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A Comprehensive Review Of Metal Additive Manufacturing: Technologies, Materials, Applications, And Future Directions

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Abstract
Metallic adding manufacturing, otherwise referred to as metal 3d printing, has become an operating paradigm in Manufacturing, which will revolutionize the creation of intricate, advanced parts in hundreds of sectors. It is a research paper that is a descriptive and comprehensive synoptic survey of the modern eternity in metal AM. The paper has begun with historical account of how metal AM has developed throughout the rapid prototyping into a successful technology in manufacturing the final parts of its product. The key AM technologies have been elaborated and these are Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Binder Jetting (BJ). The fundamentals, advantages as well as the limitations of both processes are highly criticized. Next pay attention to the editorial section of this review, which is devoted to the materials science of printable metal alloys and addresses a fairly wide range of materials of titanium alloys, nickel diesel alloys, stainless steel alloys, aluminum alloys, and cobalt-chrome alloys. The Microstructures and mechanical properties resulting as such due to the layer-wise manufacturing strategy are examined, together with the pivotal contribution of post-processing methods to attain the desired material properties. Its paper is detailed and Thomus outlines the numerous effective and beneficial uses of metal AM across several industrial areas such as aerospace, medical and automobile. Sure and definite advantages of metal AM, including weight loss, part consolidations and the production of personalized medical implants are illustrated using case studies and examples. More so, the paper discusses the which have prevailed, related to the inability to err, limitations and difficulties of metal AM, such as cost constraints, scalability, quality assurance and in standardization. Lastly, at the end of the paper, a perspective to the future regarding the trend and direction of research in the field of metal AM is noted indicating that it is possible to obtain new materials, develop exercise monitoring and control, and introduce the use of artificial intelligence and machine learning to expand the advances of this groundbreaking technology.

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I. Introduction

One innovation brought about by the 3D printing (also known as additive manufacturing or AM) is a new precedent in print fabrication of objects in three dimensions visible physically in sight according to the digital representation. Though the original applications of AM focused more on polymer-based rapid prototyping, the technology has seen an unimaginable rise and devoted immense success to the possibility to address a great number of materials, including ceramics, composite and to an even greater extent of influence, metal. The new paradigm of additive manufacturing of the metallic parts contrasts the earlier forms of manufacturing (subtractive) such as machining which features a large block of solid substance cut-down in size to shape it to the shape desired. In contrast to this, metal AM is a layer per layer type of manufacturing process in which the metal powder or metal wire is melted, or rather welded or bonded into a solid object. This key difference of perspective gives a blast of design and manufacturing solutions, that was initially inaccessible.

The possibilities of producing increasingly complex geometries, internal lattices as well as functional graded materials have made metal AM a disruptive technology whereby the technology argument has the inbuilt capability to root change the product design, the supply chains and even the very economic of the manufacturing process. One such industry has been the aerospace industry, which has been one of the earliest to adopt metal AM in manufacturing lightweight and high strength products which made weight to drop considerably to the aircrafts and hence the fuel acquisition. Even the medical engineering field is only realizing the potential of printing outpatient-specific implants and medical tools that would depend on the keep of an individual which would help improve the outcomes of the surgical procedure and also recovery. Another role of metal AM that uses Gathers impetus within the automobile sector involves utilising the technology in quick prototyping as well as tooling and production of parts that can be utilised into luxury and race cars with high-performance features.

Even under the tremendous potential and rapid innovation the use of metal AM is yet to spread. The technology has difficulties linked with it. High cost of metal powders and AM systems, relatively low rate of manufacturing large parts, post-processing necessitating it, and intricacies needed to sustain the quality and consistency of parts are great challenges that are to be surmounted. Additionally, it is in the very nature that the sophisticated interdependence between the parameters of the process, the characteristics of materials, and the performance of end components in terms of the safety and steadyness of providing the missions-critical parts delivery looks through the tunnel-anealed mirror.

This research paper is done with the aim of critically and in detail analyzing the field of metal additive manufacturing. It will delve less into the current aspect of the technology by examining the development history that will be the foundation of the analysis of its current position. The present paper will then set forth to elaborate on the numerous metal AM techniques, their physics being unravelled with their demerits and strengths equally being mentioned. They will be one of the central points of focus and talk about characteristics of materials of metal AM will be discussed having actual conversation based on the favorite types of metal alloys, which give the special microstructural and mechanical characteristics that none other but the additively manufactured portions possess. The paper will also provide a brief description of the current and focus applications of metal AM in the various industries that will indicate the groundbreaking contribution of the technology. Besides, the discussion presented on this review will assume a critical energy to address the conceivable barriers and constraints that have impeded the general industrial adoption of the metal AM and in the end observations will provide on the speculative trend and research prospects which is most likely to impact on the future of the metal production in the predictable future. Through this analysis, this paper will strive to provide a lucrative offer in consideration to the research capability, engineers as well as other industry players who feel the inherent capability of this innovative technology in manufacturing.

II. Literature Review

Review Article The literature that examines metal additive manufacturing has experienced an exponential expansion in recent years most likely due to advancements in the amount of interest and investment directed at this topic by academics and industry developers. This chapter considers a synthesis of the available literature, divided into an overview of the underlying technologies, a discussion of the materials science of printable alloys and a profile of the most important application fields along with that of the related challenges.

Foundational Metal Additive Manufacturing Technologies

Development of powder-based systems dated back to the late 1980s and early 1990s are considered as the origins of metal AM. The initial technology types that prevail in the AM market of metal include Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). Moreward, in the recent times, Binder Jetting (BJ) has come in as a viable option in case of high volume production.

Powder Bed Fusion (PBF): PBF processes are identified in that a high-energy source is used normally using a laser or an electron beam to target specific areas of a powder bed in selective depletion and fusion processes. Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM) represent the most eminent PBF technologies of metals. It is widely-reported on the documentation of the process physics of PBF, the difficult interactions between the energy source and the metal powder and the development and dynamics of the melt pool, and the rapid solidification that govern the microstructure formed (Gokuldoss et al., 2017). Much has been written about the processes of optimization since much effort is needed to achieve an acceptable balance control among various process variables, including: laser power, scan speed, hatch spacing, and layer thickness, in order to influence the density, surface finish, and mechanical properties of the final part (Aboulkhair et al., 2019). The research has also noted the issues attached to PBF such as development of defects such as porosity, no fusion and undue stress which may be counter productive in enhancing the performance of the part (Sames et al., 2016).

Directed Energy Deposition (DED): DED processing entails feeding metal wire or powder into a melting pot through a concentration of energy source. The equipment that provides the difficulty and the energy, is generally a nozzle that can be placed on a multi-axis handle, and has the ability to make large and elaborate units, not to mention the repairing and wrapping of an already secured piece. Literature on DED tends to compare it with PBF which has lower deposition rates, whereas it has the characteristic of generating materials with a functional grade through changes in the composition of the feedstock that occurs dynamically (Thompson et al., 2015). The study of process parameters that affect the geometry of the clad, microstructure, and and mechanical properties has been researched in the field of DED. The issues in DED that are often mentioned in literature are the consideration of relatively poor surface finishing relative to PBF and the impressive temperature differences, which may cause distortion and remain residual stresses (Froes et al., 2019).

Binder Jetting (BJ):

The Binder Jetting technique is two-step in which initially a liquid binding agent is deposited on top of a ray of powder to create the required shape. This is then subjected to the curing of the green part, which is then sintered in a furnace in order to attain its final density and mechanical properties. The sources on metal binder jetting indicate its main benefits, such as the fact that it can print most materials, there is no high-energy source during the printing process and thus the end result has minimal residual stresses and the volume of production could be increased (Gonzalez et al., 2019). Nevertheless, a very important and perilous part of binder jetting is the sintering phase, which may cause extensive shrinkage and deformity, as well as the end product will have remaining pores. To create high-quality metal parts, a considerable amount of research is devoted to deep optimization of interaction of binder and powder, debinding, and sintering cycle (Mostafaei et al., 2021).

Materials Science of Additively Manufactured Metals

The specific thermal Cycles of the material in the course of the layer-wise Fabrication process lead to microstructures and mechanical characteristics have no visible resemblance to what those of their traditionally manufactured counterparts.

Microstructure Evolution: The non-equilibrium elevated microstructures i.e. fine grains are produced because of the elevated rates of solidification typically landing between to to of such a type. The available literature is overflowed with the study of the columnar growth of grains, the epitaxial solidification, and the formation of certain cellular and dendrites structure of additively manufactured metals (DebRoy et al., 2018). These microstructural features may have violent effect on mechanical properties of the material that can go relatively deep.

Mechanical Properties:

Additively manufactured metals tend to show a peculiarity of the combination of high strength and good ductility. The high strength is also due to the high grain size described as a result of quick solidification, which is among the main factors and the laws governing high strength. Nonetheless, any type of defects, e.g. porosity and turnover, may severely affect the mechanical performance, especially fatigue life of the piece. Directionally dependent mechanical properties can also be the effect of the anisotropic microstructure, which consists of long grains oriented in the build direction (Herzog et al., 2016).

Printable Metal Alloys:

AM is continuing to increase the available metal alloys to be processed. The literature uses/gives a lot of information concerning the processing and properties of commonly used alloys and they include:

Titanium Alloys: Ti-6Al-4V is presently the most frequently used titanium alloy in AM as it has a great combination of high level of strength-weight, anti-corrosiveness, and biocompatibility. Studies were directed at learning how the phase changes in the AM process takes place and affect the mechanical characteristics (Sing et al., 2022).

Nickel Superalloys: Inconel 718/Inconel 625 are common high-temperature alloys, which are used in gas turbines and rocket engines, as an example. The struggles of regulating the precipitation of strengthening phases and alleviating the danger of solidification cracking are provided in the literature on the AM of nickel superalloys (Koutiri et al., 2018).

Stainless Steels: Other well known stainless steels include the Austenitic stainless steels, i.e. 316L due to their corrosion resistance and excellent mechanical properties. Precision hardening and martensitic stainless steel is also under consideration of use because of greater strength and hardness. The research on this topic usually takes the direction of personalizing the microstructure to improve the corrosiveness and mechanical effectiveness (Kurnsteiner et al., 2020).

Aluminum Alloys: Aluminium alloys are good due to their light weight and thermal conductivity. Nonetheless, Aluminum has high reflectivity and thermal conductivity, combined with its vulnerableness to oxidation, which poses a challenge to AM. The creation of new aluminum alloys that are tailored in terms of AM is a research field (Aboulkhair et al., 2019).

Cobalt-Chrome Alloys: Co-Cr alloys find extensive application in the medical and dental care, because it is biocompatible, noncorrosive and resists wear. The data about the AM of Co-Cr alloys usually is concerned with attaining the expected microstructure and surface finish of biomedical appliances (Takaichi et al., 2013).

Applications and Challenges

The test of the successful use of metal AM in any of the industries is abundant in the literature. Similar to other industries, metal AM has achieved fundamental progress in the aerospace industry through their capacity to manufacture lightweight structures and create a topologically structured part, which can be defined as the sole factor that influenced the involved adoption (Sing et al., 2022). Medical industry has not left behind on the usage of metal AM in the production of the bespoke orthopedic implantation, dental or prosthetic, and surgical guide (Singla et al., 2021). Rapid prototyping and manufacturing of intricate tooling as well as manufacturing of high-performance motor sports parts are some of the fields where manufacturers of the automotive industry are using metal AM (Mellor et al., 2014).

Along these achievements, the literature also industryedly present its struggles that should be uplifted in case of the broader adoption of metal AM. They encompass its expensive nature of equipment and materials, its extensive requirements upon its post-processing, absence of labor division requirements and qualification procedures, and the advanced awareness of process-structure-property interrelations (Sames et al., 2016).

III. Methodology/Approach

The research paper will utilize an extensive review and synthesis of what is currently available in the literature to provide a review and overview of the academic and industry knowledge on additive manufacturing of metal components. It is qualitative and interpretive methodology, which is intended to present the overview of the field in depth and comprehension. The literature used was selected using a systematic method to have a balanced and representative selection of the major topics under metal AM.

Establishing the research process was a general searching of well known academic databases such as Scopus, Web of science, and Google Scholar. Search queries were developed as comprehensive and specific, which contained the key words: metal additive manufacturing, metal 3D printing, selective laser melting, electronic beam melting, directed energy deposition, binder jetting and the names of particular metal alloys together with additive manufacturing. The search was not restricted with reference to the publication date so that it would be possible to include the seminal papers that have influenced the field; but special attention was paid to the publications that were published within the previous decade so that the review reflected the state-of-the-art.

The relevance, rigor and breakdown of research were used as inclusion criteria to select the literature. It gave preference to peer-reviewed sources of literature including journal articles, conference papers, and official technical reports of respected organizations. It was also decided that the contribution of the review articles was necessary in order to have a wide overview of the known facts about certain sub-planes within metal AM.

A thematic analysis approach was used in synthesising the collected literature. These facts were sorted into specific themes which constitute the major parts of this research paper namely: the historical development of metal AM, the in depth explanation of the leading AM technologies, the materials science of printable metallic alloys, the use of metal AM in different industries and the challenges and the future outlook of the practice.

The literature is critically evaluated and synthesized within every thematic section in order to include a well-managed complete story. The article does not merely describe the results of the respective research examples but rather synthesizes and analyzes this data, to determine essential trends, general challenges and areas of agreement and disagreement in the research world. It is to offer a comprehensive and subtle view of the complications of metal additive manufacturing.

The conception of the paper is a theoretical opener into the discipline, starting with a trail of the simple, then proceeding to the study on narrower scope of material, applications, and opportunities. Such a design is expected to reduced the barrier to the readers, both amateurs, and professionals, of the depth of the matter.

It there is a need to inculcate that this paper is by no means the meta-analysis, and it will not proceed with the data analysis using statistical methods. The advantage of the book is that it covers the scope and is comprehensive in its coverage, incorporates the large and wide literature, and provides a critical critique of the current situation and future opportunities of the metal additive manufacturing.

IV. Analysis And Findings

This part provides an in-depth-analysis of the most important issues of metal additive manufacturing, relying on obtained literature. The structure of the analysis is developed in such a manner that it gives an in-depth review of the technologies, materials, and applications that characterise the present situation in metal AM.

Metal Additive Manufacturing Technologies: A Closer Look

Although the context of the literature review has presented an overview of existed foundational technologies, this part will propose a deeper analysis of working principles, specificities of the process and comparative strengths of the main metal AM processes.

Powder Bed Fusion (PBF):

Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS): The two terms are used as synonyms, but have minor historical distinctions. In both processes, it employs a powerful laser which is used selectively to melt and fuse metallic powder. The major difference is that in SLM, the powder melts completely, whereas in DMLS it sinters hence in reality most modern DMLS systems are fully melted. It is initiated by placing a mix of teaching a thin coating of metal powder on a build platform. The laser is very powerful and directed at the cross-section of the part by a CAD model and it heats up and welds the particles of the powders. At this point, the build platform is lowered and another layer of powder is added. This is repeated until layers are added to the part. The SLM/DMLS is characterized as having great dimensional accuracy and fine feature resolution in the production of parts. The process is however prone to accumulation of residual stresses as a result of high thermal gradients and results in part distortion and cracking. The support structures are used to frequently hold the part onto the build plate as well as provide support on features over the plate.

Electron Beam Melting (EBM): EBM resembles SLM as it is also a file that is based on adding its particles on a powder bed, only that the energy source is an electron beam rather than a laser. It is done in a high-vacuum space in order to avoid scattering the electron beam. One major strength of EBM lies in its capability to work with high temperature that aids in eliminating those without making the use of huge support facilities. It is especially in cases of crack-sensitive and high-temperature materials that EBM becomes one of the most suitable methods of processes, independent of high temperatures like titanium alloys and nickel superalloys. The EBM process is usually quicker in build than the SLM, however the surface quality is usually worse and the resolution of features is less.

Directed Energy Deposition (DED):

The extensively flexible nature of ded processes provides more flexibility than PBF. Dploid of depositing material at angles and on non-planar surfaces means that DED is suitable as a technique to repair high-value parts, by addition to existing parts as well as in production of large-scale structures.

Laser Engineered Net Shaping (LENS) LENS is a DED process that involve the formation of a melt pool on a substrate by a high-power laser which in turn receives the injected metal powder material through a nozzle. This is printed by placing the nozzle onto a multi-axis robotic arm or a multi-axis gantry to be able to control the position of the material being deposited. Turbines Blades LENS can commonly be applied to repair turbine blades, molds as well as other high-wear items.

Electron Beam Additive Manufacturing (EBAM): EBAM is one more DED technique which allows an electron beam that fuses a wire feedstock. EBAM has high deposition rates that are very high and therefore, it is applicable to large scale metal parts that are to be produced fast. It is done under vacuum and similarly, provided a clean and controlled build environment.

Binder Jetting (BJ):

Binder Jetting is a cold printing technology that makes it distinguish itself among the fusion based printing techniques (PBF and DED). This is done through the selective coating of a powder bed and depositing a layer by layer. The resulting green portion is now pulled off the powder bed, and fired in a furnace to obtain its ultimate density and strength. The main benefits of binder jetting are the high build speed rate, the fact that it can produce large parts and large batches consisting of smaller parts, and a large variety of materials can be processed. Sintering is the main problem of binder jetting, and it could not be controlled easily, and the part could be shrunk and distorted. The eventually parts are also likely to have more porosity than the parts made through PBF or DED.

The Palette of Printable Metals: Properties and Performance

Investing in a metal AM part is a crucial element to the showcasing and aptness of the part concerning what the job task might need with their selected material. In this section the properties of most popular metal alloys commonly used in AM are analyzed more in details.

Titanium Alloys, Alloys Ti-6Al-4V): This type of alloy is the workhorse of the aerospace sector as well as the medical sector. Their strength to weight ratio is high, they possess high resistance to corrosion and they are biocompatible thus can be used in aircraft ultimate structures, engine operating parts and in orthopedic implants. The Ti-6Al-4V commonly produced by additive manufacturing is characterized by a fine acicular microstructure of the alpha - high strength 2 7 martensite. Nevertheless, there is also a chance that this microstructure might test low ductility in comparison to wrought one. Heat treatment The heat treatments done on post processing are usually done to modify the microstructure and to enhance the development of the strength-ductility balance.

Nickel Superalloys (e.g., Inconel 718, Inconel 625): These are used in high temperature applications and they require high strength of limiting extreme conditions of heat, pressure and corrosion. They have wide applications in gas turbines, rockets and nuclear reactors. Nickel superalloys that are susceptible to solidification cracking make their AM difficult. Nevertheless, by paying appropriate attention to the process parameters, fully dense parts exhibiting high mechanical characteristics at high temperatures can be obtained.

Stainless Steels (e.g., 316L, 17-4 PH): Stainless steels An austenitic stainless steel, 316L, offers good corrosion resistance and biocompatibility as discovered, and an even better option is a high strength, hard martensitic stainless steel, 17-4 PH. Stainless steels AM is quite developed, and the parts can be obtained that possess property surpassing or even equal to that of a wrought material.

Aluminum Alloys (e.g., AlSi10Mg): As materials, aluminum alloys are in low density, with a high thermal conductivity; they also exhibit good corrosion traits. They are mainly used in the automotive and the aerospace industry in areas where weight is a major factor to be taken into consideration. AM is difficult to do in aluminum alloys because alloys are highly reflective and thermal conducting and therefore it may be difficult to get a stable melt pool. Nevertheless, superseding alloys and optimal manufacturing conditions, high-quality aluminum components with desirable mechanical characteristics can be manufactured now.

Cobalt-Chrome Alloys (e.g., Co-Cr-Mo): Most medical and dental uses of these alloys inculcate orthopedic implants dental crowns and braces, and so on. They are characterized by high level of biocompatibility, resistance to corrosion and wear resistance. Co-Cr implants can be custom made to fit a particular anatomy of the affected person and this is possible using metal AM resulting into better coverage and functionality.

Industrial Applications: Transforming Manufacturing

In many major industries, the use of metal AM is influencing the industry in a significant manner. This brief gives a closer examination on some of the greatest uses.

Aerospace: Aerospace industry has led in using metal AM. The capability to manufacture lightweight and intricate parts is one of the key strengths in an industry where a gram of weight saved in the production results in great savings in the fuel costs. Only the LEAP engine of GE Aviation with the capability of 19 3D-printed fuel nozzles is a bright example of the potential revolution of metal AM. With AM it was possible to consolidate 20 separate parts into one and more efficient component which was also lighter in weight. Other uses in the aerospace industry are manufacture of brackets, turbine blade, and satellite parts.

Medical: The other domain that metal AM is affecting extensively is in the medical field. It is transforming orthopedic or maxillofacial surgery as the capacity to fabricate implants that are customized to patients. Based on the anatomy of the patient, specific types of hip implants, knee implants, or spinal cages can be produced and developed so that there is a perfect fit, resulting in improvements in the most successful surgical procedures and improved recovery. Dental implants, surgical instruments and surgical anatomy models based on metal AM are also manufactured.

Automotive: Metal AM is being utilized in the automotive industry in numerous ways, such as rapid prototyping up to manufacturing of final products. During the design and development process, AM can also facilitate the quick development of prototypes of the cc/fits and functional level which makes the doors to buttercup cars very wide. Complicated and weightless parts of high-practical and glamour vehicles, including brake calipers, exhaust manifolds, and turbocharger components, are also being manufactured using metal AM. More, the technology is also being used in the fabrication of bespoke tooling and jigs that can enhance the efficiency/accuracy towards the manufacturing process.

Tooling and Molds: Metallic AM is also becoming popular in producing complex tooling and molds where conformal cooling channels are to be used. These cooling channels follow the fusion of the mold cavity that enables their models to received a greater and more efficient cooling that leading to the reduction of cycle time and enhancing the quality of the molded parts. This is a great gain in the injection molding industry since plenty of savings in the cycle time may translate in immense cost savings.

V. Discussion

As the contemporary study of the metal additive manufacturing technologies, materials and application shows, it is a field characterized both by intense development and high obstacles. This section involves providing a critical evaluation of the implications of this discoveries, drawbacks of existing state of technology and their changing effects of the manufacturing boundaries in the world.

The primary justification of the metal AM takes place is an ability to create more complex geometries that are hard or unfeasible to fabricate using the conventional exportation triggers. It is a first of its kind game changer since engineers are able to design items, more efficient to serve a game, and one could have that of an internal cooling conduit, lattice structure, or assembly group. Others include notable effects such as being able to make lightweight parts or parts within the aerospace and automotive industry sector where weight reduction is one of the key performance parameters. The case of GE LEAP engine fuel nozzle is a solid example of what AM can do with AM to come up with even efficient and lightweight products.

Nevertheless, there are no smooth sails on the way to the global use of metal AM. The budget constraint in the cost is a leading hindrance to several firms. Initial costs on a metal AM system may be incurred on the scale of the initial investment, and a metal powder is costly as compared to the traditional raw materials. Another factor which makes AM not so economic in high volume production is the relatively slow rates of building large parts. The binder jetting is promising to be able to make the process faster in throughput but, similar to any growing technology, the difficulties posed by the sintering mechanism should be resolved.

The second weakness that can be mentioned against metal AM is that it requires a significant amount of post-process. The final lead time specifications are often meticulously obtained owing to the heat treatment, removal of support structure, and machining of the as-built components with surface roughness, as well. The following steps might also be costly and time-consuming and even can de-merit the input benefits of AM process. The most significant research perspective is the development of efficiencies in more automated methods of post-processing.

Quality assurance and standardization is also a big challenge to the metal AM industry. The quality and consistency of additively manufactured components is important, particularly in theraerospace and medical sector which is characterized by applications that are of particular concern. No established standards and qualification processes make up with companies that have difficulties in qualifying the AM parts to use them in their products. The in-process monitoring and controlling system and the non-destructive testing methods are the major processes that have to be developed to give the reliability and repeatability of the AM process.

Nonetheless, despite all these, the transformational impact of the metal AM to manufacturing industry cannot be ruled out. The inevitable technology is enabling an apocalypse shift to a design that it can manufacturably model/paradigm towards which the existent paradigm that is present in the manufacturing sphere is more than runs the capability of any of a single bit of a system to be designed. The outcome of this is the emerging and innovative products which perform and have better functionality.

To a greater extent, it is possible that the conventional supply chains can be disrupted by metal AM. It is able to reduce enormous stock levels and lead time utilized because format generation of components may happen on-order and where it is needed. This can lead towards leaner and resilient supply markets and this quality is more significant now with the modern changing global market. It is bringing the concept of a digital warehouse, whereby digitized records of the parts can be stored, and printed on-command, to reality.

The environmental impact of the existing metal AM is a complex topic, which has possibilities as well as various drawbacks. To the one hand, AM may lead to the necessity of the underlying economy of materials since such a process is additive that creates far less waste in comparison to subtractive technologies of production. The products also can be made using lightweight components, which leads to the ability of products to use less energy when they are at the product use stage. On the other hand, there are sources of metal powder production that can be regarded as energy intensive process and certain AM systems can be regarded as energy intensive. The life cycle assessment on the environmental impact of metal AM is a complicated project that will need to provide a comprehensive understanding of the same.

In conclusion of the debate on metal additive manufacturing, it is illustrations one of the most powerful and disruptive technologies that can reshape the designing and manufacturing of products. Even though some of the problems that must be resolved are still quite essential, the technology of this type evolves extremely fast, and the benefits of the technology are becoming more evident. Since the technology remains in its infancy up to date, not to mention all the equipments and materials continue to be less expensive, one may even expect to see metal AM being widely more deployed to many industries of all sizes.

VI. Conclusion And Future Directions

Properly consolidated metal additive manufacturing has become part of the fourth industrial revolution central leadership, as a quick and cost-effective prototyping tool and even as a lower, cheaper, but still an alternative that no longer feels need or respect as inferior yet, should remain available. It is this history of metal AM that has been allowed to explore further the horizons inside into the thinking of its founding technologies, the night and day of an ever-widening palette of printable alloys, and the many applications candy of the wide variety of metal AM that can be active presently in large industrial zones. The obstacles that consistently check the unconstrained desire of this technology have also been brought into light in the analysis including the issue of cost, magnitude, danger risk of quality, and the demand of a higher interpretation regarding the complexity union of the process, material, and performance.

The metal AM has had an impressive evolutionary road, with the constant advancement in the technology of machines, materials science, and software. Having the capability to produce parts of unequalled geometric complexities, integration of several parts into one, lightweight as well as more complicated parts, and personalization of medical implants to the special requirements of the affected patients are just to name but a few the paradigm shifting opportunities of this kind of technology. The case studies in the industry, especially those involved in the aerospace industry and the medical industry, demonstrate the tangible advantages of metal AM, such as improved performance, the decrease of lead times, and the chances to be able to create more resilient and regionalized supply chains.

The direction of the metal AM in the future will however be determined by how far the research and industrial communities can keep the technology within the current challenges as well as reach new levels with the current technology. Some of the major future directions that are going to influence the scenario of the metal additive manufacturing are as follows:

Development of New Materials: Although the number of princible metal alloys is increasing, new alloys with properties specific to AM specific thermal environment must be developed. This encompasses alloys that are higher in terms of weldability, greater strength and capacity to endure higher temperatures and greater corrosion and wear. The emergence of the ability to print in multi-materials will also determine possibilities in producing assemblies with functional grading of components with customized properties.

Efficient Process Tracking and Control: The chance to monitor and manage the process at 2D is one of the challenges of additive manufacturing that makes and produces high quality and consistent parts. In-possessing advanced sensors that will be in the form of high-speed camera system, pyrometers, and acoustic sensors will provide a surplus of information on the parameters of melt pool dynamics, temperature distributions, and defect formation. The most important part of getting there to first-time-right manufacturing will be an essential step of acquiring an artificial intelligence and machine learning algorithms to process such data and characterize the feedback to closed-loop control.

Hybrid Manufacturing Systems: One possible solution to the drawbacks of isolated AM systems is to have the additive and subtractive manufacturing models integrated into a hybrid system to combine the benefits of each. These hybrid types are capable of generating parts having the geometrical fabrication of AM and the finish on the surface and concentration of machining all achieved on the same platform. This may greatly contribute to savings in the time and cost of post-process.

Standardization and Qualification: Lack of industry standard and qualifying procedure is a huge setback in enhancing the adoption of metal AM to employ in a high-paced application. In order to establish confidence in the technology and to ensure the correctness and dependability of the additively manufactured components, the development of a potent system of process validation, material characterization, and products certification of separate components is in order.

Design for Additive Manufacturing (DfAM):To capitalize in totality of metal AM, engineers will need to be redesigned according to another philosophy of design. Design for Additive Manufacturing (DfAM) is a collection of principles or tools, that can be utilised in facilitating engineers to design parts that are optimally applicable in the AM process. It includes optimization of the topology, generative design and lattice structures as a topology design measure to create light weight and high performance components. A more usable program that is coined by some smart design will be used in executing vital functions of establishing extensive use of DfAM.

Sustainability: As more people come up to use metal AM it is seen that its impact to the environment must be put into consideration. To ensure additive manufacturing is prone to causing a more sustainable future in the manufacturing industry would require a more energy efficient version of AM process, development of a recyclable metal powder, and space age study of the life cycle assessment of manufacturing of metallic goods.

In conclusion, metal additive manufacturing is a developing process, which alternates quite rapidly, and may alter the appearance of the manufacturing of the future. Full of technical and financial hurdles passed it is most certain to be in the way. However, with further development, innovation and collaboration between in generation and industry, with the help of metal AM, one can optimistically hope that new generational possibilities of design and performance, manufacturing efficiency would open this door, which will surely make us be regarded as one of the enabling technologies of the future.

References

[1]. Aboulkhair, N. T., Everitt, N. M., Ashcroft, I., & Tuck, C. (2019). Reducing Porosity In Alsi10mg Parts Processed By Selective Laser Melting. Additive Manufacturing, 28, 1-10.

[2]. Debroy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., ... & Zhang, W. (2018). Additive Manufacturing Of Metallic Components–Process, Structure And Properties. Progress In Materials Science, 92, 112-224.

[3]. Froes, F. H., Boyer, R., & Dutta, B. (2019). Introduction To Additive Manufacturing. In Additive Manufacturing Of Titanium Alloys (Pp. 1-13). Elsevier.

[4]. Gokuldoss, P. K., Kolla, S., & Eckert, J. (2017). Additive Manufacturing Of Metallic Materials: A Review. Journal Of Materials Research, 32(11), 1983-2000.

[5]. Gonzalez, J. A., Mireles, J., Moore, C., & Liu, Y. (2019). Metal Binder Jetting: A Review. Journal Of Manufacturing Science And Engineering, 141(9).

[6]. Herzog, D., Seyda, V., Wycisk, E., & Emmelmann, C. (2016). Additive Manufacturing Of Metals. Acta Materialia, 117, 371-392.

[7]. Koutiri, I., Pessard, E., Peyre, P., Amlou, O., & De Terris, T. (2018). Influence Of SLM Process Parameters On The Surface Finish, Porosity Rate And Fatigue Behavior Of As-Built Inconel 625 Parts. Journal Of Materials Processing Technology, 255, 516-526.

[8]. Kürnsteiner, P., Wilms, M. B., Weisheit, A., Gault, B., Jägle, E. A., & Raabe, D. (2020). High-Strength Martensitic Steels By Additive Manufacturing. Acta Materialia, 189, 29-41.

[9]. Mellor, S., Hao, L., & Evans, R. (2014). A Review Of The Application Of Additive Manufacturing For The Fabrication Of Tooling In The Automotive Industry. International Journal Of Production Research, 52(17), 5035-5047.

[10]. Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., ... & Chmielus, M. (2021). Binder Jetting Additive

Manufacturing–From Process, Material, And Machine To Part Performance. Progress In Materials Science, 115, 100699.
[11]. Sames, W. J., List, F. A., Pannala, S., Dehoff, R. R., & Babu, S. S. (2016). The Metallurgy And Processing Science Of Metal Additive Manufacturing. International Materials Reviews, 61(5), 315-360.
[12]. Sing, S. L., Kuo, C. N., Shih, C. T., Chen, C. H., & Lai, P. H. (2022). A Comprehensive Review Of The Application Of Additive Manufacturing In The Aerospace Industry. Journal Of Materials Research And Technology, 17, 2230-2253.
[13]. Singla, A. K., Banerjee, P., & Sharma, A. (2021). Additive Manufacturing In The Medical Industry: A Review. Materials Today: Proceedings, 46, 4192-4198.
[14]. Takaichi, A., Nakamoto, T., Joko, N., Nomura, N., & Tsutsumi, Y. (2013). Microstructures And Mechanical Properties Of Co–29Cr–6Mo Alloy Fabricated By Selective Laser Melting Process For Dental Applications. Journal Of The Mechanical Behavior Of Biomedical Materials, 21, 67-76.
[15]. Thompson, S. M., Bian, L., Shamsaei, N., & Yadollahi, A. (2015). An Overview Of Direct Laser Deposition For Additive Manufacturing; Part I: Transport Phenomena, Modeling And Diagnostics. Additive Manufacturing, 8, 36-62.