Chapter

An Investigation of the Metal Additive Manufacturing Issues and Perspective for Solutions Approach

Omar Ahmed Al-Shebeeb

Abstract

Metal Additive Manufacturing (MAM) is delivering a new revolution in producing three-dimensional parts from metal-based material. MAM can fabricate metallic parts with complex geometry. However, this type of Additive Manufacturing (AM) is also impacted by several issues, challenges, and defects, which influence product quality and process sustainability. In this chapter, a review has been made on the types of small to medium-sized metallic parts currently manufactured using the MAM method. Then, investigation was undertaken to analyze the defects, challenges, and issues inherent to the design for additive manufacturing, by using MAM method. MAM-related obstacles are discussed in depth in this chapter and these obstacles occur in all size of metal printed parts. The reasons and solutions presented by previous researchers of these obstacles are discussed as well. A potential approach based on the author's knowledge and analysis for solving these issues and challenges is suggested in this chapter. Based on the author's conclusion, the MAM is not limited by part size, material, or geometry. In order to validate the potential solutions developed by the author of this work, performing actual MAM process is required and a local visit to manufacturing factories are also important to visualize these challenges and issues.

Keywords: metal additive manufacturing, powder bed fusion, direct metal deposition, MAM alloys, MAM problems, 3D printing

1. Introduction

The manufacturing field has developed tremendously in the last decades. Today, transforming raw materials into useful parts or products (by using different manufacturing processes) is nearly unlimited. The manufacturing research is always focusing on developing and using manufacturing processes with lower cost and waste, and higher production rate. Currently, there is fast and high variation in the design of products, and very high market competition because of global competition. Design for Additive Manufacturing (DFAM) is one of the important methods for obtaining this global competition in terms of manufacturing.

Additive Manufacturing (AM), is a type of printing (3D printing) method used to create three-dimensional products by laying the fused material layer by layer.

AM is the current and dominant future manufacturing method [1]. AM processes are considered easier as compare to subtractive processes represented by machining and other manufacturing types. This is because of producing a part through one AM process is more effortless than producing the same part through several subtractive manufacturing processes (such casting then machining). Subtractive manufacturing processes often require millions of dollars, while using AM processes can offer the same manufactured parts at a fraction of the cost, and in less than half the time [2]. In addition, manufacturing the part in one process eliminates the need for several skilled workers (which subtractive manufacturing requires), in lieu of a single knowledgeable worker.

AM is the future face of the industry, not just in manufacturing field—printing technology has even been used to construct buildings in recent years. However, the MAM process for producing small and medium size metallic parts also present difficulties and issues. These difficulties may be inherent to the MAM process itself, such as selecting the right MAM process, adjusting support materials, building direction, geometry (complexity) of the part, and printing orientation. All these difficulties might lead to some issues and defects in MAM products, such as porosity, variation in mechanical properties, microstructure evolution, residual stress, fatigue, and crystalline phase and more. In the next section a recent comprehensive literature review is presented to explain the main issues and difficulties facing MAM processes, in the production of small and medium size parts.

2. Literature review

Additive Manufacturing (AM) was employed for the first time in 1987, through use of a stereolithography (SLA) system to build the first three-dimensional model (solidifying a thin light-sensitive layers liquid polymer by using ultraviolet [UV] rays) [3]. Starting in 2017, manufacturing companies focus began orienting manufacturing processes in a new direction; these companies started to depend on AM methods to produce parts. AM methods have grown over the last year, becoming the key area of interest for many such companies [4]. However, the main focus of this literature review related to the MAM method for producing small and medium metallic parts—and asking what the main issues and challenges facing this process are.

This concerns frameworks for selecting the right MAM process, adjusting support material, building direction, geometry (complexity) of the part, and printing orientation. Some of these challenges can interrupt the process itself and cause other issues (such as defects in the final manufactured product, including: porosity, variation in mechanical properties, microstructure evolution, residual stress, and crystalline phase heat accumulative and thermal behavior). Inspection difficulties in MAM have been investigated, with the conclusion that inspection ability and metallurgical validation of highly optimized shape must be integrated with product design and process parameter during and after the CAD design [5]. Several challenges facing MAM methods have been investigated, such as financial consideration, certification and regulation, repeatability, and skills gap. Some suggestions have been made to eliminate these challenges and this researcher discusses further potential solutions for these challenges [6]. Serena et al., studied the difficulties and challenges to be facing when designing for metal additive manufacturing in Selective Laser Melting Additive Manufacturing (SLM AM) process for producing professional sport equipment (medium size cam component). These difficulties, such as functionality, manufacturability, assembly, and printability. All of these difficulties should be considered in the designing of metal additive manufacturing. They present many suggestions to enhance the redesign and printability the cam system [7].

Chergui et al. studied the schedule problem and nesting in production of MAM method by developing mathematical model in Python with a heuristic approach. The heuristic approach has been explained step-by-step as a result, improving the scheduling and nesting problems [8]. Bradley et al. created a seven degree-of-freedom, dual-arm hydraulic by using the SLM method for subsea use. Researchers have described the hydraulic system and how they created the titanium manipulators for Naval research. They have also discussed lessons learned throughout the project and process (design) changes for the future [9]. For particle size, heat treatment, shape analysis, and hardness testing, microstructural analysis in MAM, several solutions have been presented, discussed and applied [10].

Li et al. have discussed the residual stress issue in printing metal parts due to rapid heating rate, rapid solidification with high cooling, and melting back the layers that previously melted. They used Powder Bed Fusion (PBF) and Direct Energy Deposition (DED). This work was performed on small and complex geometry parts of nickel based super alloys, titanium alloys, and stainless. The results showed there is a connection between the residual stress and microstructure: the residual stress has been measured in both as-build metal part and post-processed [11]. Reza Molaei and Ali Fatemi have reviewed the main factors that influence fatigue behavior in producing metal parts. In this review, they have collected some multiaxial fatigue data for Selective Laser Melting (SLM), which is based on Powder Bed Fusion (PBF). They used titanium alloy (Ti-6Al-4 V) as metal powder for printing small sized parts [1].

In terms of energy consumption in MAM, and how it affects the quality of parts produced by MAM methods, ZY Liu et al. have studied the effect of energy consumption on microstructure and mechanical properties. Researchers have also used different types of metallic parts to perform investigations on both the machine and the process levels. On the machine level, they have studied the high-energy tool, control system, and cooling system whereas on the process consumption level, they have investigated energy flow distribution [12]. Bintao et al. reviewed the defects occurred in Wire Arc Additive Manufacturing (WAAM) related to microstructure and mechanical properties (deformation, porosity, and cracking) for high scaled fabricated components and high deposition rate. They used different size of metallic parts for different alloy types (Titanium Alloy, Aluminum Alloy and steel, Nickel based super alloy, and other alloys). Researchers concluded that WAAM is still facing many challenges in producing different materials. The WAAM needs to perform sustainable system in a reasonable time frame. There is a need to produce defect free products by using WAAM. Finally, they suggested ways to improve quality of the product [13]. Filippo et al. developed a methodology for cooling system (impinging air jet) in WAAM process to prevent heat accumulation which increases the workpiece average temperature and consequently affects the WP quality. They used small parts of Fe alloys in their study. Their results showed that the impinging air jet can prevent the heat accumulation on part produced by WAAM [14]. Bintao et al. used in-situ temperature measurement method to analyze the heat accumulation and thermal behavior in Gas Tungsten Wire Arc Additive Manufacturing (GT-WAAM) process. They used medium sized titanium alloy (Ti6Al4V) parts. The result shows that the microstructural morphology, crystalline phase, mechanical properties and fracture feature have been changed when the heat accumulation was along the building direction [15].

Xuxiao Li and Wenda Tan built a numerical model to investigate the three-dimensional grain structure in Direct Laser Deposition (DLD) for stainless steel 304 material. They enhanced the three-dimensional grain structure by using nucleation mechanism. The investigation showed that the nucleation mechanism used in this research could play a role in modifying grain structure in MAM method

[16]. Jun Du et al. developed and tested newly proposed AM method based on Metal Fused Coating Additive Manufacturing (MFCAM). This method is a combination of Fused Metal Coating and Laser Surface melting (bed-based process). They used small parts of 7075 aluminum alloy to prove the experimental work [17]. Christoph et al. developed a computational model to study the critical influence of powder cohesiveness on powder recoating process. Researchers focus on the relationship between the powder particle size and powder layer quality. Small parts of Ti-6Al-4 V were used in this study. As results from this study, decreasing the particle size (increase cohesiveness) will decrease the powder layer quality with highly non-uniform surface profile. In addition, the particle size plays the main role in mechanical properties of powder layer [18].

Lawrence et al. reviewed the development of droplet 3D printing (Droplet Additive Manufacturing). This process was used in producing large and small sized parts for three decades. They discussed the issues regarding process optimization, product structure and properties influenced by oxidation. Their investigation ended up with the conclusion that using the Droplet 3D printing process can change the structure of product, thereby reducing the weight, cost, and increasing strength [19]. Mercado et al. studied the stability and microstructure of large sized parts of nickel-base metal matrix produced by building Plasma Transferred Arc Additive Manufacturing (PTAAM) system; this process can build high scale 3D printed parts. Their study concluded that the PTAAM system has capability to build 3D printed part on nickel-base metal matrix with tungsten carbide wear resistance [20]. Yoozbashizadeh et al. developed new Novel AM method to fabricate medium sized bronze-aluminum parts with Ceramic. This process has been performed by combining Thermal Decomposition for Salt (TDS) method with Powder Bed AM (PBAM) to produce Metal Matrix Composite (MMC). Ceramic particles have been created from TDS, and then combined with bronze-aluminum to create MMC. This process is qualified for aerospace applications [21].

Livescu et al. faced challenges of AM tantalum represented by high melting temperature via utilizing Direct Metal Laser Sintering (DMLS) method. Deposition parameters such as deposition speed and building direction have been analyzed as significant factors to influence on Grain morphology, grain size, crystallographic, and deposition porosity. The authors' results showed that the obtained structure was columnar along the building direction. The deposition condition (speed) has significant effect on microstructural variation. The strip width has the main influence on grain growth [22]. Thao Le et al. tried to combine additive and subtractive strategies to manufacture new part (final part) from end of life part (existing part) by using several additive and subtractive manufacturing processes. They obtained good mechanical properties in final parts. The methodology of combining additive and subtractive manufacturing can be applied by generating process plan for both of them [23].

3. Methods used to create small and medium parts in MAM by factories

Additive Manufacturing (AM) technology, in general, qualifies to build fully functional part in one process without the need for metal removal process which would waste significant amount of raw material. In addition, this process can give more flexibility to the designer in building complex geometry part. Compared to the AM method, the Traditional Manufacturing Technology (TMT) (subtractive manufacturing) has several manufacturing processes. The first level mostly deals with creating the stock material (raw material), and the next level is responsible for material removal process which usually includes several manufacturing processes to obtain the final parts. Currently, the diversification of AM method can be used with variety of materials; it is possible to manufacture metallic parts with high quality and complex geometry by direct and indirect AM method.

3.1 Powder bed fusion meal additive manufacturing (PBF-MAM) process

There are two main categories in MAM method: Powder Bed Fusion (PBF), which is also known as Layer Based Metallic Additive Manufacturing, and Direct Metal Deposition (DMD) [24]. PBF method is based on inert atmosphere or partial vacuum, and it produces parts layer by layer with thickness of 15–20 μm. The energy source for this MAM category is laser or electron beam which is used to fuse and bind the material (powder) on each layer. Whenever the binding of a layer will finish, the table will move down, and new layer of powder will be poured on the previous one and so forth until the part is completed. For preventing the molten (sintered) between one layer and another in substrate, there is a need to use support material which can be made in the pre-processing phase from the same material [24].

3.1.1 Selective laser sintering

The Selective Laser Sintering (SLS) was the first powder-bed based AM process. This process was invented by Ross Householder in 1979 and the first material used in it was amorphous polymer powder or semi-crystalline [3]. The power source in this process was laser, and it was used to sinter (bind) the powder material. First, the model of the printed part needs to be defined by CAD design, the thickness of the layer needs to be specified, and the resulting model will be transferred to the machine software to orient the CAD model in the 3D printer software. The MAM process starts by aiming the laser on a profile representing the shape of the first layer as described by the CAD model from the base of the printed part. The laser power binds the powder layer by layer to create the final part. The new materials which could be produced by this process include ceramic and metallic alloys. The last step in this process is placing the printed part in an oven to remove the polymer (used to bind the particles), sinter the part, and improve the support material. Since this process has high production rate, it is used for rapid manufacturing or prototyping [24, 25].

3.1.2 Direct metal laser sintering

Direct Metal Laser Sintering (DMLS) process was developed by Electro Optical Systems (EOS) in the 1990s. It was used purely for building metallic parts without using the polymer to bind the particles. High power laser was used to melt the metal powder in two dimensions layer by layer. This process offers printed parts with complex shape and geometry with a reasonable cost. The DMLS process utilizes a variety of metals and alloys and operates on the same concept of SLS AM process. The residual stress in product parts is an issue with this process and will be discussed in Section 6.2.1 of this chapter [26].

3.1.3 Selective laser melting

The Selective Laser Melting (SLM) additive manufacturing process is designed to fully melt the metallic powder by using high power-density laser. Therefore, it is considered more powerful and produces parts with better quality and less porosities than either SLS or DMLS processes. At the same time, it works on the same powder-bed concept of both techniques. Because of high temperature of the laser source, shrinkage and thermal distortion are likely to influence the printed parts [27].

3.1.4 Electron beam melting

The Electronic Beam Melting (EBM) is also a powder-bed additive manufacturing process. The difference between EBM and other powder bed AM (SLS, DMLS, and SLM) processes is the source of energy; EBM utilizes electron beam instead of laser. This process was invented by Arcam in 1997. The electronic beam provides higher energy density than laser. This makes the EBM process more flexible with metallic alloys. Nevertheless, this has a drawback of increasing the chances of shrinkage. The EBM has a high scanning speed (several kilometers per second) which helps to reduce heat accumulation between the layers and improves quality [24].

3.2 Direct metal deposition additive manufacturing

Direct Metal Deposition (DMD) additive manufacturing method was invented by Precision Optical Manufacturing (POM). The metallic powder or wire used in the DMD is sprayed directly onto the laser beam or the electric arc beam. The beam melts the metallic powder or wire by the laser or electric arc heat source, then the molten metal drops on bed to build the part layer by layer. Because of that, it is called direct deposition process and not powder bed in DMD. There is a possibility to build multilateral parts from various metallic alloys. To produce complex geometry parts, the nozzle is placed onto a 5-axis CNC machine to offer more flexibility in the movement of the nozzle. Several factors control this method of MAM: layer thickness, deposition rate, nozzle feed rate, laser power, gas flow, and the gap between the nozzle and printing surface [3]. The DMD can be divided into several processes; the next sub-section outlines the main processes of DMD.

3.2.1 Wire arc additive manufacturing

The Wire Arc Additive Manufacturing (WAAM) is used to build large components of titanium, aluminum, steel, and other metals. In this method, arc welding tool and wire (feedstock) are required to perform the process. This process is distinguished by high deposition rate, low material and equipment cost, variety of used materials, and good structure. These features make WAAM process dominant over the other current methods of manufacturing [28].

3.2.2 Gas tungsten-wire arc additive manufacturing

Gas Tungsten-Wire Arc Additive Manufacturing (GT-WAAM) is the same as WAAM process with one difference; a localized gas tungsten shielding is used in GT-WAAM. The tungsten reduces the oxidation on the surface and increases the quality of the layer [15]. There are methods of Direct Energy Deposition (DED) available, and they function on the same concept of WAAM and GT-WAAM (welding method) and they are as follows:

1. Plasma Arc (PA)

2. Gas Metal Arc (GMA)

3. Plasma Transferred Arc (PTA)

4. Laser Beam (LB)

5. Electron Beam Freeform (EBF)

4. Metal additive manufacturing materials (alloys)

Several metals (alloys) can be utilized in the MAM method. In this section, the most important metals (alloys) are listed as follows:

1. **Aluminum alloys:** Al-Si, Al-Si-Mg, and AlSi10 are the most commonly used aluminum alloys for the MAM method. These materials can be used for powder-bed fusion especially in DMLS and SLM process. Performance of these alloys can be enhanced by adding Zr and Sc. Wire based additive manufacturing also uses the aluminum alloys. Aluminum powder is good for parts with thermal properties and low weight, and it is a relatively better choice for parts with thin wall and complex geometry. According to current studies, the aluminum alloys will be the major metal in MAM [29].

2. **Titanium alloys:** Ti6Al47 is the dominant titanium alloy; it can be used for the MAM method. This alloy is mainly implemented with SLM, EBM powder-bed and other MAM processes. However, printing parts with these alloys exhibits residual stress and fatigue as defects which affects the quality of the parts. Ti64 is also assigned as a common titanium alloy for MAM. It has high corrosion resistance and is implemented with DMLS-MAM process. The part produced by this process can be used for medical application, aerospace, firearm, and automotive parts which require high corrosion resistance [9, 15].

3. **Iron-based alloys:** Different types of iron alloys can be utilized in MAM method: 316 L stainless steel, 314 L stainless steel, 15–5 stainless steel, 17–4 stainless steel, and Fe-6.9% Si, maraging steel MS1 and more. These iron-based alloys can be used in powder-bed fusion methods, such as SLM and DMLS. The MAM parts produced from stainless steel can be used for high corrosion resistance and strength applications such as medical, firearms, energy and automation, and tooling applications [30, 31].

4. **Super nickel/chromium alloys:** Nickel/Chromium alloys include IN718, IN625, HX, MK500, and Haynes 282. The parts produced from the powder of these alloys have excellent heat and corrosion resistance with hardness of 40–47 HRC. Different sized parts can be produced from these alloys with different applications such as rockets, space, aerospace, firearm, energy, and automotive. DMLS and SLM MAM methods can also be used with these alloys [11, 30].

5. **Other alloys:** The above-mentioned alloys are the most famous alloys which are used to produce parts by MAM method. However, there are other types of metals that can be utilized to produce parts by different processes of MAM method. Some of these metals can be a real challenge to be melted layer by layer from their powder. For example, Inconel 718 is utilized by EBM process, Inconel 625 is produced by SLM process, copper is printed by EBM process, and Fe65Cu17.5Ni17.5 is printed by SLM. Most of these metals (alloys) can be used to produce parts for different applications, however some of them are still in the stage of study [29].

5. Parts size produced by MAM

MAM method has no limitation on size, shape and geometric complexity. Small, medium and large sized parts with complex geometry can be obtained from MAM method. For example, different size and geometry of gears, pistons, pullies, junctions, turbines, manipulator arm, robot arm, fins, rocket, firearms, automobile parts, impellers, fans, and medical tools. However, printing these parts by the MAM method without difficulties and issues is a challenge. This will be discussed in the next section.

6. Metal additive manufacturing (MAM) challenges, issues, and approached solutions

Metal Additive Manufacturing (MAM) is a process used to fabricate and repair parts that have a complex geometry or need to be functionally graded. The process can be performed by depositing multiple layers to produce the required part. Several MAM methods can be used to manufacture metallic parts. They are categorized into two types according to their method of performing (Direct Metal Deposition and Powder Bed Fusion). A successful manufacturing process depends on the deposition technique used, the parameters selected, and the materials used. Moreover, the MAM depends on deposition conditions such as temperature and protective atmosphere to determine whether cracking and oxidation of the deposited layers occurred or not. In the present study, the MAM methods are discussed and evaluated for different manufacturing parameters and deposition conditions for different metallic materials. Multiple challenges and issues encountering the MAM methods will be discussed in the next sub-sections. This study has shown that some suggested solutions can be successfully processed by MAM by using different methods. A significant number of MAM methods are being utilized these days.

6.1 MAM challenges, issues, and approached solutions

Despite the ability of the MAM method in reducing the complexity of parts to simple 2D slices and machining super hard alloys, the MAM method is still suffering from several issues and challenges which are interrupting its progress. In this sub-section, these challenges and issues will be discussed, and the solution approached by the author will be presented.

6.1.1 Lack of knowledge of design for additive manufacturing

Understanding how the materials work in MAM and how the metals are printed layer by layer to print three dimensional models are big concerns in the design for additive manufacturing. Lack of understanding the differences between plastic 3D printing and metal 3D printing can lead to parts with low quality, high defects, and high probability of failure. Skills gap in MAM method is considered an important issue. The knowledge of transferring several subtractive manufacturing processes to one metal additive manufacturing process is a big step. Selecting the appropriate metals (powder or wire) to print the parts and the appropriate process requires a significant amount of knowledge. Also, understanding the orientation of parts and adjusting the support materials in right place by using the printer software before printing is important to obtain desirable quality and characteristics. Similarly, printing high quality parts with complex geometry is also a big challenge with the MAM method, especially when printing aerospace or firearm parts. Therefore, lack of education issue can cause companies to lag or fail in performing successful MAM.

6.1.1.1 Proposed solution

Well-trained workers or engineers and skilled workforce are necessary to diminish this problem. Building and finding capable workforce is not easy and requires effort and time. It also requires a significant work to shift into new, important method such as MAM. To enable the transition between general AM and MAM, more focus is needed on hiring well educated people in this field. Transition process from conventional manufacturing to MAM does need to shrink the workforce. Small workforce is required in MAM. For example, traditional manufacturing system needs 12 skilled workers and 7 engineers to run and manage the system, but MAM system might only require two well-trained, knowledgeable engineers to perform the same work. Building new techniques such as generative design and generative orientation is also beneficial to perform this transition. Finally, in the opinion of author, transformation to MAM should be executed by an educated and a knowledgeable workforce. This could be obtained by creating a custom plan for every company about the transmission and the risk of it.

6.1.2 Repeatability

The MAM method is still facing a lot of variation in parts. The problem that companies encounter is to create two similar parts, then make these parts repeatedly. America Makes Company is still suffering from this problem in MAM and only 30% from the produced parts meet the specifications of the company. In addition to this problem, the MAM method is also suffering from mass production process [2].

6.1.2.1 Proposed solution

The repeatability inside the MAM system can be acquired by developing the standardization of quality. A standardization should be set for the MAM process. This standardization should be developed after a massive study on every MAM process and from this study several factors, such as MAM process type, printing time, environment, used materials, part size, production rate, complexity of the part, functionality and process setting need to be discussed and assigned to standardize the process. All these factors need to be organized and assigned inside specific range which can provide the quality that is required to obtain the repeatability.

6.1.3 Selecting an appropriate MAM process

Every MAM process has different strength and ability to produce specific metallic part, whether the process is Powder Bed Fusion (PBF) or Direct Energy Deposition (DED) process. Using an appropriate process in MAM method will lead to produce defect-free parts. For example, using EBM process that has a high-power source will allow to produce a thicker layer, and will lead to high production rate. However, using the EBM process to produce tiny and complex part with lot of features will be a challenge because the residual powder in each layer will be semi sintered with thicker layer that will create part with undesired quality. Therefore, complex parts can be produced successfully on a SLM or DMLS system.

6.1.3.1 Proposed solution

Making MAM process selection map is a good solution for eliminating this obstacle. This map will contain inputs and outputs. The inputs will have process parameters, such as part size, part geometry, material used, quality and mechanical properties required, and design parameters. These inputs will be analyzed and addressed, then they will be matched with each MAM process capability. Finally, the outputs will be extracted from all of that and the priority of using the MAM processes will be ordered according to their fitness for printing the required parts.

6.1.4 Materials issues

Using the appropriate material (metal) for MAM is also a challenge in this process. The metals used for printing parts should match the selected 3D printing machine. MAM still faces problems in printing some metals, such as Inconel 718, Inconel 625, titanium, and tantalum. Secondly, some parts have multi-features in their design resulting in a variable mechanical properties for every feature. This will increase the probability of failure for these parts. However, it is worth mentioning that the list of metals can be used in MAM is still relatively short.

6.1.4.1 Proposed solution

Using multi-material (metal) machine will solve the problem of parts with multi features. These machines can provide appropriate material for every feature in complex parts. As a result, it will fix the issue of failure in these parts. Performing this solution is not easy and needs a lot of study to get the machine structure that will be used for printing multi-materials (metals). Especially, there is one important condition; the multi-materials can be banded together to create the final parts. This solution can perform with direct deposition MAM method because the multi-material can be melted separately and then combined, but it will be a big challenge with the powder-bed MAM method.

6.1.5 Heat treatment

The metal 3D printing is different than other types of 3D printing. In metal 3D printing, the printed metal part needs heat treatments to obtain the desired mechanical properties which meets the quality of printed parts. Since the MAM is shifting from rapid prototyping to the actual production: aerospace, firearm applications, highly customized parts, the heat treatments play a significant role in the cost and the quality of the part. Mixing different types of raw materials and creating alloys for machining, such as titanium steel, aluminum is not easy, but it can be done in MAM. However, the parts produced by MAM need heat treatments to obtain the desired mechanical properties.

6.1.5.1 Proposed solution

Producing metal part in MAM method without internal stress is an issue in additive manufacturing. Some MAM machines have heat treatments in their structure. Some produced parts in MAM require more levels of heat treatment to obtain specific mechanical properties, such as the elongation to failure and the fatigue strength. Excellent vacuum furnace is required to perform the heat treatment which eliminates the oxygen from entering the machine and obtain the required temperature control and deep vacuum level. Another issue with this process might be the cost of heat treatment itself. Producing vacuum furnace with these characteristics may cost $100 K, thus the cost of heat treatment part of titanium may reach $600. This solution of using high maintained vacuum furnace might give high corrosion resistance with excellent strength, toughness, and low weight part of titanium alloy. Therefore, this process should be used in producing parts having important and expensive applications.

6.1.6 Financial considerations

The cost of MAM method is an issue as compared to the plastic AM. The cost of some MAM machine may reach up to $350 k. The cost of facility and raw materials (powder or wire) is also expensive. Providing the metallic powder with specific particles size for expensive metals will also add capital expenditures. In addition, with all these expenses, failures in printing the parts will push such MAM companies out of business.

6.1.6.1 Proposed solution

A comprehensive study regarding this financial consideration should be performed. This study will be about the investment and profit that can be obtained with transition to MAM from traditional (subtractive) manufacturing processes. A criterion should be considered about the expenses and cost of MAM and compared to the capital expenditures of subtractive manufacturing. The entire cost for structure should also be noted. Moreover, an evaluation on the throughput and type of the parts being printed should be used to make a final decision about the transition from a subtractive manufacturing process to MAM. This decision should be made between company management because it will affect the entire company's structure including the supply chain.

6.1.7 Certification and regulation

The key of success for MAM is to obtain the quality and reliability required on the printed parts. Certification and regulation means assigning a customization and individualization to the additive manufactured part [2]. Certification process is considered as another challenge which manufacturing companies are suffering from in the MAM field. The MAM method without certification is a disadvantage, especially with the evaluation of the additive parts. Certification is important in the field of MAM in printing parts which requires excellent quality and reliability, such as aerospace industries, where the safety is the main requirement.

6.1.7.1 Proposed solution

MAM part should be certified by setting methods of measurement, monitoring, and control in order to acquire the desirable quality and reliability in parts. Then, the issues in parts will be addressed and analyzed to come up with some actual solutions. Better the measurement and control methods, better the results it gives which accelerates the certification of the MAM method. The measurement method is a trigger to develop standards for addressing these MAM issues and assigning solution to fix them.

6.1.8 Inspection difficulty

Producing complex and non-homogeneous MAM parts, which contains significant numbers of different features, requires high level of inspection. By assigning inspection, the quality of additive part can be retained. The importance of the inspection is equal to the importance of the measurement which has been mentioned in the previous section. Inspection and metallurgical validation methods should be integrated with MAM parts printing. That will allow the production of highly optimized shapes. According to the current study, there is a real need to build non-traditional inspection system inherent to the MAM parts manufacturing [5]. Now, traditional nondestructive inspection methods are used in the MAM method, and these methods are not enough to detect the defect during the printing process.

6.1.8.1 Proposed solution

Studies should be developed on the required inspection methods. Internal inspection needs to be performed during the printing process. It will act like a monitoring system during the process. In other words, layer inspection should be performed inherent to comparison with slandered. In layer inspection, the defects can be detected when it occurs. Let us assume that a very expensive and complex part is being printed. If there are some defects like undesired mechanical properties or porosities in the middle of printing, it would be wise to stop the process and fix the problem rather than rejecting the part after the expensive and time-consuming process is finished.

6.1.9 Scheduling

While increasing the demand and purchasing the MAM parts, the scheduling and nesting processes of metal parts to be printed plays a major role in manufacturing cost. It is beneficial in different ways, such as reducing the operational cost, reducing the parts price, and increasing profit for factories. This issue is also important in supply chain to schedule delivering or requesting metal parts. A very little literature has addressed this issue since it is still new issue [8].

6.1.9.1 Proposed solution

The scheduling issue is very important, especially with the rapid development of MAM method. Existing production planning and scheduling approach should be developed based on preliminary heuristic studies and models generated from this heuristic study. The scheduling should include all the sections of manufacturing system ranging from ordering the raw materials to delivering the metal parts to the customers. Based on that, scheduling system related to all sectors of MAM method with forecasting technologies can be used to organize the production line on MAM with optimal results.

6.1.10 Energy consumption

Energy consumption in MAM method is important to keep the sustainability of the MAM printing. However, it is affecting the microstructure and mechanical properties of the printed parts especially with metal 3D printing process that requires high source of energy, such as EBM process. This issue has a significant influence on the quality of the part.

6.1.10.1 Proposed solution

The relationship between energy consumption and printed metal parts with microstructure and mechanical properties should be analyzed to approach the solution of this problem. This solution can be implemented by using variable optimal energy density for every MAM process that depends on factors, such as part size, part geometry, and material used with strategies to reduce this consumption. Then, the variable optimal energy density map can be generated according to the characteristics of the part, 3D printing machine used, and used material. Therefore, the variable optimal energy used can be specified from the CAD model of the part. This can be done by inserting this CAD model on previously created software responsible for calculating the map of optimal energy density for the 3D printed metal part. This method of using the optimal energy might be useful to remove the undesirable mechanical properties and microstructure from metal printed part.

6.2 MAM defects

The most common challenges and issues that the MAM method faces have been discussed in the previous sections. MAM is a manufacturing process, and every process has its pros and cons. The part produced by MAM also has parameters and defects that may affect the functionality of the part and lead to the failure. These defects are residual stress, fatigue, porosity, variation in mechanical properties, surface oxidation, cracks, delamination, variation in grain size, and heat accumulation. Similarly, parameters such as microstructure, building direction, surface roughness, and powder particle size may lead to these defects or affect the quality and reliability of the printed metal parts. Some of these defects will be discussed next.

6.2.1 Residual stress

Residual stress is a stress stored inside the metallic part in different ways. For example, forging on the surface of some plate creates residual stress which is required to reinforce the plate. Laser peening creates desired compressive residual stress in metal part. Similarly, residual stress is stored in the metal after casting stock material which is mostly undesirable. Therefore, the residual stress can be desirable or undesirable. In the MAM method, one of the main defects is influencing the printed metallic parts with undesirable residual stress which may lead to premature failure. Residual stress in MAM method can lead to distortion failure, changing in tolerance, fracture, fatigue, and delamination. A lot of literature review discussed this problem and it is the focus of leading researchers. Several factors may cause the residual stress in MAM parts, such as rapid heating rate, rapid solidification with high cooling, and melting back previous layer for both PBF and DED MAM categories [11].

6.2.1.1 Proposed solution

It is advantageous to use well maintained heat treatment machine (vacuum furnace) to remove the residual stress from the MAM parts. Based on the author's understanding, melting back of the previous layer is the main issue which generates the residual stress. This melting back can be reduced by reducing the pace of heating while building the next layer. Reducing the melting back can be done by installing a cooling unit to reduce the heat between layers, such as air jet to reduce the heat generated when a new layer is being melted and laying down on the previous one. Also, using variable building direction might help in reducing heat accumulation in one direction. More comprehensive study should be conducted to build inspection system rather than in-situ method. This inspection system is used to analyze the melting back spot and figure out where it exists and assign permanent solution for that. Moreover, post process control (a type of heat treatment control) should be applied on the printed metal parts which contain residual stress after inspection.

6.2.2 Fatigue

Fatigue is a damage in a solid material which causes it to weaken. The main reason for fatigue is fluctuating (cyclic) loads applied on metal parts which causes damage at the end and failure in the parts. Several parameters, such as surface finish, shape and geometry of the part, grain size and direction, functionality of the part, load type, part size, corrosion, temperature, and surface treatment cause fatigue. For the MAM method, the temperature is the most affective parameter to cause fatigue in printed metallic parts. Some literature studies have been performed on this subject, especially on multiaxial fatigue in many industries for small and medium size of metallic parts [1].

6.2.2.1 Proposed solution

Analyze the functionality and the geometry of printed parts to specify where the fatigue can happen for a particular temperature and surface finish. This fatigue could be avoided by assigning specific heat treatment and surface finish. Similarly, the geometry of metallic parts which can induce fatigue can be changed after comprehensive analysis to avoid undesirable residual stress in these features. Finally, using different environments with different temperature during the process can also be used to eliminate fatigue.

6.2.3 Porosity

Another common defect in MAM method that needs to be prevented during the process is porosity. The porosity is a void or hole in the solid printed metal. In the MAM method, the porosity happens between the layers and is mostly inherent to Direct Energy Deposition (DED) category of metal printing, such as WAAM. It occurs while the printed layer is in liquid form because of gas or solidification shrinkage. Porosity is a defect that will end in producing parts that have undesirable mechanical properties, such as low strength and cracks. Unstable deposition process and poor path planning, especially with complex path cause porosity as well [13].

6.2.3.1 Proposed solution

The gap between the torch of DED processes and the melting surface should be continuously adjusted to prevent any slags that might happen and lead to porosity. Using inert vacuum environment during the printing process will eliminate the oxidation that will lead to porosity. Keeping the printing surface (substrate) clean from any dirt or slags either on the previous printed layer or the main surface of the bed will also reduce porosity. While using the optimal gas flow for GT-WAAM process, incorrect gas flow may cause a lot of slags during the printing which may lead to porosity. Optimal energy density can play a main role in eliminating the porosity because it will generate fine printed layer without defects. Creating a map for optimal deposition rate and gap for every specific alloy and reducing the complexity of the printing path can be another solution. Similarly, installing inspection system to check the printing process layer by layer during the process can fix the porosity simultaneously.

6.2.4 Oxidation

Oxidation (Redox) is a process when a chemical reaction happens in metal and leads to change in the structure of atom by losing electrons. Oxidation happens with the availability of oxygen and it is a defect that generates cracks and distortion failure in the printed metal part. It creates a weak insulation material between the printed layers, mostly in DED MAM category. Oxidation is the main reason for variation on mechanical properties. It causes minute or unstable printing gaps between the torch and the bed surface or the previous printed layer. Not enough flow of gas during the process might also lead to oxidation.

6.2.4.1 Proposed solution

The best way to prevent oxidation is by eliminating oxygen from the printing environment. That can be obtained by using air vacuumed chamber 3D metal printer. However, if the vacuumed environment is difficult to be adjusted, optimal stable gap of the torch should be used with optimal gas flow.

6.2.5 Heat accumulation

One of the main defects that interrupt the metal 3D printing part is a heat accumulation. This issue happens when the average temperature of the workpiece increases continuously. That will cause many other defects, such variation in mechanical properties and microstructure evolution, and variation in grain size which will, consequently, lead to undesirable part quality, such structural collapse [14]. This issue is also mostly inherent to DED category of the MAM. According to the author analysis, it happens in DED category mostly because in DED process, metal is melted. As a new layer is created over the previous hot one, it will initiate the heat accumulation. Thus, this issue depends on the philosophy of metal printing process. As compared to PBF, in which lower powered laser is used with lower heat, a new layer of powder will be poured over the previous one and that will absorb the heat of the previous layer.

6.2.5.1 Proposed solution

The previously printed layer should be cooled completely before printing the new layer. That could be performed by installing a cooling unit with the help of in-situ method. The cooling unit will work simultaneously while recording temperature of in-situ method. Similarly, variant building direction will accumulate heat in different direction and reduce the average heat. Heat treatment can be a traditional solution if the workpiece could not be collapsed during the printing process. According to the author's understanding, another way to solve the issue of heat accumulation or residual stress is by using nucleation after printing. Nucleation is a process of formation of a new crystalline structure during solidification. This process might be applied on the printed parts by heating it to a temperature lower than the melting point and building new crystalline structure with the desired mechanical properties, grain size, free residual stress and heat accumulation.

6.2.6 Cracks and delamination

Two types of cracks mainly occur in MAM method (DED processes) and they are: grain boundary cracks and solidification cracks. Cracks happen because of the method of solidification. Delamination is a type of failure in metal alloys or composite material. In defective parts, the layers of metal are separated because of repeated fluctuated stress and the material characteristic of the deposited metal. A drawback of delamination is that it cannot be repaired by post-process heat treatment, but it could be avoided [13].

6.2.6.1 Proposed solution

The only way to fix the problem of delamination and cracks is by preventing them. It can be achieved by optimizing solidification. Preheating the printing environment and substrate can be a good solution as well. Avoid using combined material in the DED processes that might separate the layers between them when the dissimilar material has significant difference in the chemical reaction and solubility. Comprehensive study should be performed on the metals which are difficult to melt and solidify without cracks and delamination such as Inconel. Developing temperature map of the printed surface, that might help to optimize the preheating, can avoid cracking and delamination. The high cooling rate is also a cause of cracks and delamination. However, it is mentioned previously that it is a good solution to avoid some defect such as heat accumulation. Therefore, an optimal cooling rate should be used to avoid and consider these defects.

7. Summary and conclusion

In this chapter, a review on design for additive manufacturing was conducted to address and answer some concerns about Metal Additive Manufacturing (MAM). These concerns were related to challenges, issues, and defects which are prevalent in MAM method in factories while printing small and medium sized parts. Explanations about the printing procedures and materials are also discussed in this chapter. Moreover, potential approach and solutions are inferred by the author to diminish these problems. Comprehensive literature review was developed from a recent research paper to address and understand these manufacturing obstacles. The MAM method is divided into two main processes: PBF and DED. These processes were explained in detail by the author.

The main obstacles which the MAM methods encounter are categorized into two types: challenges (difficulties) and defects. Several obstacles have been explained in this chapter, such as repeatability, material issue, schedule, certification, heat treatment, and inspection. Also, several defects which obstruct high quality and reliability, such as fatigue, stress analysis, porosity, heat accumulation, delaminating, and cracks were listed and discussed. For every challenge and defect, a potential solution was suggested and discussed by the author. Some of these suggested solutions need to be tested and validated on actual metal three-dimensional printing processes. Other suggested solutions, such as inspection and orientation, should be implemented by visiting manufacturing companies and making local study on to solve the problems.

However, based on the literature review and analysis, DED processes, especially WAAM, have more defects and challenges than PBF processes. Some of these challenges and defects are common in three-dimensional printing, a fast-growing manufacturing process. More study and analysis are required to fix these obstacles and make MAM method smooth. Such concurrent failures can induce huge losses in industries and force them out of business. Therefore, future studies can eliminate these failures and yield higher production rate and profits.

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Author details

Omar Ahmed Al-Shebeeb
Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV, USA

*Address all correspondence to: oaalshebeeb@mix.wvu.edu

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