

Review:

Review of Wire Arc Additive Manufacturing for 3D Metal Printing

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Wire arc additive manufacturing (WAAM) is a crucial technique in the fabrication of 3D metallic structures. It is increasingly being used worldwide to reduce costs and time. Generally, AM technology is used to overcome the limitations of traditional subtractive manufacturing (SM) for fabricating large-scale components with lower buy-to-fly ratios. There are three heat sources commonly used in WAAM: metal inert gas welding (MIG), tungsten inert gas welding (TIG), and plasma arc welding (PAW). MIG is easier and more convenient than TIG and PAW because it uses a continuous wire spool with the welding torch. Unlike MIG, tungsten inert gas welding (TIG) and plasma arc welding (PAW) need an external wire feed machine to supply the additive materials. WAAM is gaining popularity in the fabrication of 3D metal components, but the process is hard to control due to its inherent residual stress and distortion, which are generated by the high thermal input from its heat sources. Distortion and residual stress are always a challenge for WAAM because they can affect the component's geometric accuracy and drastically degrade the mechanical properties of the components. In this paper, wire-based and wire arc technology processes for 3D metal printing, including their advantages and limitations are reviewed. The optimization parametric study and modification of WAAM to reduce both residual stress and distortion are tabulated, summarized, and discussed.

Keywords: wire arc additive manufacturing (WAAM), 3D printing, additive manufacturing (AM), welding, fused deposition modeling (FDM)

1. Introduction

Over the past two decades, additive manufacturing (AM) has seen rapid development in industry. It was previously known as rapid prototyping (RP), rapid tooling (RT), and layered manufacturing (LM) [1, 2]. AM was started in the 1980s with stereolithography [3]. AM

can potentially fabricate a practical product directly from computer-aided-design (CAD) data [4]. Traditionally, subtractive manufacturing (SM) has been more widely used than AM. SM starts with raw material that is larger in size than the designed component and removes unwanted material until the component is fabricated. Unlike SM, AM has the beneficial effect of diminishing the cost of manufacturing, as its layer-upon-layer deposition process does not waste any material. AM also produces relatively complex shapes better than does SM [5]. It has been conclusively shown that AM contributes significantly to decreasing the high casting buy-to-fly ratio. This design can be attached to a 3D printing machine to greatly reduce the cost of additive materials. Nowadays, a considerable number of 3D printing machines are open source, which can minimize their cost. The CAD component design will transfer to the machines in standard tessellation language format (STL). The machines receive the data and fabricate the component according to the settings of the 3D-modelling software.

WAAM was inspired by the fused deposition modeling (FDM) technique. The additive materials used have mainly been plastic, polymer, and ceramic [6]. FDM was introduced in the 1990s with thermoplastic as the additive material [7]. FDM can manufacture low-budget structures relatively quickly, but FDM cannot be used to fabricate overhang structures [8]. Concurrently, the uses of metal have been gaining in popularity in AM technology. Among the seven categories developed to fabricate metal components are four AM technologies: binder jetting, power bead fusion, sheet lamination, and direct energy deposition. Each of the categories consists of different technologies, as shown in **Fig. 1**. Another way of classifying them is based on the state of the raw material during metal 3D printing. **Fig. 2** shows the types of materials and their technologies. The application of liquid-based material is relatively new in metal 3D printing. This technology melts the raw material from the solid state to the liquid state and propels the liquefied metal droplets to fabricate a metal component using an electromagnetic field [9]. This speeds up the fabricating process and allows high-intensity metal components to be fabricated.



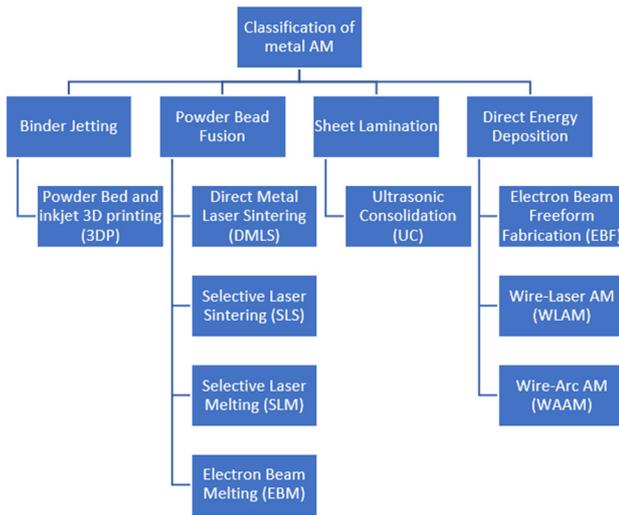


Fig. 1. Classification of metal additive manufacturing technologies.

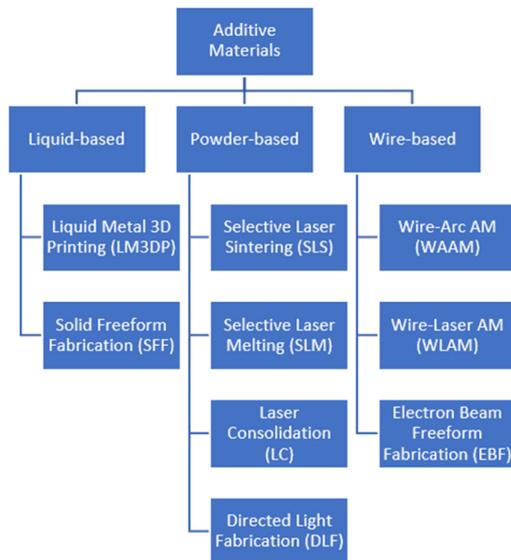


Fig. 2. State of additive materials for 3D metal printing.

Powder-based materials were used before wire-based materials to fabricate metal components. Powder-based materials are suitable for the fabrication of small components because of better geometrical and dimensional accuracy. However, the deposition rate and the fabricated build volume from powder bed based fusion process is relatively low [10]. Therefore, powder-based additive manufacturing (PBAM) can be used to fabricate high-quality and high-precision metal components, and the fabricated structures are sufficiently strong for practical applications. The heat sources used are lasers or electron beams. Powder-based processes include direct metal sintering (DMLS), selective laser sintering (SLS), selective laser melting (SLM), and electron beam machining (EBM). Powder-based metal additive materials are often used in the SLS and SLM processes. There are more than 50 parameters that can influence the SLS process, but the

main parameters are laser beam spot size, scanning speed, laser power, and fabricated layer thickness [11]. Unfortunately, PBAM has limited use in the large-scale manufacturing of metal components due to its low deposition rate. Thus, wire-based additive materials have been studied to overcome the limitations of powder-based additive materials in large-scale metal component manufacturing.

Wire-based additive manufacturing (WBAM) has recently been studied extensively due to its high potential for use in metal 3D printing. WBAM has advantages in terms of material usage efficiency, as the wire additive material is fully deposited into the metallic parts or components. Besides, WBAM has no limitations in terms of build volume. There are three different groups in WBAM: laser-based, arc welding-based, and electron beam-based [12, 13]. Generally, three of these groups have the same process but differ in their power sources and deposition rates.

Laser-based and electron beam-based technologies are typically the same, as both of these power sources can produce 2–10 g/min deposition. Surprisingly, the arc welding-based power sources have larger deposition gaps among the technologies, as they can reach 50–130 g/min. The deposition rate depends on the energy efficiency. Among the three power sources, laser-based has the lowest energy efficiency, approximately 30% to 50%, whereas the energy efficiency of the electron beam-based is slightly higher than that of the laser-based. Arc welding-based has the highest energy efficiency, around 90% [14].

2. Wire-Arc Additive Manufacturing

WAAM is also known as shaped metal deposition (SMD) [15]. This technology can produce large-scale metal components relatively economically, but it is inferior to other AM technologies in terms of accuracy and surface roughness. Besides, high residual stress and distortion are common in WAAM due to its high heat input. WAAM is a direct feeding process that involves the combination of electric sources, a motion system, and wire-based feedstock. There are three heat sources in WAAM technology: metal inert gas (MIG), tungsten inert gas (TIG), and plasma arc welding (PAW) [16, 17]. **Fig. 3** is a schematic diagram of these three heat sources. MIG is the most common choice of heat source because of its direct-feeding spool of welding wire, which is coaxial with the welding torch [19]. MIG is a welding process that generates an electric arc between the consumable wire electrode and the workpiece. There are four welding modes in MIG: the globular mode, short-circuiting mode, spray mode, and pulsed-spray mode. Cold metal transfer (CMT) was later introduced as modified MIG. CMT has better performance than MIG owing to its capability to produce a high deposition rate with lower heat input. TIG and PAW have the same welding process that produces the electric arc through a non-consumable tungsten electrode. Unlike the MIG or CMT direct wire feeding

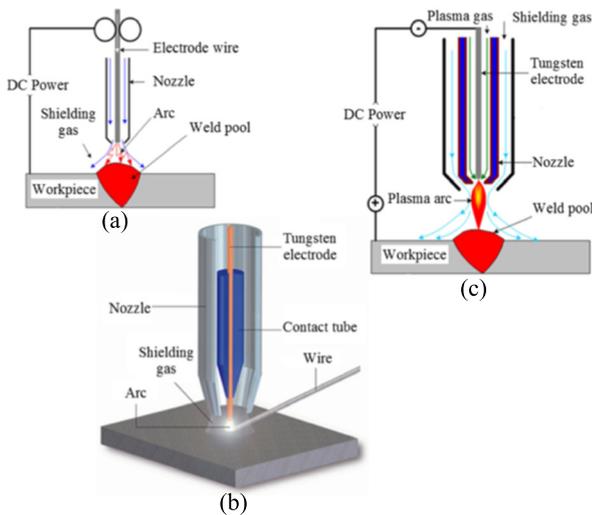


Fig. 3. Schematic of WAAM: (a) MIG, (b) TIG, and (c) PAW [18].

spool, the wire feed orientation of TIG and PAW is externally provided. This requires a wire feeding machine to supply the additive materials, and this additional equipment complicates the process. PAW generates an electric arc that is three times higher than that of TIG. In addition, the heating zone of the plasma arc is narrower than that of the TIG, and this allows it to deposit smaller components [20]. When the plasma arc current is below 30 A, the process is called microplasma arc welding (MPAW) [21]. MPAW has a smaller heat-affected zone than does a normal plasma arc. Thus, the formation of distortion is lower than with PAW [22]. Additive materials for WAAM can be aluminum [23], nickel alloys, titanium alloys, or stainless steel.

Many studies involving the design and modification of the WAAM system have been done. One of the modifications based on the concept was ready-to-use additive layer manufacturing (RUAM), introduced by Mehnen et al. [24]. The design and modification were made in order to fabricate large-scale metal components. It was shown that the concept can be used to fabricate complex geometrical structures and minimize the distortion and residual stress through FEM. Rosli et al. developed a low cost WAAM motion system to reduce the cost of WAAM [25]. The author successfully built a low-cost system for metal 3D printing at about RM 3496.

Kazanas et al. and Xiong et al. utilized the positional welding method to build an inclined and horizontal wall [16, 26]. The effect of travel speed on the angled wall quality was identified. Experiment work was carried out by Colegroves et al. to reduce the residual stress instead of using FEM calculation [27]. A profiled roller is attached to the back of the welding torch to flatten the manufactured layer to reduce the residual stress and improve the surface roughness of the layer. The roller design concept of Colegroves et al. was used by Donoghue et al. to refine the coarse β grain structure [28]. The authors stated that the β grain size can be reduced to $< 100 \mu\text{m}$

through roller grain refinement. These findings agree with the findings of Colegrove et al., which showed that the roller system can convert the improper β grains structures to a fine equiaxed structure [29]. The results also stated that the bulk deformation method can reduce the porosity and enhance the ductility of aluminum alloy. This was in line with the findings of Honnige et al. [30]. McAndrew et al. modified the roller by enlarging the roller radius to provide a more uniform grain size [31]. Another study conducted by Ding et al. [32] proposed the design of a divide-and-conquer strategy to generate an optimal tool path to fabricate convex structures. The starting/stopping points are minimized to provide a path to build up convex structures that are smoother than those obtained using the hybrid method. Later, Ding et al. presented another new path design, medial axis transformation, to improve the geometrical accuracy of structures [33]. The T-shaped optimization was then studied by Venturiri et al. [34]. They found that the intersections between the walls were the most crucial issue to be eradicated, and they demonstrated the fabrication of corners. Kapil et al. combined the advantages of AM technology and SM technology to achieve a high-quality structure [35]. AM technology is used to fabricate metal structures, overcoming the accuracy limitations of AM through the SM machining process. Similar experimental work has been performed by other researchers [36–38]. Additionally, ultrasonic vibration was used to stabilize and increase the amount of extrusion [39]. Liang et al. combined the TIG arc and CMT arc to perform multipass welding. TIG-CMT is suitable for WAAM [36]. Kapil and Liang's studies were similar to Karanukaran et al.'s studies, in which WAAM technology was combined with the milling process to reduce surface roughness [40]. The twin wire weld deposition concept was presented by Somashekara and Suryakumar [41]. They studied the effects of parameters on bead geometries. Qi et al. conducted experimental work using twin wire weld deposition with aluminum-magnesium and aluminum-copper to increase the mechanical properties of structures [42]. Yang et al. compared the fabricated structure of single electrode gas arc welding (MIG) to that of double electrode gas arc welding (combination of MIG-TIG). Double electrode gas arc welding can reduce the molten pool volume by 30% [43]. Besides, the length, depth, and width were narrower than when a single MIG torch was used. **Table 1** presents the designs and modifications of WAAM.

3. Parametric Studies of WAAM

Previous studies have reported some factors that can affect the WAAM structures. An optimization parametric study was carried out by Clark et al. who used MIG to study the cracking and shrinking porosity through the post-deposition, heat-treated condition [48]. Baufeld et al. studied the microstructure by using different parameters [49]. They found that the microstructure varies based on the thermal history. The ultimate tensile strength

Table 1. Designs and modifications of WAAM.

Year	Specific area	Material	Heat source	Improvement features	Author
2012	Positional welding-inclined fabrication	Mild steel and aluminium	CMT	<ul style="list-style-type: none"> – Limited accessibility and no manipulation needed – Produces walls from different angles – Closed shapes can be printed 	Kazanas et al. [26]
2013	Profiled roller and slotted roller	Mild steel	CMT	<ul style="list-style-type: none"> – Minimizes the distortion phenomena – Decreases surface roughness 	Colegroves et al. [27]
2014	Design of tool-path generation strategy	Mild steel	MIG	<ul style="list-style-type: none"> – Shortens the starting-stopping point rate – Increases surface accuracy 	Ding et al. [32]
2016	Double wire feedstock	Iron and aluminium wire rods	TIG	<ul style="list-style-type: none"> – Fabricates components with two materials at the same time – Reduces the deposition rate 	Shen et al. [44]
2016	Optimization of T-shaped structure	Carbon steel	MIG	<ul style="list-style-type: none"> – Optimizes deposition strategy – Reduces residual stress and strain – Increases height accuracy 	Venturiri et al. [34]
2016	Hybrid manufacturing	Mild steel (ER70S-6)	TIG	<ul style="list-style-type: none"> – Refines dimensional accuracy – Fabricates cylindrical geometries 	Kapil et al. [35]
2016	Adaptive path planning	Copper steel	MIG	<ul style="list-style-type: none"> – Enhances geometrical accuracy – Prevents void form during deposition 	Ding et al. [33]
2016	Rolling deformation	Ti-6Al-4V	TIG	<ul style="list-style-type: none"> – Enhances β grain – Reduces strain level 	Donoghue et al. [28]
2017	Combination of TIG and MIG	Aluminium ER4043	TIG-CMT	<ul style="list-style-type: none"> – Improves contact angle and weld bead dilution 	Liang et al. [36]
2017	Bulk deformation method	Not stated	Not stated	<ul style="list-style-type: none"> – Improves grain structure – Lessens residual stress and distortion 	Colegroves et al. [29]
2017	Double wire deposition	Copper (ER 70S-6 and ER110S-G)	MIG	<ul style="list-style-type: none"> – Optimizes mechanical properties, especially hardness of structure 	Somashekara and Suryakumar [41]
2017	Slicer and process improvement-MOSTMetalCura	Mild steel (ER70S6)	MIG	<ul style="list-style-type: none"> – Eliminates overlap movement – Infill deposition starts instantly – Complex geometries can be fabricated 	Nilsiam et al. [45]
2017	Single electrode (MIG) and double electrode (MIG-TIG)	Steel (H08Mn2Si)	MIG and TIG	<ul style="list-style-type: none"> – Decreases molten pool volume 30% – Decreases heat accumulation 	Yang et al. [43]
2017	Flat and inclined position deposition	Steel (H08Mn2Si)	MIG	<ul style="list-style-type: none"> – Contact inclined-angle can be set greater than 45° 	Xiong et al. [16]
2018	Thermal stress relief and rolling	Ti-6Al-4V	PAW	<ul style="list-style-type: none"> – Removes crystallographic texture – Decreases hydrostatic tensile stresses 	Honnige et al. [30]
2018	Doubled wire system	Al-Co (ER2319) and Al-Mg (ER5087)	TIG	<ul style="list-style-type: none"> – Refines mechanical properties – Optionally uses two different materials simultaneously during deposition 	Qi et al. [42]
2018	Combination of AM and SM	Mild steel (ER70S-6)	MIG and CMT	<ul style="list-style-type: none"> – Allows advanced geometric shapes to be fabricated – Decreases heat accumulation – Includes surface finishing process 	Prado-Cerqueira et al. [37]
2018	Inert gas trailing shield	Ti-6Al-4V	TIG	<ul style="list-style-type: none"> – Prevents atmosphere oxidation – Enhances inert gas shielding 	Birmingham et al. [46]
2018	Double wire feeding	Stainless steel	PAW	<ul style="list-style-type: none"> – Increases process efficiency – Raises deposition rate higher than that with single wire feeding process 	Feng et al. [38]
2018	Low cost application	Mild steel (ER70S-6)	MIG	<ul style="list-style-type: none"> – Lowers cost of application – Advances material properties – Is sustainable 	Nilsiam et al. [47]
2018	Enlargement of roller size	Ti-6Al-4V	PAW and TIG	<ul style="list-style-type: none"> – Increases recrystallised extent area – Allows roller load to be increased – Further refines grain 	McAndrew et al. [31]

(UTS) of fabricated structures was tested. The UTS is between 929 MPa and 1014 MPa, depending on the testing position. The location greatly affects the UTS of structures. UTS can be tested in the travel direction and build direction [50]. Later, Baufled et al. compared the microstructures, UTS, stain failures, and fatigue limit of WLAM and WAAM [51]. It was reported that the UTS of both WLAM and WAAM structures are slightly different, around 900–1000 MPa. This result is similar to the findings of Brand et al. [52]. The data shows the UTS of WLAM and WAAM is 872–940 MPa and 930–981 MPa, respectively. Voltage affects the arc length of the heat source. The linear relation between voltage and length of arc was illustrated in the work of Bonaccorso et al. [53]. The dimensional properties of PAW structures were reported by Martina et al. [54]. Total wall width was around

17.4 mm whereas the effective wall width and layer height were 15.9 mm and 6.0 mm, respectively. Xu et al. carried out an experiment to explore the impact of an intercooling strategy and continuous deposition strategy on microhardness, UTS, yield strength (YS), and the elongation of fabricated structures [55]. Four different heat treatment processes were applied and compared in terms of mechanical properties. Jhavar et al. tried to use microplasma to fabricate 3D structures [56]. The structures were successfully built, and their microhardness was 253–616 HV. The microstructure metal components of WAAM were found to be free from porosity, inclusions, and cracks. Xiong et al. described the current as being the main parameter affecting the appearance of fabricated metal components [57].

Another test was conducted by Xiong et al. to revamp the stability of the process through a sensing and con-

tol system [58]. Cong et al. used different CMT processes, such as pulsed CMT (CMT-P), advanced-CMT (CMT-ADV), and pulsed-advanced CMT (CMT-PADV), to study physical properties of additively manufactured component [23]. They deduced that the pore count of CMT-PADV was nearly eliminated. Cong et al. further compared CMT-P and CMT-ADV [59]. Their paper reported that the width and height of the CMT-ADV structure is wider and lower than that of CMT-P. Similarly, Ma et al. indicated how the interpass temperature affects the structure's α phase fraction and microhardness [60]. The interpass temperature was increased from 100°C to 500°C in the experiment, and minor reductions in α phase and microhardness were observed. Lin et al. proposed a method to enhance the structure's physical properties and mechanical properties [61]. Different current values and voltage values were tested on different layers. The first layer current and voltage were set to 250 A and 21.7 V, respectively. The current and voltage values were gradually decreased as the manufacturing layer increased. Remarkable improvements in the mechanical properties of the structure were reported. The material and deposition strategy is also one of the common factors affecting the WAAM structures. Zhang et al. performed an experiment with different materials and different deposit directions [62]. They studied three different directions, namely, single pass, oscillation, and parallel, to determine the effects of these differences on mechanical properties. The results showed that different materials and deposit directions will have different YS values. To date, few studies have focused on a single parameter because the parameters of WAAM are all interrelated.

4. Applications and Limitations of WAAM

WAAM technologies are popular in manufacturing industries, including aerospace, automotive, and rapid tooling, owing to their large-scale fabrication. WAAM is widely used in developing aerospace components having complex geometries [10]. The cost of high-budget materials, such as titanium alloys and nickel alloys, can be reduced, decreasing the buy-to-fly ratio in turn. This technology can shorten manufacture times, reduce production costs, and increase the productivity of designing and prototyping. Most components manufactured by using WAAM technology have simple geometries, but geometrical accuracy might not be as high as with other AM technologies [14]. Besides, WAAM uses an extremely high-temperature heat source. Two major issues are caused by high thermal input: residual stress and distortion. Both of these phenomena often occur in WAAM. Residual stress and distortion affect geometrical accuracy through the deformation of plastic, drastically affecting the mechanical properties and performance of components. Besides, the lifespan of the fabricated metal components is shortened due to the reduction in the effective fatigue life and tensile strength of the components. Residual stress is classified into two types, compressive stress and tensile

stress [63]. During the fusion process, the surrounding cold substances are constrained by the thermal expansion of the heated specimen, causing compression stress. The contraction of cooling substances with nearby cold substances can induce the formation of tensile stress behind the heat source.

Fortunately, counterstrategies to minimize or eliminate the residual stress and distortion were found with substantial effort. Colegroves et al. introduced two rollers, a profiled roller and a slotted roller, that can be used to reduce the residual stress of a specimen [27]. Both rollers can reduce the surface roughness and distortion, but the slotted roller is the more effective of the two. The welding parameter was studied using a finite element modeling program to observe the effects of beam size, scan speed, power density, and the distribution of residual stress [64]. Transient calculations of residual stress and distortion were then estimated using numerical thermomechanical models [65].

In order to reduce residual stress, Colegrove et al. used the bulk deformation method to reduce the residual stress and layer distortion [29]. A rolling system was attached to the WAAM to slide through the layer at room temperature to refine the layer grain structure. It was proved that the porosity of the specimen is dramatically reduced. A similar experiment was carried out by Honnige et al., who found that the stress of discontinuous deposition is lower than that of continuous deposition [30]. Later, McAndrew et al. modified the size and load of the roller to achieve better grain refinement [31]. It was shown that the structural strain was forced toward the edge of the roller groove. This finding allowed them to refine the grain of large-scale components. Szost et al. studied the microstructure and residual stress of both WLAM and WAAM [15]. The researchers stated that components fabricated with WLAM and WAAM both exhibited fully dense structures with several pores in the vicinity of the base plate. It was found that the WAAM component had a larger heat zone and coarser grain than did the WLAM component. It was concluded that residual stress is higher with WAAM than with WLAM.

5. Conclusion

WAAM is increasingly being used as an AM option. Many studies claim that WAAM can significantly reduce costs and improve production efficiency in industrial fields, especially the aerospace and automotive fields [66]. Hence, many studies have concentrated on improving the WAAM process through modifications during the printing. Aluminum alloy, titanium alloy, stainless steel, nickel alloy, and mild steel are the additive materials that are often used in WAAM. MIG, TIG, and PAW are the heat sources that can be used in WAAM due to their high heat input. In addition, a double torch has been proposed in place of a single torch. Double heat sources can reduce the molten pool volume by 30%. The length, depth, and width of the molten pool were narrower with a double

torch. Unfortunately, high thermal input can generate residual stress and distortion, but counterstrategies have been found. One of the potential strategies is through the roller application method, in which bulk deformation can reduce residual stress and distortion. The roller slides through the layer to minimize porosity and refine the grain size. This method produces better-quality printed parts than does normal WAAM.

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