



WIRE ARC ADDITIVE MANUFACTURING TECHNOLOGY OF STEELS

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<https://doi.org/10.30572/2018/KJE/170111>

ABSTRACT

Metal additive manufacturing (AM), often known as 3D printing, is revolutionizing the production of complex engineering components by constructing them layer by layer. This innovative process utilizes a high-energy heat source and various materials, such as powder, wire, or sheets, as feedstock. The latest review is focused on the progress made in AM, with its potential to produce steel materials of outstanding properties that cannot be matched by conventional manufacturing techniques. This is mainly attributed to the characteristic microstructural changes in the course for AM. This review indicates that many steel types could be process successfully with AM processes. The microstructure, consisting of hierarchical (sub) grains and fine precipitates formed in the process, is largely responsible for its high strength and wear resistance relative to conventional steel. However, ductility remains an issue with AM steels. Moreover, additive manufacturing is an intrinsic heat treatment process and “in situ” phase transformations such as tempering and different type of precipitations are possible when applied to a range of steel grades. In short, the review amply discusses the effects of these unique microstructure features on the properties of steels made by AM.

KEYWORDS

Additive manufacturing (AM), 3D printers' technology, Arc welding, Steel.



1. INTRODUCTION

3D printing, also called additive layer manufacturing (ALM), is a novel process which produces fully dense metal parts by depositing material in layers, thus eliminating the need for generation of complex metallic parts using conventional machining methods (Baufeld, B et al., 2010). This technology has shown great promise in terms of waste materials reduction, emitted pollutants minimization and energy demand reduction (Huang, R.Z et al 2016). ALM is considered to be a revolutionary methodology for producing net, or near-net shape solid parts by forming (or fusing) layers of material (e.g. powder, wire etc.) on top of each other. The technique is based on melting metal by the heat produced from electron beams, laser beams, plasma or electric arc (Buckner M.A. and Lonnie J.L., 2012). During the last twenty years, manufacturing has shown growing interest in additive manufacturing; its most common applications are component prototypes and versions. A brief history of AM can be found elsewhere (Wohlers T. and Gornet T., 2014). Early AM methods used were stereolithography and 3D printing which initially served to as an aid for the production of polymer parts such as moulds for connections or inspection tools and are increasingly moving into final production applications. Rapid prototyping eliminates the long process of casting and assembly as samples are taken directly from CAD models, thus greatly reducing time in production (Adnan A. et al 2019). Traditional manufacturing processes may encounter difficulties in cutting some materials, such as titanium and nickel-based alloys. Therefore, there is a real need for other types of manufacturing processes that can address these concerns. AM is a very advantageous solution since it requires no dedicated tooling and thus can be easily used for rapid manufacturing. (Adnan A. et al 2019 and Mahmood, R.M.et al 2013).

A roadmap to AM has been published by (D.L. Bourell et al. 2009) that are drawn from a workshop with 65 leading AM figures. The key aspects of AM including design, control, evolution modeling, material constituents, machinery and processes were reviewed in this report. This process variant reduces lead times, permits the manufacture of complex geometries with internal features, design and part consolidation for substitute of several sub-parts and material/financial savings possible.

The purpose of this review is to investigate and assess the abilities and developments achieved in wire arc additive manufacturing (WAAM), with a strong focus on steels. The objective is to research application of WAAM for large metallic constructions which can be economically beneficial characterised by high deposition rates and low-cost, thus being appropriate for a wide range of industrial applications. This overall approach also seeks to address other R&D needs to further improve/add capability to WAAM, such as increasing deposition rates, controlling

quality processes better and understanding more about thermal cycles incl. their effects on the microstructure. This integrated approach is intended to place WAAM as an alternative process for manufacturing high quality steel parts in several applications (D.L. Bourell et al. 2009).

2. ADDITIVE MANUFACTURING PROCESS

In contrast to a subtractive manufacturing process, such as conventional machining, an additive-building-process (ABP), as defined in ASTM Standard F2792, is one that forms a 3-D part by combining materials layer upon layer using 3-D model data. Analysis The AM process can typically be broken down into several key steps, starting with the conception and 3D model of the object that is going to be produced – generally designed using computer aided Design (CAD) software. This object can be created from new, downloaded if pre-made or reverse engineered from an existing product. If your product is a new one, modeling even has no bondage of creativity. Several modelling software exist and are used in engineering and architecture. Once modeling wraps up, the software slices your design into cross sections to produce a digital file. During the printing, the object is formed layer by stack as new material is printed on top of a previous layer (Elif Karayel and Yahya Bozkurt, 2020). The advancement of 3D printing technology has made it possible to manufacture items that are challenging to make or even impossible with traditional methods. Moreover, due to the fact that most of constraints on traditional manufacturing methods are not put on 3D printing, the ability for manufacturing is mostly boundless (Yahya Bozkurt and Elif Karayel, 2020 and Horvath J., 2014).

AM comprises a number of techniques, based on the materials and layer processing methods. Each method has its own advantages and disadvantages. Therefore, when the layered manufacturing technology method is selected, consideration must be given to the material- and method- dependent parameters in order to select an appropriate option. These approaches can be categorized in several ways (Elif Karayel and Yahya Bozkurt, 2020 and Gao W et al.,2015) as illustrated in Fig.1.

Some of the core techniques include powder bed fusion, material extrusion, stereolithography (SLA), material jetting, directed energy deposition (DED), and binder jetting. The basic concept of SLA is to polymerize a liquid photopolymer with the aid of a light source, such that individual small molecules form from several tiny structure units with crosslinked bonding. The part is built up layer by layer as the curing layer adheres, and cures, onto the previous one. The mechanism of DED is based on a concept in which the local melting of the material due to an energy source such as an electron or laser beam is followed by deposition of the molten

materials onto a layer. The filament is fed into an extruder and forced through a nozzle in the material extrusion method, where it is liquefied in a heat chamber. The filament is placed on the built platform by the extrusion head's movement, where it cools and solidifies to form the layered structure (Elif Karayel and Yahya Bozkurt, 2020 and Redwood B. et al.,2017).

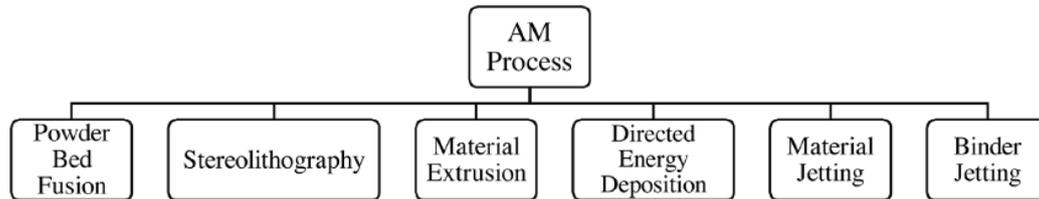


Fig. 1 AM process techniques.

3. WELDING TECHNOLOGY IN ADDITIVE MANUFACTURING

AM technology is noteworthy in the field of welding because of its benefits, including the ability to manufacture complex parts and reduce material waste throughout production. The integration of AM with welding techniques for small to medium-sized components is a novel development in the industry. AM not only mitigates some challenges associated with traditional welding processes but also produces parts with high dimensional precision. This results in components that are strong, non-porous, and highly resistant to fatigue. However, parts created through AM do have size limitations. To solve this problem, in production capacity has been increased; however when combining several sources to produce a large amount of output, errors in calibration can cause mechanical properties variations. Therefore, the components produced additively in small series can be upscaled using different welding techniques. The researches of the combination of AM technology and different welding methods are in progress targeted for expanding its application. Although this is an emerging technology, it has some limitations which do not allow its high scale production commercialization; However, researchers are working to improve the potential application of this technique. Additive manufacturing (AM) lists different procedures that make it industrially applicable, as Laser Additive Manufacturing (LAM), Wire Arc Additive Manufacturing (WAAM) and Electron beam additive Manufacturing (EBAM), can combine AM to welding techniques (Elif Karayel and Yahya Bozkurt, 2020, González J et al 2017; Thijs L. et al.,2013).

3.1. Wire arc additive manufacturing

Welding technology is an improvement to address one of the cons in AM, i.e., limited size of build components. It has been discovered that AM is frequently restricted in the minimum size of parts it can produce, leading to attempts at combining welding processes that can more easily achieve larger sizes. This limitation is overcome using AM processes and welding technology

in combination. Melting is the process that beam based methods and WAAM rely on. So, for the method WAAM depicted in Fig. 2 (AM), wire close to the net form components is deposited in layers by electrical arc processing as heat source. The WAAM technique has enabled higher print resolution, faster deposition rates and better surface quality, reduced production cost and the fabrication of large scale components. Furthermore, WAAM is compatible with a variety of materials and their alloys such as titanium, aluminum, nickel and steel. The WAAM process can be realized by using different welding technologies, e.g., GTAW/TIG, GMAW/MIG or PAW. Much research has been done, especially for performance optimization via parameter tuning. There is a significant body of research on the integration of GMAW process in parts manufactured through AM, highlighting key benefits such as high efficiency and cost-effectiveness. Numerous studies focus on enhancing the application of welding and multilayer manufacturing techniques. Previous research utilizing GMAW as part of AM has demonstrated that outcomes are directly influenced by the instruments and supplies utilized (Xiong J and Zhang G. 2014; Xiong J et al 2017 and Md. Imam Hossain et al 2024). Compared to other metal additive methods, the WAAM process has been a cost-effective means of making some large, individual parts. In addition, this process can be integrated with other welding devices such as a robot or numerically controlled milling machine and used in combination. The WAAM process includes, without limitation, a welding power supply, a computerized robotic system that is computer controlled, a welding glance, and wire feed. AM has profited from the simple use of the MIG-MAG welding process. The combination of AM with welding to produce metal parts of desired sizes and forms has been the subject of numerous investigations. Since MIG is a widely used welding technique, its combination with AM has been considered important. The efficiency and cost-effectiveness of joining are improved by using MIG welding and AM. Effective research has shown the best parameter configurations for combining the MIG approach with AM. For industries like aviation, welding parts made with the AM process increases design freedom. Widespread adoption of this technology is expected, particularly for steel and titanium materials. This approach avoids casting flaws, uses less material, and ultimately saves money as compared to traditional machining methods (TMM) (Elif Karayel and Yahya Bozkurt, 2020, Ammar Yasir Akkar, and Muhaed Alali 2023 and Klobčar D. et al.,2018).

WAAM technique can classify into three strategies based on the type of electric arc torch utilized to melt the filler wire: 3D-TIG welding process, 3D-MIG welding process, and 3D-Plasma welding process (Adnan A. et al 2019 and H. Xin, I. et al 2021), as shown in Fig.3.

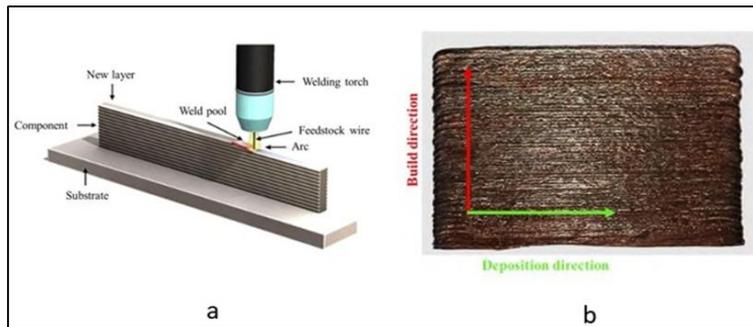


Fig. 2. (a) WAAM schematic, (b) construction and deposition orientation instructions (Klobčar D. et al.,2018).

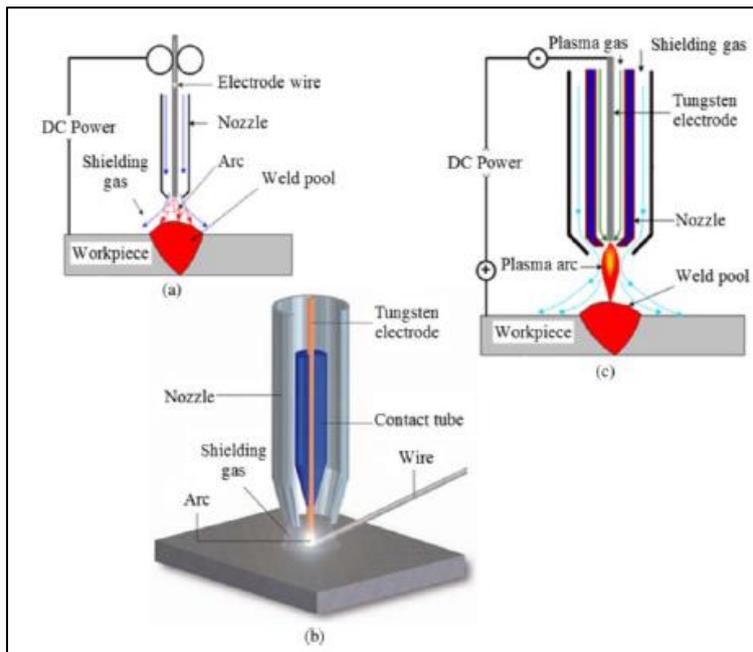


Fig. 3: schematic illustration of the (a) GMAW, (b) GTAW, and (c) PAW process (H. Xin, I. et al 2021)

3.1.1. Types of electric arc

There are three primary types of electric arc utilized in WAAM: Metal Inert Gas (MIG), Plasma Arc (PA), and Tungsten Inert Gas (TIG). MIG is typically the preferred process due to the wire serving as a consumable electrode, aligning coaxially with the welding torch, which simplifies the tool path. In contrast, TIG or PA welding involve non-consumable electrodes, necessitating the feeding of an external wire into the melt pool. For TIG or PA welding, the torch must be capable of rotation to ensure consistent wire feeding from a fixed direction, adding complexity to the manufacturing programming (Ding, D et al 2015 and S. W. Williams et al 2016). Because molten droplets are occasionally released from the arc or weld pool during MIG welding, the metal is transferred from the consumable electrode to the melt pool via the arc, creating surface imperfections and spatter. However, PA and TIG welding are less likely to spatter since the filler metal is delivered straight to the weld pool (W. Williams et al 2016).

Cold Metal Transfer (CMT) is an advanced kind of MIG welding, ideal for aluminum and steel

feed stocks (P. M. Sequeira Almeida and S. W. Williams, 2010). Its controlled dip transfer mode mechanism allows it to produce high-quality beads with less spatter and less heat input. Finer grains result from the decreased heat input, improving mechanical qualities. Construction parts are enormous, thus in order to build them in a reasonable amount of time, a high deposition rate is required. In the construction industry, MIG is the preferred approach since it usually offers the highest deposition rate. As a result, MIG has been the focus of the majority of WAAM construction research (P. M. Sequeira Almeida and S. W. Williams, 2010 and Md. Abdul Hassib 2024).

3.1.2. Control of geometry

WAAM processes are recognized for their high deposition rates; however, they face challenges related to part accuracy and geometry control when compared to other AM techniques, such as laser-based methods. Geometry control is a critical factor in selecting process parameters and has become a significant area of research within WAAM. Research efforts have concentrated on predicting and controlling layer dimensions, in terms of height or width, for a number of metallic materials (Md. Abdul Hassib 2024 and Sian I. Evans 2022). Wire diameter as well as wire feeding speed, heat input and travel/scan speed have the largest influences on the wall thickness and deposition efficiency at single pass deposition. Wire gauges of 0.8 to 1.2 mm are commonly used with construction materials like carbon steels and stainless steels for wall thicknesses of a single-pass in the range of 3.5mm to several millimeters (T.Abe and H. Sasahara, 2019 and Ding et al., 2011).

The dimension of every layer, which is influenced by different kinds of process variables and their combined interactions, should not only be predicted but also managed due to the geometric accuracy requirement in WAAM components. One of the first methods of digital modeling in order to predict the right parameter values for machining was given by (Ding et al 2011). For the prediction of accumulated residual stress and distortion, they modelled in finite element the thermo-mechanical behavior related to multi-layer wall structure produced by WAAM process. (Xiong et al. 2013) studied the control and prediction of the deposition geometry in the GMAW- WAAM process. They established a closed-loop iteration mechanism for inferring the process parameters, and determined neural network modeling as the geometry prediction approach. This digital modeling technique has enhanced the confidence of residual stress analysis and geometric control of WAAM components.

3.1.3. Slicing and path planning

The geometrical design of WAAM's parts is governed by a number of manufacturing constraints (Xiong et al. 2013, Mufutau Adeniyi. 2025 and P. Kyvelou et al 2021):

- Reduced starts and stops: Consistent operation of the process is essential, including reducing the number of starts and stops of the power source to eliminate breakage in one trajectory throughout production.
- Overhang Angles: The overhanging angles should be kept to a minimum in order to avoid structural instability, when the part is printed.
- Torch Location: Proper location of the welding torch is required to avoid interference with the AM parts.
- Junctions: Bridging T or X junctions is a key to the structural integrity.
- Circular Cross-Sections: Items with simple cross-sections can be formed in a continuous mode (one wall pass) to reduce the number of process steps.

For constructing complex structures such as WAAM tubular trusses, path planning solutions are created. These strategies are based on clustering the like geometric feature to follow the same printing strategy, minimizing the substrate side flip-over, and keeping a vertical building orientation. The viability of these methodologies is tested via simulations in virtual parts like Metal XL, based on the principles of slicing and kinematic analysis (M. Bruggi et al 2021 and F. Michel et al 2019).

3.1.4. Microstructure

Microstructure The microstructural characteristics of WAAM products play an important role in determining the material properties similar to that of welds. Nevertheless, different printing methodologies like parallel paths or antiphased scan direction can result in various microstructures. Grains tend to grow into the centreline of the melt pool in conventional welds. On the other hand, if changing the scan direction between layers, it enables to make the grains grow more erect (V. Laghi et al 2020 and W. Jin et al 2020). The microstructure generated in WAAM manufactured parts tends to be complex and cannot always be described using an individual grain size number, as one might expect from the layer-by-layer production process (M. J. Bermingham et al 2019).

4. APPLICATIONS

There has been significant research in the AM that contributed to its adoption in a range of industries and gave rise to new applications. AM technologies have seemed to be the trend in various domains ranging from automotive, aerospace, medicine and building, see Figs 4, 5, and 6. This is because each of those industries have so many uses for them. In 2012, an overview was given of the application areas for AM technologies as seen in Fig.3, (Elif Karayel and Yahya Bozkurt, 2020 and Guo N, Leu MC. 2013).

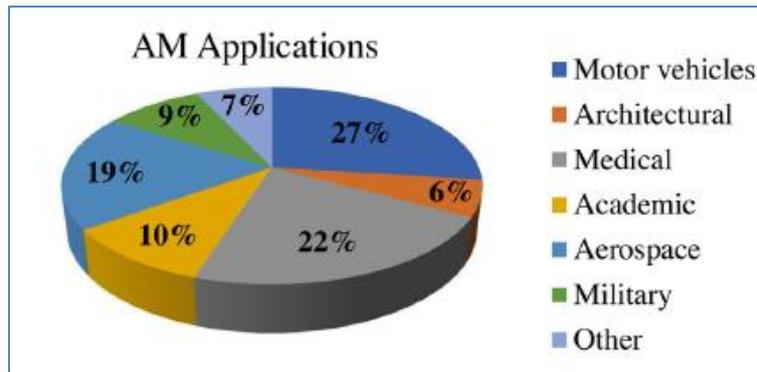


Fig. 4: AM applications worldwide market share (Elif Karayel and Yahya Bozkurt, 2020).

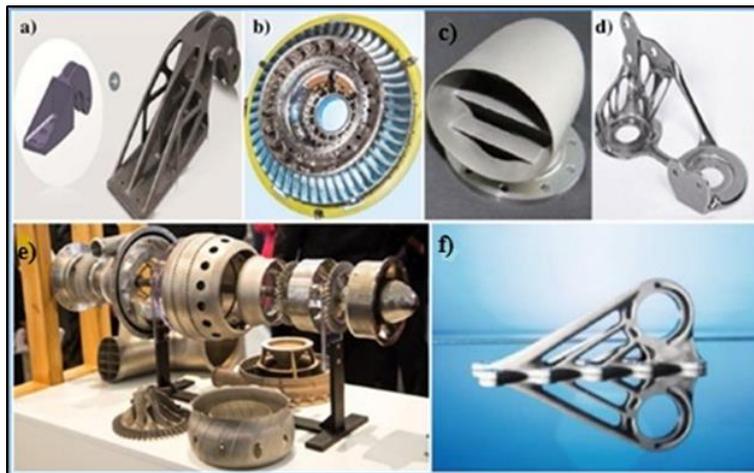


Fig. 5. Aerospace components made with AM technology include (a) Airbus's Hing holder, (b) the Rolls-Royce Trent XWB engine made with the EBM method, (c) AM's liquid oxygen flange, (d) an aerospace hinge part made with the laser powder bed method, (e) a gas turbine engine made with 3D printing, and (f) an Airbus bracket connector. (Elif Karayel and Yahya Bozkurt, 2020)

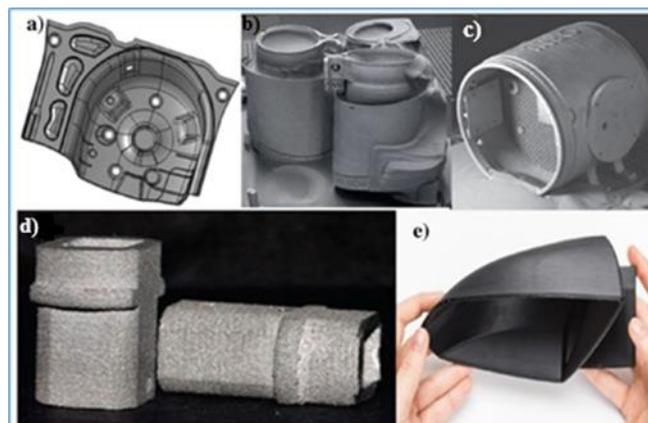


Fig. 6: AM-produced automotive components include: (a) a body panel model to be generated with AM; (b) a titanium tailpipe made with powder bed fusion; (c) a hydraulic manifold made with EBM; (d) a turbocharger made with a 3D printer; and (e) a motorcycle wing mirror made with FDM. (Elif Karayel and Yahya Bozkurt, 2020)

5. CONCLUSIONS

The conclusion of this study emphasizes several key findings and implications for the future of this innovative manufacturing process. Wire Arc Additive Manufacturing (WAAM)

demonstrates significant potential for producing large steel components efficiently, offering high deposition rates and lower costs compared to traditional methods. This places WAAM on a potential level for other industries in need of large metallic structures. The work demonstrates that WAAM process can introduce unique microstructural features in steels, e.g. exceptionally fine precipitates and hierarchical (sub) grains, resulting in enhanced properties such as strength and tribological performance. These microstructural features are essential to the improvement of WAAM-manufactured parts. The above conclusions highlight the necessity for further research focusing on development of more advanced WAAM technology, quality control and a complete understanding of the influence of different process parameters on final microstructure and mechanical properties. Moreover, the study of fatigue resistance and corrosion behavior will be necessary to broaden WAAM in industrial applications.

Overall, the study concludes that while WAAM presents numerous advantages for steel manufacturing, addressing its challenges will be essential for maximizing its potential in various engineering applications.

6. THE RESEARCHER'S PERSPECTIVE

As a researcher, I view Wire Arc Additive Manufacturing technology for steels as a highly promising field that offers significant advantages over traditional manufacturing methods. Here are some key perspectives on this technology:

- **Efficiency and Cost Savings:** WAAM allows for the rapid production of large, complex components with high deposition rates, reducing production time and costs compared to conventional methods.
- **Material Properties:** WAAM can produce steels with unique microstructural features, such as fine precipitates and hierarchical grains, which enhance mechanical properties.
- **Environmental Benefits:** The process generally has a lower environmental impact due to reduced material waste and energy consumption.
- **Microstructural Optimization:** Understanding how process parameters influence microstructure is essential for optimizing material properties. This includes the role of shielding gases, thermal history, and post-processing treatments.
- **Mechanical Properties and Anisotropy:** WAAM components often exhibit anisotropy in mechanical properties due to layer-wise deposition. Developing strategies to mitigate this, such as in-situ rolling, is a key research area.
- **Industrial Adoption:** For widespread industrial adoption, further research is needed to improve deposition rates, reduce defects, and enhance quality control systems.

Generally, WAAM technology holds great potential for transforming steel manufacturing, but addressing its challenges through ongoing research will be essential for realizing its full benefits.

ACKNOWLEDGMENTS

The authors would like to extend a huge thank you to everybody who has encouraged this scientific work.

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