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A Review Of Wire Arc Additive Manufacturing: Principle, Defects, And Future Scope

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Abstract: Additive Manufacturing (AM) has opened up new possibilities for researchers to fabricate products and has even replaced older techniques in certain industrial settings by reducing material usage. Wire Arc-Additive Manufacturing(WAAM) has gained considerable popularity in the study of additive industry attributable its exceptional efficiency and numerous advantages. This technique offers several key benefits, including high-deposition rates, improved material usage, reduced lead-times, enhanced element efficiency, and decreased inventory capital. Like welding, which is a conventional method, Wire Arc-Additive Manufacturing utilizes a layer-by-layer deposition approach to construct larger objects with comparatively lower complexity. The attainment of manufacture of the highest calibre in WAAM is impeded by the significant levels of heat input, leading to various processing challenges and defects. This article primarily addresses the common challenges encountered during the fabrication of various metals and alloys using Wire Arc-Additive Manufacturing (WAAM). These challenges encompass elevated residual stresses, porosity, cracking, and delamination. It provides a comprehensive overview of the fundamental aspects of the WAAM method, crucial steps involved, defects, and process planning. Additionally, it includes a review of previous works, addresses challenges, and discusses future prospects in the field.

Index Terms - Wire Arc Additive Manufacturing, WAAM, defects, Additive Manufacturing

I. Introduction

At the forefront of technology, Additive Manufacturing (AM), is an advanced manufacturing process. Someone can consider it as a revolutionary discovery in the industry. Additive Manufacturing also called 3D printing and in industry it is also referred it as rapid prototyping. So the idea behind additive manufacturing is building a product layer wise, one layer at a time using material in powder form or wire form over a predefined tool path given by the computer for that product. In the 1980s, 3D Systems Inc. achieved a significant milestone by becoming the first company to produce a product using a CAD model through a layer-by-layer additive-manufacturing process. [1]

The reason it is so famous in the industry is because of its tremendous advantages over the conventional manufacturing techniques. The biggest advantage is that it does not require any external tools such as casting moulds, dies and punches. AM allows complex and precise product to be made as per the requirement of the customer. As compared to its counter technique Subtractive Manufacturing (SM) it require negligible additional material therefore little to none material waste. AM's other advantages include it minimizes the time required for the production [2,3] and since it is providing less material wastage so we can use it to make products which were expensive to make when they were made by conventional techniques [4-9].

The material extrusion and material jetting is mainly used in manufacturing polymer based product. Binder Jetting and Sheet Lamination both of these process can be used to make products from polymer, ceramics, metals and composites. For metal additive-manufacturing, Powder-Bed Fusion and Direct-Energy Deposition(DED) are the commonly utilized techniques [10]. Among these, Wire Arc-Additive Manufacturing

(WAAM) is widely used in the production. For process to be used in Industry should have high deposition rate but also should be economical.

Panchenko et al. conducted a comparative evaluation of benefits of WAAM over alternative additive manufacturing methods. These findings are presented in Figure 2 [11]. As seen from the figure 2 we can see that WAAM surpass other AM techniques in Material properties, Degree of utilization of material and Economic efficiency, which are crucial factors in industry and thus currently WAAM is by far the most popular AM technique among industy. In 1920, Baker Ralph employed an electric arc to melt metallic wire and create an ornament, marking the initial application of Wire Arc-Additive Manufacturing [12]. Since then, continuous progress has been made to refine and enhance the WAAM process.

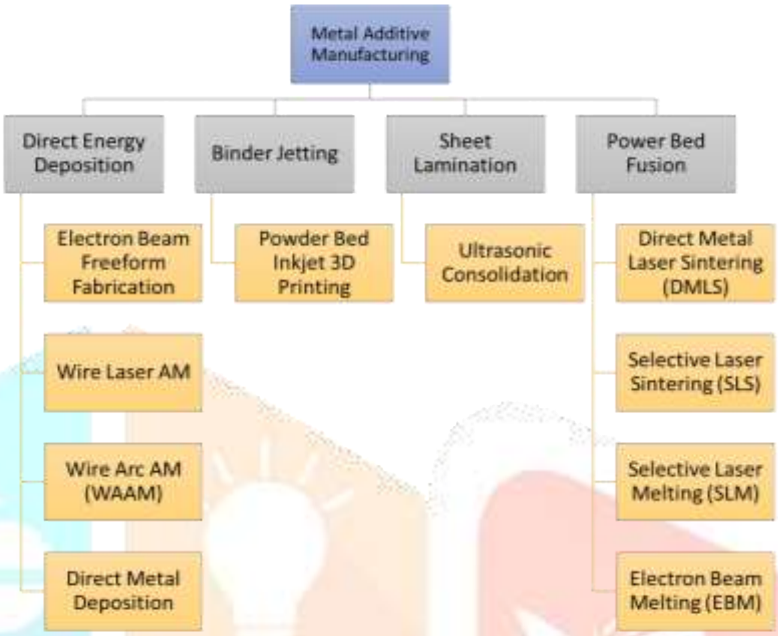


Figure 1. Metal Additive-Manufacturing techniques

To understand WAAM, It's crucial to have a foundational knowledge of wire-arc welding. Arc-welding is a technique that employs an electric-arc to generate heat, which allows for the melting and fusion of metals. This method involves utilizing a electricity source for starting an electric arc between two electrodes, which can be non-consumable or consumable, and the base material. The power supply can operate with either AC (alternating current) or DC (direct current).

According to the type of energy source used, Arc-welding is divided into several categories. Some of these types include Plasma-Arc Welding (PAW), Gas-Tungsten Arc Welding (GTAW), and Gas-Metal Arc Welding (GMAW). The principles utilized in Wire Arc-Additive Manufacturing (WAAM) are indeed related to those employed in arc-welding. In fact, the primary types of arc welding, such as Plasma-Arc Welding (PAW), Gas-Tungsten Arc Welding (GTAW), and Gas-Metal Arc Welding (GMAW) is another commonly utilized method in Wire Arc-Additive Manufacturing (WAAM), catering to different user preferences and application needs. In WAAM we melt the wire but instead of joining metals (like in arc welding), we let the molten bead fall on the pre-defined path layout and after we repeat this process multiple times we would have a stack of molten beads melted together in the specific layout creating a additive manufactured product. Apart from the process planning and execution of these processes, they also differ in a basic thermal conductance to the metal and surrounding, which is found by Cunningham, Mohebbi et al.[13].

Figure 2. comparison between different AM techniques [11]

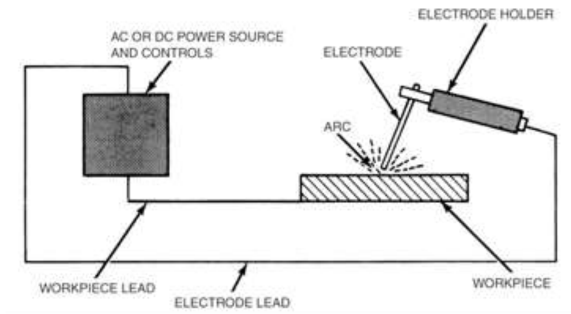
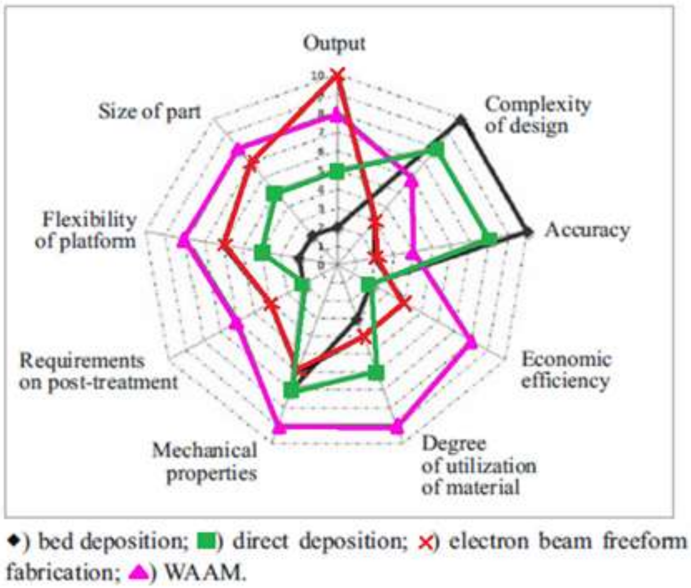


Fig 3. Basic wire arc welding [13]



So in WAAM the energy lost by the melted bead is mainly to the layer below it, thus melting and joining to the layer below it. In the additive-manufacturing process, every layer is sequentially placed on top of the preceding layer. During this process, the material undergoes repeated cycles of heating and cooling, ultimately leading to the creation of unique and final net shape parts. An important benefit of this approach is that it eliminates the need for additional tooling processes[14].

Process planning is a major aspect of WAAM. To understand it we must first define major WAAM components. Figure 5 presents the fundamental schematic of the Wire Arc-Additive Manufacturing process [15]. To enhance comprehension, let's divide WAAM into three distinct parts: process-planning, depositions, and post processes. During process planning, the initial step involves creating a CAD model of the desired product. Then this 3D model is sent to a software to be converted into 2D layers of thickness according to requirement. After this a programme would make a layout according to these 2D layers.

After the program is prepared, it is transferred to a CNC machine. The CNC code is generated based on this program. Furthermore, in Figure 5, there are multiple sensors, such as cameras and thermocouples, which are utilized to gather real-time data during the melting process. This data includes information on the table speed, material feed rate, gas flow rate, arc current, heat input, path strategy, and more. These data are then feedback to the computer to generate new process parameter values which can give more accuracy to the product. Hence it explains the closed circuit loop in the figure 5.

The process planning makes WAAM little complicated than the conventional. Moreover, the materials which we can use in WAAM is very limited right now. Researchers are testing new materials and conducting experiments to reduce the defects in the product so that they are industry ready. Some of the common materials are aluminium alloys, titanium alloys, nickel based alloys and steel based alloys etc. more details can be found later in this paper.

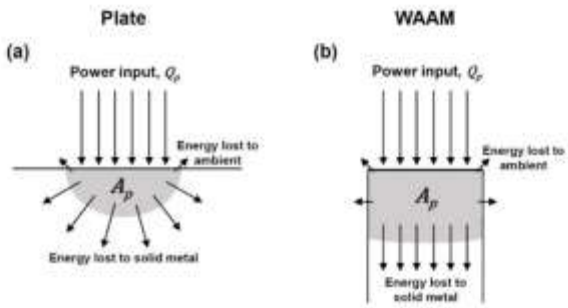


Fig 4. Thermal conductance in arc welding and WAAM [13]

As there are many parameters which are directly related to the manufacturing of the product, this will inevitably make it more vulnerable to defects. Later in the paper, defects such as cracking, porosity, and residual stress are thoroughly discussed. The paper also explores geometry and its relationship to particular parameters of the fabricated part in subsequent sections. Many post processing methods has also been researched that can reduce the defects to such an extent that their properties even extend the properties of the same product manufactured by conventional ways.

As WAAM's benefits are much more than its defects, they are already used in many different fields. Some of which are construction Industry, Aerospace, Automobile Industry, waterpower plants etc. below are the some of the examples.

The figure 6 shows a world's first ship propeller made by WAAM process by RAMLAB. After 298 layers of 3D printing of Nickel Aluminium Bronze alloy they got this propeller. This propeller has been tested and currently used in the industry. Fig 7 shows pelton wheel used in water power plants. It is developed by hydroworld. It weighs around 38 ton and has the capacity to generate 335 MW. Harlow-FasTech company in US which makes 3D printed parts for aerospace/space, shipbuilding, tools and die etc. used a combination of WAAM and machining to build the impeller shown in fig 8.

The steel bridge constructed by MX3D stands out as the pioneering example of a bridge fabricated using 3D printing technology. Additionally, the bridge incorporates sensors to gather data regarding the structural health of the bridge. The sensor collect data on structural measurement like strain, displacement and vibrations.

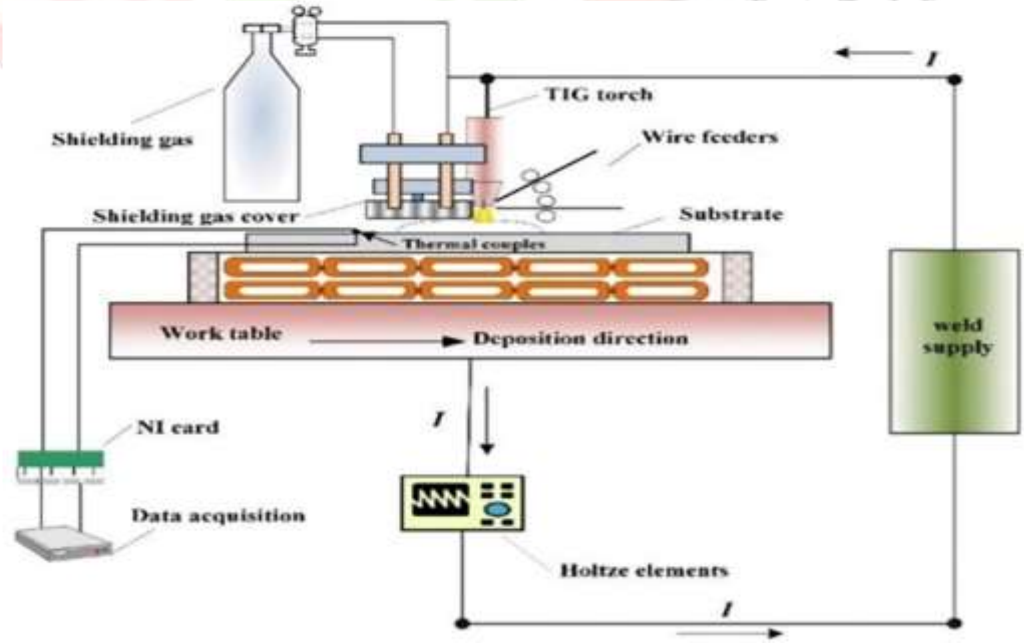


Figure 5. Schematic diagram of WAAM [15]

Figure 6. WAAM-manufactured propeller [16]

Figure 7. WAAM-manufactured water turbine blades [16]

Figure 8. Impeller shaft [17]

Figure 9. Cylinder head printed by Lincoln Electric via WAAM [18]

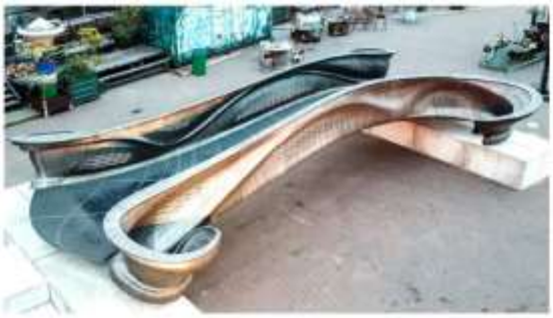


Figure 10. 3D printed bridge in Amsterdam[19]

Wire Arc-Additive Manufacturing extends beyond the making of new parts and can also be effectively utilized for modifying or repurposing existing components. Josten and Höfemann utilized WAAM for reinforcing car components [20], while van Le et al. employed it for repurposing steel in another notable case. [21]. Moreover, Wu et al. showed that WAAM has the capability to be employed for spot repairs of molds and other parts [22] and Li et al. have shown with repairing a sprocket [23].

So we can see from these applications, that WAAM can be revolutionary process in Industry. This paper is for the beginners who want to study WAAM. This paper will study about WAAM processes and the challenges faced by it. In the end it will also discuss some future scope of WAAM process.

II. WAAM (Explanation of Technique)

A element is constructed using the layer approach of WAAM instead of subtractive manufacturing methods. This results in improved material efficiency and cost-effectiveness since the material is selectively deposited only where it is required. By employing the WAAM process, the production of parts is streamlined, significantly reducing the need for additional machining due to the attainment of close-to-final shape components. Compared to products manufactured using traditional subtractive methods, WAAM components exhibit favorable density and high mechanical properties. Additionally, WAAM can be utilized for repairing structures and parts such as bridges, turbine blades, molds, and dies. Worn-out parts can be restored by depositing new material onto their surfaces using WAAM, eliminating the need for additional raw materials and processes, leading to significant cost savings. Furthermore, WAAM demonstrates a deposition rate that falls within the range of 10 to 130 g/min, surpassing the deposition rates achieved by additive manufacturing techniques that employ laser power sources or electron beam (2-10 g/min) [28]. Within the WAAM process, an electric-arc generated by a power supply unit serves as the energy source. This electric arc induces the liquefying of the electrode wire, resulting in the formation of a liquid metal pool. By carefully selecting suitable welding settings and tool paths, it becomes possible to fabricate products with desired shapes and sizes. The planning and construction of the tool path are designed to efficiently produce higher volume shapes or components with slightly less complex forms.

2.1 Electric Arc types

WAAM utilizes three primary electric arc types: MIG, TIG, and PA. Among these, MIG is the most commonly used method due to its shorter tool path and the use of wire as a consumable electrode, which is aligned with the melting source. In contrast, Tungsten-inert Gas (TIG) and Plasma-Arc welding(PAW) techniques necessitate the introduction of an external wire into the melt pool since the electrode used is not disposable. In such cases, programming the torch for consistent deposition becomes more challenging because it requires rotation to enable continuous feeding of the wire from the same direction. [29]. During the Metal Inert Gas (MIG) welding process, the arc causes molten metal to be transferred from the consumable electrode, which may lead to the expulsion of molten droplets. This phenomenon results in spatter and the formation of surface balling. Unlike other welding methods, such as Metal-inert Gas, Tungsten-inert Gas and Plasma-Arc welding processes do not encounter spatter. This phenomenon occurs due to the direct supply of filler metal to the weld pool in these processes [30]. In the case of aluminum and steel feedstocks, the Cold Metal Transfer variant of MIG is well-suited. The CMT technique utilizes a mechanism known as controlled dip transfer mode, which allows for the production of high-quality beads with minimal spatter and reduced heat input. The finer grains achieved through reduced heat input can enhance mechanical characteristics [27]. Unlike standard MIG, CMT synchronizes the mechanical motion of the wire with the electrical process control, which monitors parameters such as thermal input, short-circuiting phase, and arc length [28]. For more detailed information, refer to references [27-29]. When considering the size of construction parts, a high deposition rate is crucial to ensure timely fabrication. For this reason, MIG (Metal Inert Gas) welding is preferred in the construction sector due to its higher deposition rate, which can reach several kilograms per hour. In contrast, TIG (Tungsten Inert Gas) welding typically achieves an approximate deposition rate of one kilogram per hour. [27]. Consequently, earlier research on WAAM construction has predominantly focused on MIG, which might have limited the exploration of its potential applications. Civil engineers should also explore different variants of WAAM for various structural applications. For example, TIG (Tungsten Inert Gas) welding can be utilized when higher geometric accuracy and improved surface finish are required [27], while PA (Plasma Arc) welding can be employed to produce parts with a larger deposition width compared to MIG (Metal Inert Gas) welding [30].

2.2 Materials

A broad range of spooled wires, which are commonly used in the welding industry, can be readily utilized as feedstock material for the WAAM process. The availability of wires in diverse alloys is vital as they have a great significance in ensuring the production of defect-free and dependable parts. Having a solid understanding of the available processes, process control variables, key concepts, and input materials is essential. Table 1 presents a compilation of frequently employed alloys in WAAM along with their respective applications. In this part of the article, we will explore the metals generally considered in the WAAM technique.

2.2.1 Titanium alloys

Extensive research has been done to inspect the use of titanium alloys in various industries using WAAM technology. This focus arises from factors such as the difficulties in machining, the comparatively higher cost of materials, and the advantageous ratio of strength to weight exhibited by titanium alloys. In WAAM, the deposition rates for titanium alloys typically range from 0.75 to 2 kg/hour. Additionally, the typical values for resolution, surface-roughness (including surface waviness) are about 0.5 mm. As a result, the resulting metal layers exhibit high density, eliminating the need for additional processes like Hot Isostatic Pressing (HIPing). Moreover, the size of the component that can be produced is solely restricted by the reach of the manipulator. [39]. Notably, WAAM-deposited Ti-6Al-4V exhibits improved damage tolerance properties, particularly when subjected to heavy cyclic loads, surpassing the performance of the wrought alloy by one order [40]. However, it is important to consider that titanium alloys demonstrate significant anisotropy in terms of elongation and tensile strength. The rolling process induces strains in the component in both the transverse and normal directions [41,42].

Area of Application	Alloys				
Aerospace	Ti-as major	Al-as major	Ni-as major	Bimetal	
Automotive	-	Al-as major	-	Bimetal	Steel-as major
Maritime	Ti-as major	-	-	-	Steel-as major
Corrosion resistance	Ti-as major	-	Ni-as major	Bimetal	-
High temperature	Ti-as major	-	Ni-as major	Bimetal	-
Tools and molds	-	-	-	-	Steel-as major

Table 1. Some commonly considered major metal alloy and their application for WAAM

2.2.2 Aluminium alloys

Successful fabrication trials have been conducted on various series of aluminum alloys, including Aluminum-Copper (2xxx), Aluminum-Silicon (4xxx), and Aluminum-Magnesium (5xxx). While conventional machining costs tend to be lower for simple and small components, WAAM technology proves to be economically feasible for complex parts with large and thin walls [43 However, it is essential to acknowledge that there is a disparity in the mechanical properties between deposited aluminum alloy parts and billet aluminum alloy parts. To improve the strength, properties, and microstructure of aluminum parts, post-process heat treatment is necessary. The welding of alloys such as Al7xxx and 6xxx poses challenges, mainly due to the occurrence of weld-defects and the generation of a turbulent melt-pool while deposition process, which restricts the application of aluminum in this technique. The most common flaw encountered in deposited aluminum is "porosity." To mitigate porosity, it is crucial to optimize synergistic operating parameters and employ high-quality feedstock wires.

2.2.3 Nickel alloys

Nickel-based superalloys are in high demand for additive manufacturing (AM) due to their exceptional capability to maintain high strength even at elevated temperatures. Conventional fabrication methods for these alloys tend to be expensive, which has led to the widespread adoption of the WAAM technique for commercial applications. Among the different alloys based on nickel, significant attention has been drawn to Inconel 625 and Inconel 718, which have been extensively studied in numerous research investigations to understand their properties. Concerning microstructure, WAAM-produced Inconel 718 exhibits distinct columnar grains distinguished by dendritic boundaries [44]. The ultimate strength, yield strength, and ductility of deposited nickel alloys typically exhibit similar or slightly lower values equating to that of wrought or cast materials [45].

2.2.4 Steel alloys

The high ductility and corrosion resistance of stainless steel make it an attractive material for fabrication using the WAAM technique, leading to numerous investigations in this field. Research studies have shown that WAAM technology can generate stainless steel components with favorable mechanical property and micro-structure [46]. During welding or deposition processes, the micro-structure of stainless-steel is predominantly austenitic, consisting of both austenitic and ferritic phases [47]. The phase fraction of stainless steel is affected by several factors, such as the thermal cycle experienced during welding or deposition and the chemical content of the element [48]. The rate at which the material cools down after welding or deposition is a significant factor in determining the content of ferrite in the final part. By controlling the cooling rate, it is possible to achieve a volume fraction of up to 30% ferrite [49, 50]. Choosing the right process parameters is crucial in order to attain a well-balanced microstructure in stainless steel. These parameters directly impact the outcome and help achieve the desired properties and characteristics of the element. Faster cooling can result in precipitation of non-equilibrium nitrides and a restricted formation of austenite [51,52]. Although components may exhibit slight anisotropy, this can be eliminated through suitable post-process heat treatment, resulting in properties similar to those of conventionally produced products. WAAM-deposited stainless steel parts are extensively employed in the manufacturing of high-performance alloy components [48].

2.2.5 Bimetal alloys

Extensive research has been conducted to evaluate the viability of a broad spectrum of metals for Wire Arc-Additive Manufacturing (WAAM). These investigations encompass bimetallic combinations such as steel/nickel and steel/bronze, as well as magnesium alloys. Moreover, alloys frequently used in aerospace applications, such as Fe/Al and Al/Ti, as well as in the automotive industry, have also undergone extensive examination and analysis. These alloys are being examined due to their unique properties and potential for various engineering applications. [45]. The main aim of the investigation has been to assess the mechanical and microstructural properties, particularly for simple parts with straight walls, rather than placing significant emphasis on the overall advancement of the process for manufacturing functional components.

2.3 Geometric aspects in WAAM

Unlike other additive-manufacturing processes, Wire Arc-Additive Manufacturing (WAAM) techniques are widely recognized as high deposition rates can be achieved. This characteristic sets WAAM apart from other methods in the field of additive-manufacturing. However, it is important to keep in mind that Wire Arc-Additive Manufacturing (WAAM) techniques, while offering higher deposition rate, are often associated with lower part precision compared to other additive manufacturing processes. As a result, research efforts have predominantly focused on addressing geometry control as a crucial area of interest in WAAM [27, 28]. Investigations into dimensional control, encompassing the height and width of each layer, have been conducted for various metallic materials [27, 28]. Parameters such as the thickness of the wire and various process variables, including wire-feed speed, heat input, and travel speed, have a significant impact on the wall-thickness and deposition effectiveness achieved during a single pass deposition. Commonly used wire sizes for constructing materials like stainless steel and carbon steels ranging from 0.8 mm to 1.2 mm. The use of these wire sizes leads to section thicknesses that typically ranging from 3.5 mm to 8 mm for a single pass wall [36, 29, 30]. Thus far, the majority of WAAM builds in construction applications have utilized single-pass walls with consistent thickness [35]. Nonetheless, achieving thicker walls can be accomplished by employing multiple wire feeds and printing passes, introducing complexities to path planning [37].

A ground breaking hybrid directed energy deposition (DED) technique [38] has been developed, which combines laser and plasma transferred arc (PTA) as the primary energy sources. This innovative hybrid process enables precise modulation of wall thickness, offering smoother control over geometry. Furthermore, it offers considerably higher deposition rates in comparison to pure arc or laser-based AM processes. [38]. Further exploration of different combinations of energy sources holds promising research possibilities to meet diverse objectives [60].

Relying solely on traditional welding criterion, consisting arc-current, arc-voltage, wire-feed speed, shielding gas flow, and travel-speed monitoring, is inadequate for comprehensive control as these parameters primarily pertain to the system rather than the specific component itself. Consideration of additional environmental factors, such as heat build-up, is necessary to address potential flaws and their detrimental effects. Various monitoring modalities, including thermal signal, optical signal X-ray CT, and acoustic signal, have been described in [33]. Effective inspection are crucial for in-situ detecting defect and it’s prevention. [33].

The precision of WAAM components largely depends on accurately predicting and controlling the dimensions of each layer, which are influenced by multiple process parameters and their cumulative effects. Early digital modeling approaches, such as the one proposed by Ding et al. [34], employed finite element analysis to simulate the thermo-mechanical properties of many layered wall construction during the WAAM. This approach allowed for the estimation of accumulated deformation and residual stress. Xiong et al. [35] investigated the use of neural network modeling for predicting deposition geometry and optimizing process parameters in GMAW-based WAAM. Digital modeling techniques have significantly enhanced confidence in geometric control and residual stress analysis of WAAM parts. Nevertheless, the impact of process factors can differ across various materials, posing challenges in collecting and leveraging process knowledge from extensive literature. To overcome this, digital technology and machine learning [36] can be utilized to optimize process parameters and attain the desired geometry. The development of a computerized tool for data collection from diverse literature sources, as demonstrated in [36], has shown potential in data-driven process control for additive manufacturing.

III. WAAM PROCESS PARAMETERS

WAAM allows for the production of products with the desired shape and acceptable surface roughness. However, it is necessary to machine finish the end product before it can be utilized in the industry. But the post processing process can be minimized if the product is made with the accurate processing parameter. The processing parameter plays the major role in deciding quality of the product. In this section we will discuss about the main parameters which affects the product directly.

3.1 CAD model parameter

The initial stages of manufacturing a 3D product involve preparing a CAD model and performing 2D slicing of the CAD model to generate tool paths. It is helpful to get the model in ".stl" file format because it would be then easy to slice it in 2D layer [39]. There are mainly two type of slicing available unidirectional slicing and multidirectional slicing. In most of the applications unidirectional slicing is used because it relatively simple. However, a drawback of unidirectional slicing is the need for numerous support structures when dealing with complex and overhanging structures. On the other hand, multidirectional slicing (MDS) does not require as much support. As a result, modern AM machines are increasingly utilizing MDS. In MDS, the slicing process is performed in a manner that allows the multiaxial robot to deposit each layer in any orientation [40,41]. Since MDS require such complex algorithms to control the nozzle and the orientation of the robot, that's why it requires complete robotic configuration [42]. An example of unidirectional vs multidirectional slicing is showed in figure 11.

3.2 Tool path

This is crucial step in ensuring the production of a high-quality 3D printed product as it guides the nozzle to deposit the melted bead on the 2D layout got from the slicing process. The type of deposition technique used affects the property of the product. Moreover, there is always some mathematical uncertainty in routing path that can also affect the property of the product. There are many types of tool path that we can program the nozzle to follow, some of which are discussed below.

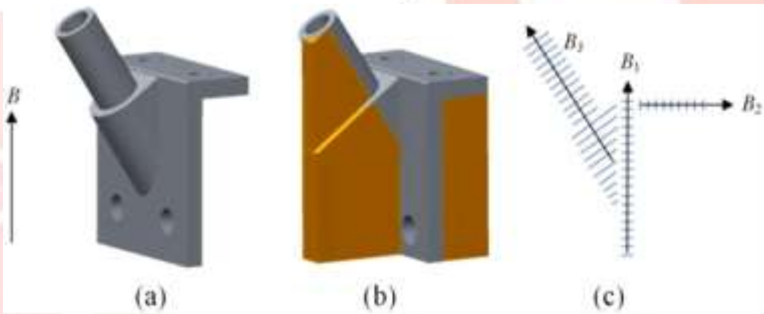


Figure 11. (a) and (b) represents the unidirectional build B denotes the direction as we can see in (b) support is needed whereas in (c) we can see there are 3 build-direction that is B1, B2 and B3 [40],[41]

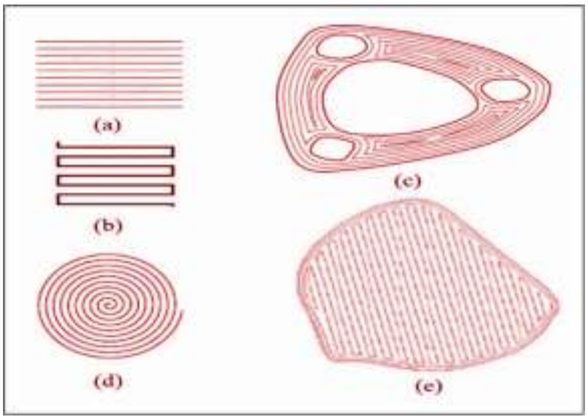


Figure 12. Various methods of tool path a) Raster, b) Zig-zag, c) Contour, d) Spiral, e) Hybrid [43],[44]

a) Raster: as seen from fig 12. (a), in raster straight parallel beams is used to cover the contour. It is discontinuous that means when it deposits one layer it goes back to the same side it started and then offsets downwards by pre-programmed distance and starts depositing again parallel to the first layer. It is simple and sufficiently can be used in any boundary therefore more frequently used than other tool paths [44].

b) Zig zag: it is similar to Raster but instead it is continuous as we can see from fig 12 (b). therefore, reducing the tool path. The raster and zig zag both have same disadvantage, and that is, at boundary of the layout If the layout at the edge is not uniform and moreover if it is not in the path of the depositing layer, then we will not get the accurate results. Thus both have poor accuracy [45].

c) Contour: as shown in fig 12 (c) contour path overcome the disadvantage that raster and zig zag had. It follows the layout of the outer boundary for depositing the layer and thus eliminating the boundary problems. The inner part is filled based on the outer boundary, as illustrated in the figure 12 (c) [46].

d) Spiral: spiral tool path as shown in fig 12 (d) it eliminates any boundary problems but it can be applicable to some specific geometric shapes only.

e) Hybrid: out of the four tool paths discussed above zig zag is the most economical but if see the accuracy wise the contour is the best. In the industry we need the path which is both economical and also should give high accuracy. Solution of this problem is to use multiple tool path like the one shown in fig 12 (e). it shows the boundary is done by following contour path and the inner side of the layout is done by zig zag path. Therefore, this path is most suitable for industry use.

Problem with contour path is that as it starts filling from the outside it leaves some unfilled space inside as given in fig 13. The green lines in figure 13 (b) show the path to be followed and the distance between the adjacent green lines or the offset from the boundary is given by, for the nth track offset is (n-0.5d) where d is the distance between the centre of the two beads as shown in fig 14.

For the optimal overlapping the d = 0.667w, where w represents bead width. From fig 13 (c) the unfilled area is because of the poor selection of the value of d. so in order to avoid these kind of defects the value of d needs to be chose appropriately. The value of d depends on the wire diameter, travel speed, wire feed rate etc.

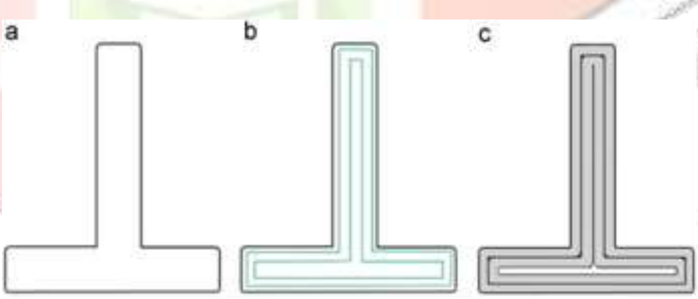


Figure 13. a) path layout b) contour path generated c) layer deposited after following contour path [39]

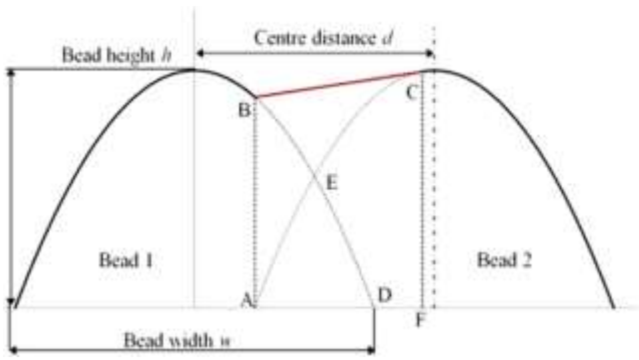


Figure 14 . basic bead geometry [10]

3.3 Welding process parameter

As we have established, the precise shape and size of the basic bead are crucial for achieving a high-quality 3D printed product. This property relies on essential parameters including electric current, wire-electrodes extension, wire-feed speed, welding speed, and supply voltage. These parameters vary based on the material and the specific type of product being produced. Below are specific examples that illustrate how different parameters can affect various materials in different scenarios.

A study carried out by Malcolm Dinovitzera and his team in 2019 [49] explored the impacts of process parameters in TIG-based WAAM. It was observed that during the solidification of the weld pool, several interfacial defects formed on the substrate. The travel speed and current were identified as the main factors influencing the bead microstructure and overall surface properties. Raising the wire feed rate led to an elevation in the height of the bead. However, melt-through depth and surface roughness were not influenced by the wire feed rate. Bead width and melt-through depth showed an inverse relationship with travel speed, indicating that higher travel speed led to narrower bead width and reduced melt-through depth. Travel speed was found to be inversely proportional to heat input, meaning that higher travel speed resulted in lower roughness. The study also found that the distance from the substrate influenced the microstructure, resulting in the presence of three distinct zones across the multiple layers. In columnar grain matrix adjacent to the bead substrate interface, the first zone displays the presence of finely dispensed carbides. In contrast, the second zone displays larger carbides with a less uniform distribution compared to the first zone. However, in the third zone, a fine and even distribution of carbides was restored within a cellular grain structure, as depicted in Figure 15.

In a study conducted on Al5Si alloy, it was discovered that ensuring a wire-feed rate in between 10 m/min. and 45 m/min. is essential for achieving a consistent and uninterrupted deposition. When the wire-feed rate fell less than 10 m/min. or exceeded 45 m/min., the deposition resulted in an irregular and interrupted pattern. The most consistent bead, characterized by a standard deviation of 0.1 mm, was obtained at a wire feed speed of 35 m/min. [50]. In the study of ER5356 (aluminum-magnesium alloy), it was noted that the grain growth rate was decelerated by the input of heat. Furthermore, supplying heat alternately between the layers led to the formation of pores, cracks, larger grain size, and lower microhardness [51].

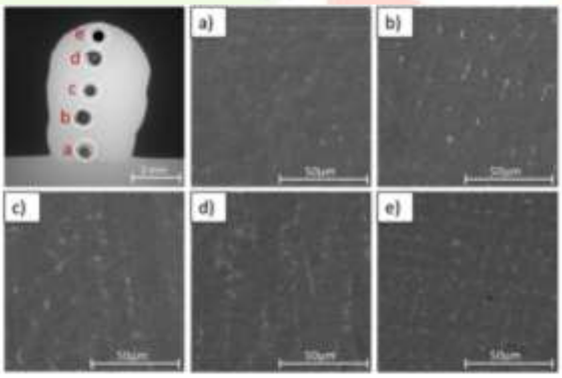


Figure 15 Micro-structure of specimen (top and bottom of cross section) [49]

In a study conducted on Ti6Al4V alloy, it was observed that the bead structure varied with increasing height until a certain point, after which the differences became insignificant. These variations were attributed to changes in the heat dissipation route [52]. The microstructure and grain size of Ti6Al4V were found to change along the construction direction. The optimum temperature for achieving the best mechanical properties was determined to be 2000°C [53]. It was also noted that a lower wire feeding angle (30°-40°) resulted in cracking [54]. In a study performed by Evangeline et al. [55], it was observed that the width of a weld bead was directly related to the welding current. This relationship was attributed to the increased welding current magnitude applying additional pressure on the droplet of the molten metal, which resulted in the formation of a wider bead. The steady welding current, combined with an increase in welding speed, contributed to this relationship.

IV. Evolution of Defects in WAAM process

Significant efforts have been dedicated to addressing the challenges associated with the manufacturing of products using WAAM technique. The fabrication of components using the WAAM technique presents several challenges that have been addressed through ongoing research and development. These challenges encompass various aspects of the process, including programming, control of deposition parameters, weld pool dynamics, thermal deformation, machine reliability, and environmental considerations. Additionally, specific materials used in WAAM can introduce their own set of issues. For instance, titanium alloys may experience oxidation, aluminum alloys can exhibit porosity, steel components may encounter significant deformation and surface roughness problems, and bimetal parts may be susceptible to crack formation. This section focuses on discussing these issues in relation to the materials involved. In industries such as aerospace and automotive, Welding Arc-based Additive Manufacturing (WAAM) techniques are preferred over traditional subtractive manufacturing and other methods for fabricating intricate product structures. However, the difference in micro-mechanical properties of the WAAM made products remains a significant challenge. This is mainly attributed to factors such as the stair-step effect, residual stress, porosity, and solidification cracking. Figure 16 illustrates that specific defects tend to be more prominent in certain materials. For instance, severe oxidation is observed in titanium alloys, porosity is common in aluminum alloys, steel often exhibits poor surface roughness, and bimetal components are susceptible to severe deformation and crack formation.

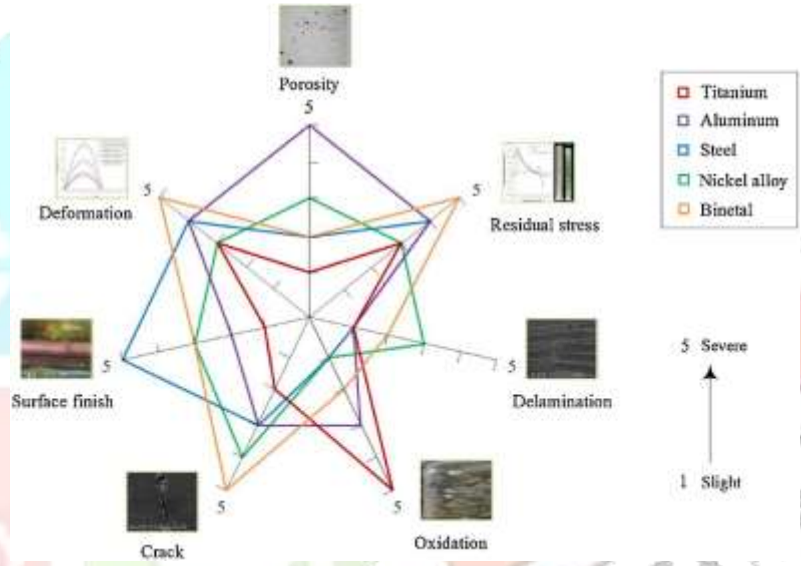


Figure 16. The correlation between materials and defects in WAAM processes [66].

4.1 Porosity

Surface contaminants, including grease, moisture, dust particles, and hydrocarbons, present in the raw materials such as the substrate and feedstock wire, can be absorbed into the molten pool throughout the WAAM process. This absorption results in formation of porosity during solidification, with aluminum alloy being particularly susceptible to this challenge. The presence of a small volumes of dissolved hydrogen in the liquid form might transcend the optimal solubility, resulting in the formation of porosity in the final part. Therefore, it is crucial to thoroughly clean the raw materials, especially aluminum alloys. The occurrence of porosity induced by the process is primarily caused by unstable deposition, insufficient shielding, and inadequate path planning. There are several methods available to control porosity in WAAM:

1.Utilizing a cold-metal transfer sourced GMAW or controlled short circuit process (CMT-PADV).

2.Employing higher effective shielding gas, ensuring gas tight closures, utilizing shorter and non-organic pipes.

3.Employing clean wire and substrate during fabrication.

4.Utilizing high-quality feedstock.

5.Optimizing the shape of the deposited bead.

6.Considering heat treatment as a post-processing step.

Implementing these measures can help reduce the occurrence of porosity and enhance the overall quality of WAAM components.

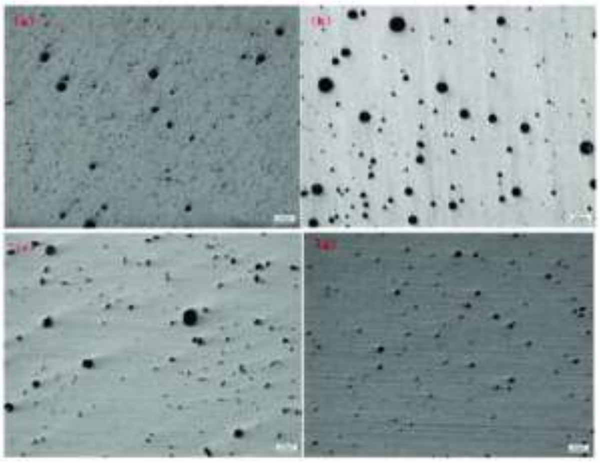


Figure 17. Porosity present in WAAM of Al 2219: (a) CMT; (b) CMT-ADV; (c) CMT-P, and (d) CMT-PADV.

4.2 Residual stress

Residual stress is the term used to describe the internal stresses that persist within a material even after all external forces acting on it have been removed. The presence of residual stresses can significantly effect the fatigue properties and net performance of the product. When the part is no longer held in place or supported, the presence of residual stress can result in issues such as distortion, separation between layers, compromised precision in the shape and dimensions, and a notable reduction in the ability to withstand fractures and fatigue. During fabrication, the continuous process of melting and cooling leads to thermal shrinkage and expansion, causing distortion in the part. This effect is especially prominent in large thin-walled components, where the stresses and deformation can be significant. Moreover, the stresses are most notable in the direction of deposition.

4.3 Solidification cracking

In WAAM, it is essential to carefully select and design a fixture as it directly affects crack propagation during the final stage of solidification. The use of restraints during this stage has a crucial impact on the occurrence of crack formation. Cracking, a visible defect commonly observed in the solidification process of aluminum components during WAAM, is mainly attributed to the broad temperature range required for solidification in aluminum alloys. To mitigate the risk of solidification cracking, preheating and/or post-heat treatment methods can be employed. These measures help reduce the likelihood of crack formation.

Figure 18 shows Scanning-Electron Microscope (SEM) images illustrating the fractured surface morphology observed of WAAM of Al 2219 alloy during horizontal tensile tests conducted under different conditions. On the fractured surfaces, the appearance of dimples indicates a fracture of a ductile metal behavior. The dimension of the dimples varies among specimens subjected to different processing conditions.

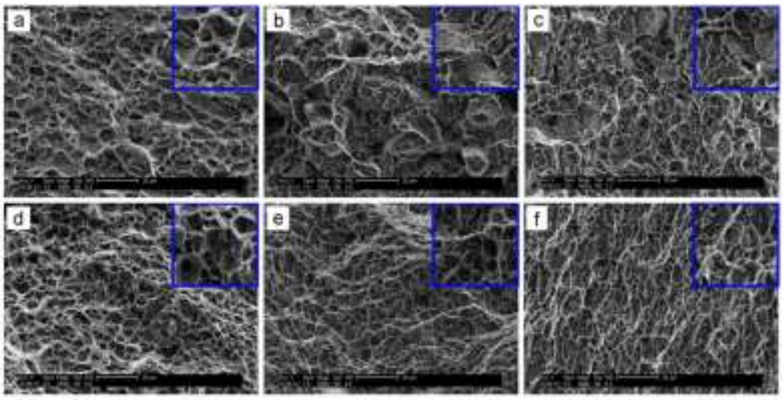


Figure 18. The Scanning Electron Microscope (SEM) images shows morphology of tensile metal made from WAAM Al 2219 alloy is depicted in the following conditions: (a) as-deposited metal, (b) T6 treated part, (c) 45k-N rolled followed by T6 treatment, and (d-f) 15 k-N, 30 k-N, and 45 k-N rolled part [67].

4.4 Fabrication set-up

Automation plays a vital role in extending the capabilities of WAAM technology, but it also poses significant challenges when it comes to practical implementation. The full potential of WAAM technology, which involves additive fabrication of components to achieve near net shape, cannot be realized without automation. To ensure efficient component production in WAAM, the utilization of automation resources is crucial. These resources consist of a CNC robotic system featuring a power source, a welding torch connected to a wire feed setup, and an online control setup. These automation tools play a vital role in recording and regulating key parameters, thereby facilitating the effective execution of the WAAM process.

4.5 Anisotropy

The characteristics of WAAM products vary depending on the direction of deposition and the thickness of the material. The variation in properties observed in additive manufacturing is mainly attributed to the layer deposition approach. It is observed that the hardness in the final product is directly influenced by the number of layers. Specifically, the layers closer to the component's surface undergo fewer thermal cycles, resulting in an improvement in material hardness. This phenomenon is illustrated in Figure 19 [65].

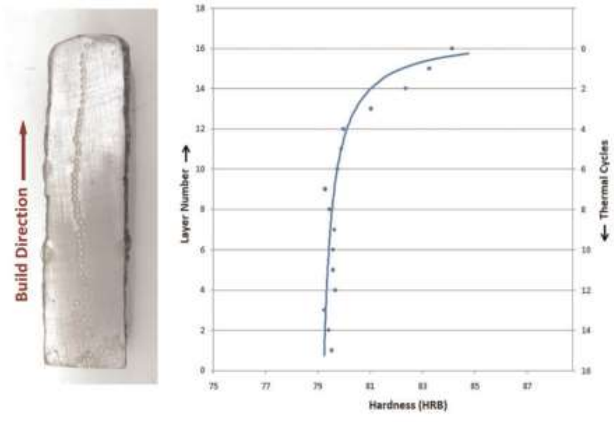


Figure 19. Hardness of WAAM part v/s number of layers [65]

4.6 Process modernisation

Automation is crucial for the widespread adoption of WAAM technology, but it also poses significant practical challenges. Achieving the main objective of WAAM, which is the additive production of components with near net shape, is dependent on the implementation of automation. Automation resources are crucial for harnessing the complete capabilities of the WAAM process. The available resources comprise a setup consisting of a CNC robot, a welding-power source, welding torch integrated with a wire-feed setup, and an online control setup. These tools enable the recording and regulation of essential parameters, facilitating effective control and management of the WAAM process. These automation tools are essential for effectively implementing the WAAM process and ensuring efficient production of components.

V. Future Scope

WAAM is considered the future of the industry due to its ability to offer cost-effective manufacturing and achieve high deposition rates. But for WAAM to become more feasible the researchers need to work on some of its limitations. This section provides some problems that if we solve can make WAAM more useful than ever. In future the WAAM can make use of multi-material wires and make complex structure which are difficult to made even with the conventional techniques. although there are many defects regarding multi material WAAM. In future, work can be done to minimize multi-material defects.

Many WAAM finished products require additional post processing treatment like heat treatment, rolling and plastic deformation to get to the strength as of the same product produced from the conventional way. In future the work can be done to reduce the post processing to the minimum so that it will take less time for production. In future the work can be done to produce more functional products rather than simple geometric shapes. So that it can be reached in commercial market also. And also since we are testing on the standard shapes, we have very little idea of how the product will perform in the application so more test can be made to test the performance of the product in respective applications.

A complete WAAM setup can be made that can work from start from the beginning like slicing of the 3d cad model to end like post processing of the product. The integrated setup can also work on the mechanism to reduce the defects like interpass cooling, interpass cold rolling etc. This will help in reducing time taken for production. Apart from the load testing, environmental testing should also be done so that the product can be used in aerospace and marine applications. A setup should be made to check whether the product will be defective or not while it is being processed. If at any layer a major defect is caught, then the machine should stop processing of that material and cast it aside. This will save both time and material.

As we have discussed in the process parameter section that as each layer goes through the cycle of heating and cooling and therefore its microstructure changes and is different to its previous layers. For manufacturing of the taller structures some more ways and processes can be made to make the product more homogenous in microstructure.

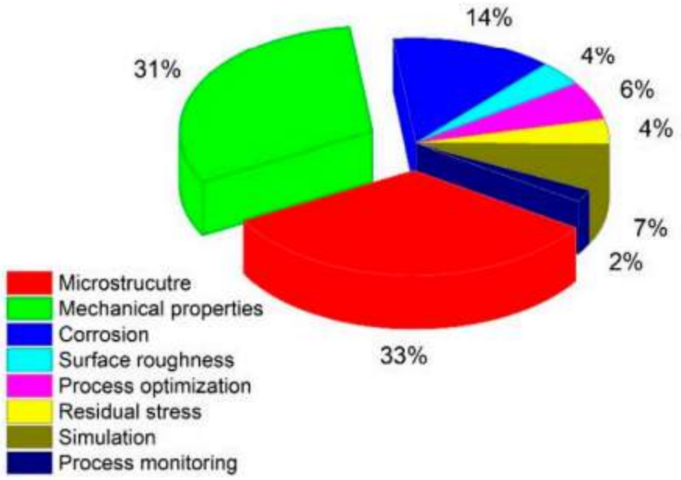


Figure 20. Pie chart shows the work done in research (in form of publications) on different parameters of the DED process [68].

VI. Conclusions

This comprehensive review discusses the essential steps and planning techniques involved in welding arc-based additive manufacturing (WAAM), providing an introduction to WAAM methods. The paper also explores the current trends and challenges in WAAM development. As a cost-effective metal additive manufacturing approach, WAAM is gaining popularity. Successful implementation of WAAM relies on meticulous process planning and optimal resource utilization. Key steps in WAAM process planning include optimizing welding parameters and selecting the most suitable tool path. Ongoing advancements in WAAM encompass areas such as porosity control, management of residual stresses, and addressing high heat input. The relationship between fabrication quality, material properties, and the composition and microstructure of the material is pivotal. Achieving effective that is higher quality and defect less part in WAAM requires a harmonious integration of the process's performance characteristics and a thorough comprehension of material properties. The interdisciplinary nature of WAAM presents a challenge that encompasses thermo-mechanical engineering, process planning, automated welding, mechatronics, materials science, and control systems. This collective effort aims to transform WAAM into a commercially viable fabrication process. By synergizing these diverse fields, the goal is to optimize the performance and reliability of WAAM, making it a reliable and efficient manufacturing method. Among various metal deposition additive manufacturing techniques, WAAM stands out as a strong candidate for replacing current methods of producing parts, particularly in the aerospace industry. Instead of attempting to address all potential issues and challenges with a single system, optimizing WAAM techniques for specific applications is crucial. Ongoing research and development in WAAM aim to advance it from a process focused on approximate shaping to one that achieves precise shaping, thereby significantly increasing its acceptance and utilization across diverse industries. This advancement would enable WAAM to produce finished components with minimal additional machining or processing requirements, thereby streamlining manufacturing workflows and increasing efficiency. With ongoing efforts to optimize process parameters, enhance material properties, and refine deposition techniques, WAAM is poised to become a more prominent and valuable manufacturing solution in the future.

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