed fusion or directed energy deposition
Drill bits	To create the hole	Steel with tungsten carbide buttons	Powder bed fusion or directed energy deposition
Stators	Direct fluid through to a rotor or direct flow type	Stainless steel	Powder bed fusion

After the use cases were identified, an analysis of the various technologies and the available hardware was performed. To assist with producing the metal components, laser powder bed fusion was selected on the basis that the electron beam melting process was too complex and required additional facility requirements that may not be feasible in an African context. A Concept Laser M2 Series 5 machine from GE Additive was specified due to the stringent quality requirements from GE and the great reputation of reliability of the equipment on the African continent. For industrial scanning of components, a Creaform HandyScan Black Elite was specified due to the conformance to standards as well as the digital training platform offered with the Creaform scanners. All the additive manufacturing and scanning hardware will be housed at the NNPC RTI building along with the trained team to successfully operate the equipment. The RTI will act as the central knowledge hub and collaborate with the various departments and business units of NNPC to disseminate knowledge through training, whitepapers, conference and journal articles. Forming strategic partnerships with specific partners and other oil and gas companies will also form part of the functions of the NNPC RTI team.

In order to validate the viability of the various AM technologies for the earmarked use cases, specific use case components were manufactured with technology partners as part of proof of concept and can be observed in Fig. 7.

3.2. Methodology

This outlines the approach adopted to investigate the challenges of the adoption of metal

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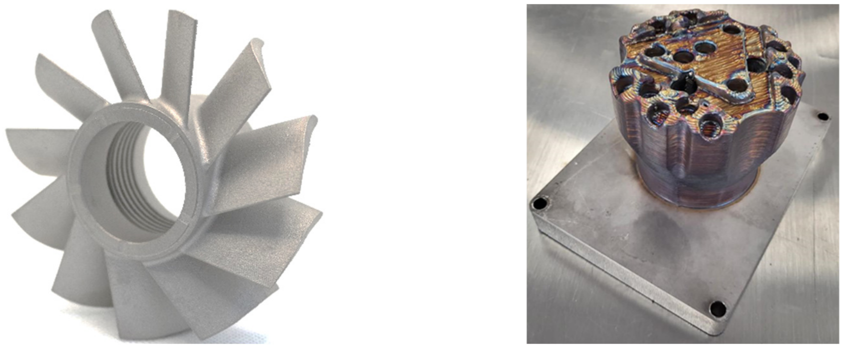
additive manufacturing in the NNPC. The methodology encompasses the data collection and the analysis methods.



a) b)

Fig. 7. a) Proof of concept parts manufactured by HH Industries/RTI, NNPC Limited, inconel drill rig stator, b) steel drill Bit without tungsten carbide buttons [14]

3.2.1. Data collection

Primary and secondary data sources were employed to comprehensively analyse the adoption and challenges of metal additive manufacturing in NNPC.

Primary Data Collection: Structured interviews and focused discussions were conducted with key stakeholders within NNPC, including personnel from the Research, Technology, and Innovation division (RTI). These interviews aimed to gain insights into the existing state of metal additive manufacturing, ongoing initiatives, and perceptions of challenges.

Secondary Data Collection: Extensive literature review was conducted to gather relevant academic articles, industry reports, and case studies. These secondary sources provided insights into global trends, best practices, and challenges associated with metal additive manufacturing in the oil and gas sector.

3.2.2. Analysis methods

To comprehensively address the identified challenges of metal additive manufacturing in NNPC, the following analysis methods were employed:

SWOT Analysis: A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis was conducted to evaluate the internal strengths and weaknesses of NNPC's current approach to metal additive manufacturing, as well as external opportunities and threats posed by the industry landscape.

Case Study Analysis: A detailed analysis of a specific case study within NNPC, where metal additive manufacturing has been implemented or is under consideration, was conducted. This provided a contextual understanding of the practical application, challenges faced, and lessons learned.

Comparative Study: A comparative study was carried out to benchmark NNPC's approach against global best practices in metal additive manufacturing within the oil and gas sector. This involved analysing successful implementations in other organizations and identifying key strategies for overcoming challenges.

3.3. Challenges faced in adopting metal additive manufacturing in NNPC

The challenges associated with the adoption of metal AM in NNPC are organisational mindset, development of applicable standards and certification processes, high initial investment costs, and electrical power stability. Each of these challenges are discussed in further detail in the proceeding sections.

3.3.1. Organisational mindset

The necessity for a change in NNPC organisational thinking and culture to embrace this disruptive technology is one of the main issues. Reverse engineering and metal additive manufacturing methods must be utilised and integrated effectively; thus, the staff must receive the necessary training and upskilling. Education and training courses organisation wide are crucial for the successful uptake and acceptance of these disruptive technologies. Communication and training to such a large organisation will need to be performed strategically and with the aid of digital marketing infrastructure.

3.3.2. Development of applicable standards and certification process

One of the main obstacles to the general acceptance of additive manufacturing technologies in the oil and gas sector is the establishment of AM standards applicable to industrial products for the oil and gas sector. The creation of items that adhere to internationally recognized standard specifications and are compatible with goods given by other suppliers that desire the same quality, performance, and interchangeability would be made possible by the establishment of standards in additive manufacturing. Standards for additive manufacturing in NNPC will increase product quality and stop components from failing repeatedly while also boosting equipment and process accuracy, safety, and dependability [3].

3.3.3. High initial investment cost

Financial difficulties arise due to the high initial investment cost of metal additive manufacturing tools and materials. To purchase and maintain cutting-edge machinery, as well as to purchase premium metal powders and other consumables required for the additive manufacturing process, adequate money and budget allocation are required.

3.3.4. Electrical power effects

One of the challenges that needs in-depth research is the effect of power quality on equipment used in additive manufacturing. Power variances can significantly affect the quality of an additively manufactured product by introducing flaws that may not be readily apparent during the component printing process. The power quality features of AM equipment that will have a better impact on the best mechanical properties of the manufactured parts require evaluation through research. In Nigeria or even Africa as a whole, power generation is significantly less reliable than in other developed countries. Thus, the need for customised power solutions will be required for adoption of additive manufacturing technologies.

3.3.5. Other challenges

Poor fabricated part qualities, a small material selection, resolution, repeatability, and poor surface finish of the printed parts are further process challenges. When compared to components made using conventional machining, the strength and tolerances of AM parts is lower. Additionally, removing support structures from the parts may result in surface damage and have an impact on the surface finish [15].

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4. Strategies, future directions and opportunities

4.1. Strategies for overcoming challenges

In this section, various strategies for overcoming the challenges in adopting metal additive manufacturing are discussed. To address the challenge of organisational mindset, it is imperative to instigate a comprehensive training and upskilling program, imparting a deep understanding of metal additive manufacturing's benefits across NNPC staff. Simultaneously, a change management initiative should be introduced, fostering a culture of innovation and proactive technology adoption throughout the organisation. A user-friendly digital portal dedicated to spare parts production through additive manufacturing should be developed, simplifying staff interaction with this transformative technology. Once the benefits of utilising additive manufacturing technologies to assist with plant uptime is realised, a technology pull effect will start to take place within the NNPC. At such point the NNPC RTI team should have the technical expertise in place to service the needs of the NNPC as the centralised knowledge hub.

For the development of applicable standards and a certification process, the strategy necessitates collaborative efforts with prominent oil and gas companies to formulate AM standards tailored to the sector's industrial products. Extensive research and testing protocols should be established, ensuring these standards align with the unique demands of oil and gas operations. A comprehensive certification process must be instituted, assuring product quality, performance, and interchangeability by adhering to international standards. Other projects within the NNPC RTI are allowing for the procurement of state-of-the-art quality control and testing equipment to assist in process and part certification for AM. Collaboration between the various large oil and gas companies to develop applicable standards and a digital inventory platform is already underway.

Mitigating the challenge of high initial investment costs requires a strategic approach that hinges on prioritizing projects with a high potential for ROI. It also involves the dedicated allocation of budgets for cutting-edge machinery, premium metal powders, and consumables, crucial for additive manufacturing processes. Seeking partnerships with tertiary education institutions could further alleviate financial burdens and assist in creating a competent skill pool to further grow and disseminate knowledge into Nigeria. With the development of use cases that have a high ROI potential, the high capital expenses can be offset from the operational and downtime losses in revenue. If operations are brought online by even a day sooner in a plant that has high revenue potential, the costs of the equipment and powders can be seen as negligible.

To address electrical power effects, an in-depth assessment of power quality requirements for additive manufacturing equipment is imperative. This evaluation would pinpoint potential areas where power fluctuations could compromise product quality. The development and deployment of tailored uninterruptable power supply (UPS) solutions custom-made to NNPC's unique operational requirements would ensure consistent and stable power supply during AM processes. These customised solutions should be designed and specified to run all the applicable AM equipment with their ancillary devices such that quality would not be affected in the event of a surge in power or even a power outage.

Moreover, confronting challenges like poor fabricated part quality, limited material selection, and surface finish issues necessitates a multifaceted approach. Prioritizing use case development that aligns with additive manufacturing strengths, integrating advanced post-processing techniques, and embracing design for additive manufacturing (DfAM) methodologies can collectively enhance component quality and performance.

By implementing this comprehensive strategy, the NNPC can surmount the obstacles currently inhibiting the effective integration of metal additive manufacturing. This approach not only addresses challenges head-on but also positions the NNPC to harness the transformative power of additive manufacturing, thus driving operational efficiency, reducing costs, and fortifying the organisation's competitive standing within the oil and gas industry.

4.2. Future directions and opportunities

The future directions of the NNPC RTI are coupled with the unique opportunities faced in Africa and Nigeria as a whole. Spare parts and materials are difficult to obtain in Nigeria due to factors like aging equipment, procurement restrictions, and challenges with the local supply chain infrastructure. Thus, the future opportunities to mitigate these restrictive factors are creating a 3D digital infrastructure for parts and developing material locally for additive manufacturing.

4.3. 3D digital infrastructure for oil and gas parts

The evolution of the oil and gas sectors hinges on the establishment of a robust digital infrastructure capable of efficiently managing the intricate 3D data systems. Such a development holds the potential to substantially amplify the widespread adoption of additive manufacturing. By cultivating a digital ecosystem that facilitates large-scale additive manufacturing, a groundbreaking avenue emerges for the creation of spare parts tailored to the oil and gas industries. This, in turn, streamlines the process of generating on-site 3D data for the manufacture of necessary parts, eradicating the need for maintaining a substantial inventory of equipment components. The integration of such a digitally driven approach effectively redefines the landscape of oil and gas services. An additional facet of this initiative involves engineering teams strategically preparing digital assets for seamless on-site utilization, thereby maximizing the practicality and time savings offered by additive manufacturing.

4.4. Material development for additive manufacturing

Central to NNPC RTI's vision is an active pursuit of advancing additive manufacturing and petrochemical based materials. This includes a range of ongoing initiatives aimed at enriching the palette of materials compatible with additive manufacturing techniques. By investing in research, innovation, and partnerships, NNPC RTI is dedicated to pioneering materials optimised for additive manufacturing for its own use as well as commercial gain. These endeavours are anticipated to not only enhance the effectiveness and adaptability of additive manufacturing in the oil and gas sector, but also open new avenues for tailoring materials, managing costs, and optimising performance. This collaborative effort to develop advanced materials underscores NNPC RTI's steadfast commitment to shaping the future of additive manufacturing applications within the industry and within Nigeria.

5. Conclusions

In Conclusion, the adoption of metal additive manufacturing in the NNPC represents a significant opportunity for enhancing operational efficiency and competitiveness in the dynamic oil and gas sector. However, successful implementation requires overcoming challenges related to organisational culture, development of applicable standards and certification process related to industrial products for the oil and gas sector that adhere to internationally recognized standard specifications, financial difficulties due to the high initial investment cost of the metal AM machines and tools, quality control, and infrastructure management. By addressing these obstacles and fostering collaboration among stakeholders, the NNPC can harness the full potential of metal additive manufacturing and realise its benefits in the oil and gas industry. Strategies and future directions that are currently being implemented such as the development of material locally for additive manufacturing in NNPC Limited as well as establishment of a robust digital infrastructure capable of efficiently managing the intricate 3D data systems and creation of spare parts tailored to the oil and gas industries will further aid in securing the NNPC supply chain especially for the aging equipment that is no longer supported by OEM’s.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Dr. Al-Amin Barambu Umar: conceptualization, data curation, formal analysis, methodology, resources, visualisation.

Muniru M. Mai: project administration, supervision, writing-review and editing.

Dr. Devon Hagedorn-Hansen: resources, validation, formal analysis, writing-review and editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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