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REVIEW

A Review of Challenges for Wire and Arc Additive Manufacturing (WAAM)

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Abstract Wire and arc additive manufacturing (WAAM) has a high deposition rate, high material utilization, and compact structure, so it is especially suitable for low-cost, high-efficiency, and fast near-net-shape manufacturing of large-scale complex parts. However, in the WAAM process, many challenges limiting the quality and performance of the deposited layers, such as the WAAM process options and material selections limiting deposition performance and microstructure, manufacturing defects weakening the quality of the deposited layer, and the difficulty in predicting the quality and the performance. This paper outlines the challenges of WAAM, summarizes the challenges of material selections and processing methods, improving microstructure and performance, defect monitoring and improvement, simulation technology and artificial intelligence technology introducing predictive WAAM, and finally analyzes its development trends.

Keywords Wire and arc additive manufacturing (WAAM) · Microstructure · Performance · Defects · Artificial intelligence

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1 Introduction

With a trend of complexity of the large-scale metal material components used in the aerospace field, shipbuilding and other high-end equipment manufacturing, making traditional processing technologies increasingly unable to meet the processing needs, however, wire arc additive manufacturing (WAAM) shows special advantages in complex component manufacturing [1–3]. WAAM uses an electric arc as an energy source to add materials to parts through layer-by-layer surfacing, with high heat input, fast forming speed, easier deposition and more economical [4–8]. Currently, WAAM has become a promising manufacturing process for various industrial and scientific materials. For example, it has been successfully applied to aluminum alloys, magnesium alloys, titanium alloys, steel and gradient materials [9–11]. However, when WAAM is used for metal additive manufacturing, due to poor arc stability and poor controllability of the molten pool, defects such as molten pool metal overflow and deposition structure collapse are prone to occur, which affects the forming quality of additive manufacturing components and the deposition performance of WAAM [12, 13]. Therefore, improving the quality and performance of deposit are important.

In the process of WAAM, there are many challenges, especially in the following four aspects. The first difficulty is that, the inherent physical or chemical properties of the material during processing will greatly affect the quality and properties of the deposition. For example, during WAAM, the periodic heat input to the deposited layer due to the good thermal conductivity of the aluminum alloy may result in thicker columnar grains and periodic cracks [14, 15]. Second, in the wire and arc additive manufacturing process, there are many factors that affect the processing technology and the challenge of poor molding process stability. Take

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CMT (cold metal transfer) technology as an example. CMT is a combination of droplet transfer and wire withdrawal technology [16–18]. In the process of droplet transfer, the arc is extinguished, and the welding current is reduced to almost zero, which greatly reduces the welding heat input [19, 20]. In other words, a variety of factors determine the quality and performance of WAAM. Third, the challenge is how to raise the threshold of microstructure and performance, for example, the regulation of performance and microstructure through external energy [21–23].For example, the heat input within the optimized range will improve the fluidity of the molten metal, reduce the stress concentration of the molten metal, and improve the quality of the deposited layer [24–27]. The fourth challenge is the online diagnosis and improvement of defects, which is particularly important for overall quality monitoring and improvement [28–31]. Sometimes, the added part and the surface fluctuate greatly, resulting in poor surface quality of the WAAM-deposited part [32–34]. The fifth challenge is how to predict the reliability introduced by simulation technology and artificial intelligence technology, for example, to plan the path of arm motion to explore the impact on WAAM performance improvement [35–40].

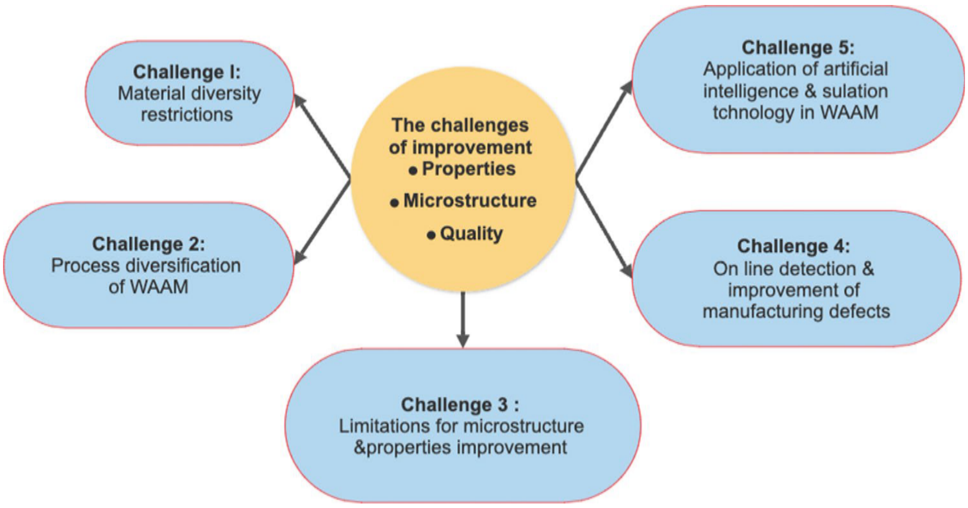
Owing to the obvious economy and promising application prospects, these challenges of the WAAM process and properties have been studied, including the arc feature of metal materials, manufacturing process, defect diagnosis and improvement and simulation and artificial intelligence application in WAAM. In preceding publications, these challenges were proposed and researched to discuss the lack of research and predict the future development direction of wire arc additive manufacturing [41–43], including material challenges on mechanical properties in lightweight alloys [44, 45] and process diversification of WAAM [46, 47]. However, previous studies do not deeply summarize and discuss from the above 4 challenges, so it is important to generalize and summarize previous studies. In particular, simulation and artificial intelligence can more reliably predict repository dimensions, enable accurate manufacturing and lead this WAAM to a high-performance, defect-free deposition.

This paper reviews the major challenges of WAAM in the research of metallic materials. Special attention is given to the challenges of material diversity, WAAM process diversification, limitations of microstructure and performance improvement, improvement of online detection and manufacturing defects, and application of WAAM artificial intelligence and simulation technology, shown in Fig. 1. During the manufacturing process, this greatly determines the properties, microstructure, and quality of WAAM deposition. In total, 5 types of WAAM challenges are discussed, and many encouraging research results have been achieved. On this basis, from the authors' viewpoint, some important research directions or ideas are proposed for future work.

2 Material Characteristics During WAAM

Metal materials are the key objects of WAAM, and the properties of the metal materials directly determine the properties of the WAAM deposition. However, metal materials processed by manufacturing materials have diversified performance due to their physical properties and heat treatment [48, 49]. WAAM has the characteristics of high energy, high efficiency and large molten pool volume; thus, its application is a range of large-scale shape, low-cost and high-efficiency rapid-forming components and has been successfully applied in a large kind of metal material, such as stainless steels, aluminum alloy and nickel-based materials [50, 51]. However, with the production of metal materials, it seems that the limitations of various materials have been overcome, and multiple advantages have improved WAAM deposition. Figure 2 shows the advantages and disadvantages

Fig. 1 Challenges of wire and arc additive manufacturing



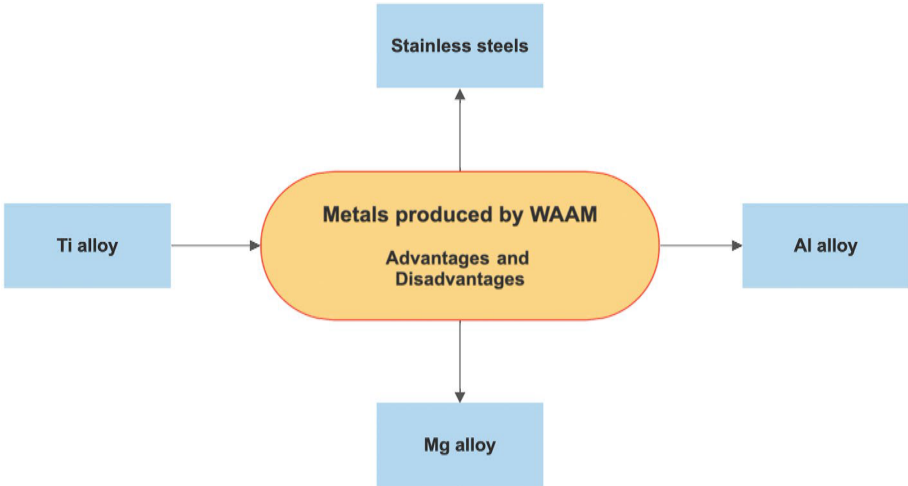


Fig. 2 The advantages and disadvantages of typical metal materials produced by WAAM

of typical metal materials produced by wire and arc additive manufacturing, which is the focus of this discussion.

2.1 Al Alloy

Aluminum alloy has the advantages of high strength, good corrosion resistance and conductivity, low-cost, good forming process and good weldability, it is possible to produce complex WAAM microstructure deposition in the application prospect of metal arc additive manufacturing, such as the car wheels and aluminum alloy brackets [52, 53]. However, during the arc additive manufacturing process of aluminum alloy, the periodic heat input will cause the formation of coarse columnar grains and periodic cracks that affect the performance of the microstructure, which has a greater impact on the performance of WAAM. Moreover, the microstructure defects that restrict the performance of WAAM have become an urgent problem to be solved. Therefore, improving the properties by optimizing the microstructure is of great significance to the improvement of the quality of WAAM.

In addition, the content or composition of a certain element also has an impact on the quality of aluminum alloy. Production by WAAM sometimes has a significant impact on WAAM deposition. Peng J et al. [54] studied the crystal orientation evolution, columnar to equiaxed transformation and mechanical properties achieved by adding TiCps to the wire and arc additive manufacturing 2219 aluminum alloy. As shown in Fig. 3, the results show that as the weight fraction of TiCps increases, the average grain size first decreases and then increases.

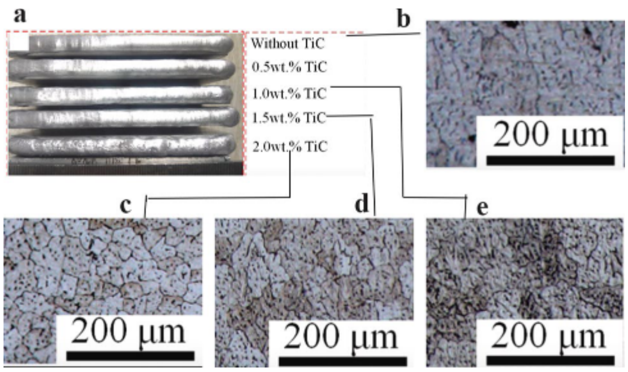


Fig. 3 Microstructures of 2219 Al alloy deposited after adding different mass fractions of TiCps, **a** as deposited, **b** without TiC, **c** 1.0 wt%, **d** 1.5 wt%, **e** 2.0 wt% [54]

2.2 Mg Alloy

Owing to its high specific strength, magnesium alloy is a promising material for further lightweighting in WAAM material applications, such as aircraft (propellers) and components of new energy vehicles (steering wheels). Magnesium is the lightest construction metal available and is mainly used in the form of cast components. It can be processed in a variety of casting processes, including gravity casting, low- and high-pressure die casting, and theorizing [55]. However, magnesium alloys used in wire and arc additive manufacturing also present some challenges (Fig. 4).

2.3 Ti Alloy

The traditional preparation process of titanium and titanium alloy parts has been smelted many times to forging or rolling, and then the excess material on the blank is removed by turning, grinding, polishing and other methods. The forming process is complicated, resulting in a lower utilization rate of titanium and titanium alloy [56, 57]. For example, in the manufacturing process of the titanium alloy fuselage of the Boeing 787 aircraft, approximately 83% of the titanium alloy is cut off during the processing process, causing

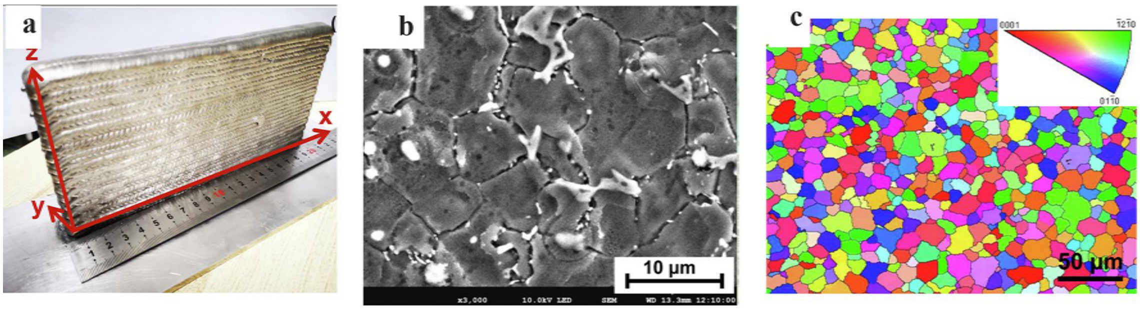


Fig. 4 **a** wire arc-formed deposits. **b** microstructure of WAAM, **c** grain orientation map [55]

considerable waste. [58]. For example, Mereddy et al. [59] studied the influence of silicon on the grains of WAAM-processed titanium alloys, which can be used in scientific research and 3D printing of aeronautical parts, as shown in Fig. 5.

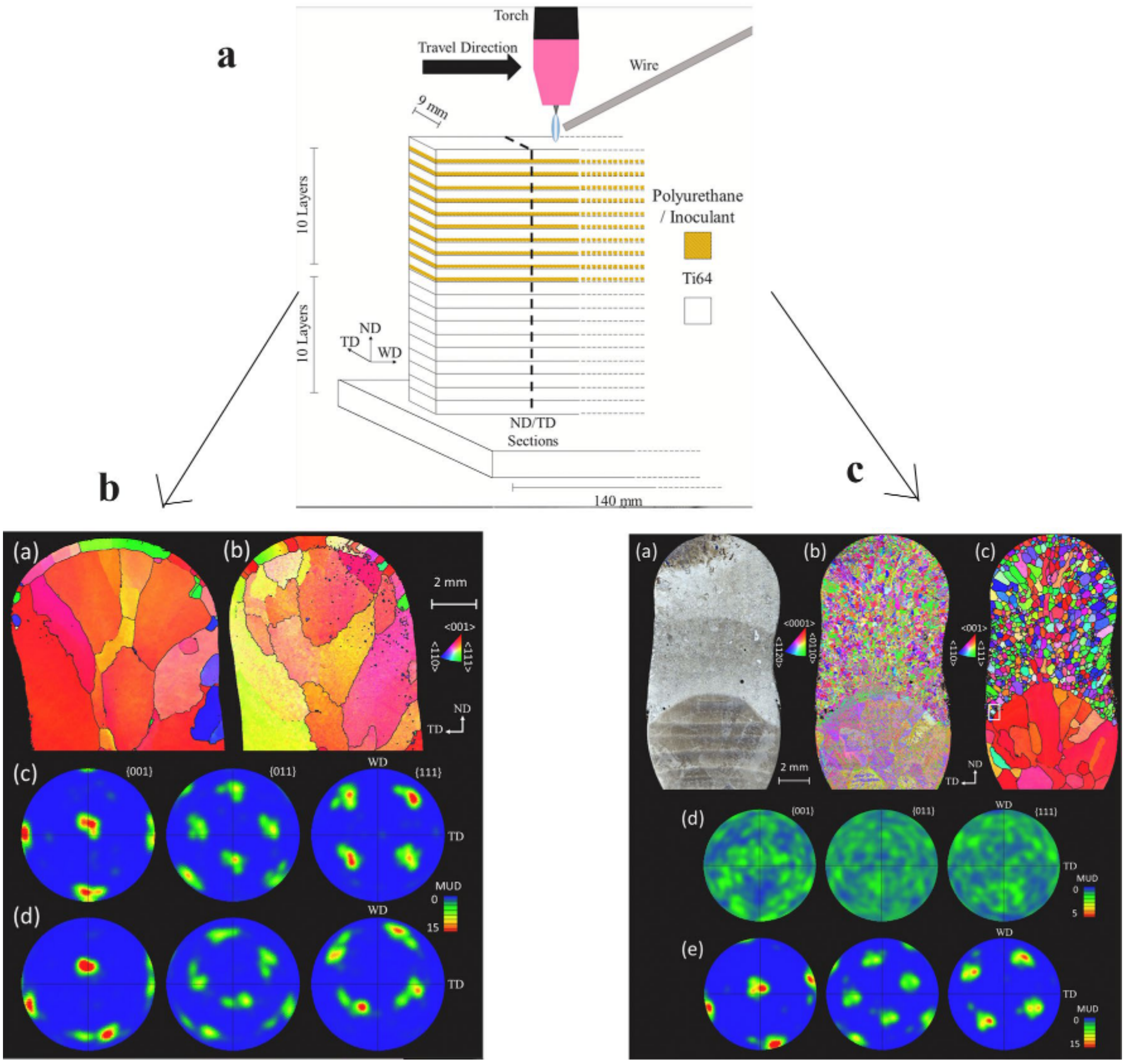


Fig. 5 **a** Test sample schematic and reference frame. **b** IPF//ND reconstructed β orientation EBSD maps for the baseline **c** cross section of the sample produced with TiN additions [60]

2.4 Stainless Steels

Stainless steel produced by WAAM no longer meets a certain stainless steel's performance; therefore, an increasing trend in stainless steel research is to compound the properties between stainless steels and other metals/other stainless steels into WAAM deposition. For example, Kim SG [60] investigated the fabrication of 304 SS workpieces with three main deposition directions (X, Y, and Z) using WAAM. The results showed that the YS, UTS, and elongation of the X-, Y-, and Z-direction specimens satisfied the ASTM standard specification of the 304 SS plate and the YS, UTS, and elongation were up to 35, 20, and 45% higher, respectively. This results can be used in construction of building materials. Dharmendra. C [61] studied the hybrid parts of nickel aluminum bronze/316 L stainless steel. The results showed that Fe3Al intermetallic was formed at the nickel aluminum bronze/316 L bimetallic-joint interface, and occasional liquation cracks on the grain boundaries were observed in the heat-affected zone (HAZ) of 316 L substrate, in as shown in Fig. 6.

Therefore, Table 1 summarizes the advantages and disadvantages of different materials in the additive manufacturing process, which provides a reference for the development of additive manufacturing of the same metal and dissimilar metals.

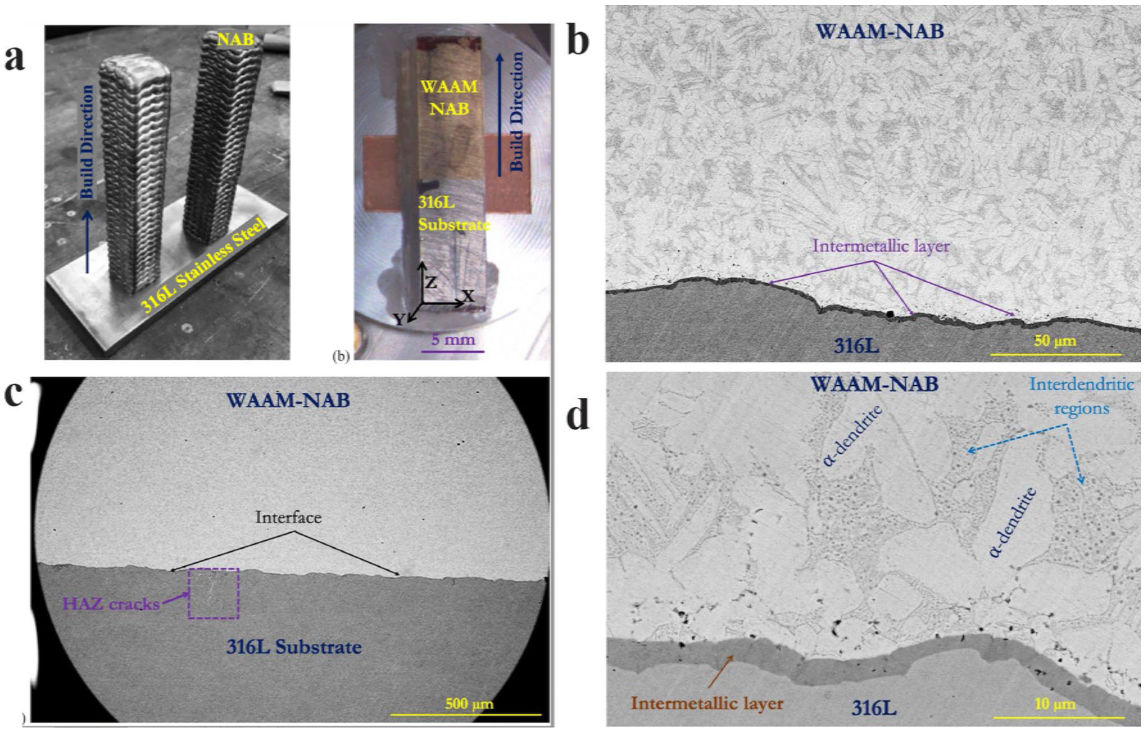


Fig. 6 **a** Picture of NAB/316L SS hybrid part, **b** photograph of WAAM-NAB deposit on 316L SS substrate, and **c** low-magnification SEM image of NAB/316L sample showing a well-bonded interface **d**. Note occasional heat affected zone cracks in 316L substrate [61]. Metals produced by WAAM

Table 1 Variety of materials for WAAM

Materials	Advantages	Disadvantages
Al alloy	Low density, high specific strength, strong corrosion resistance, high thermal conductivity, easy processing and forming, low-cost	When the heat input is large, the precision of the molded sample is poor, and it is easy to form pores
Mg alloy	High specific strength and specific stiffness, superior damping performance and electromagnetic shielding performance, high recovery rate	Poor flame resistance; deformation defects
Ti alloy	Low-cost, simple machining procedures, and direct production of near-net-shape parts	High melting point, low density, high oxidation resistance
Stainless steels	Low-cost, widely employed for producing large dimensional metallic components	Large size error; deformation defects

3 Diversified Processing Technology Selection

Additive manufacturing can be divided into various processing types according to the heat source. Typical heat sources include lasers, electric arcs, and electron beams. According to different heat sources, metal additive manufacturing can be divided into laser additive manufacturing (LAM), wire arc additive manufacturing (WAAM) and electron beam additive manufacturing (EBAM) [1, 2, 62, 63]. In contrast, wire and arc additive manufacturing (WAAM) has obvious characteristics among the three heat source processes. For example, the advantages of WAAM equipment are fast molding speed, low equipment requirements, and well adapt to complex environments. On the other hand, the disadvantages are that the forming accuracy of WAAM is low and energy-consuming. For the scope of an application of additive manufacturing, the characteristics of WAAM are remarkable. For example, it can manufacture large-scale steel structures/composite parts and can repair parts in harsh environments such as outer space and underwater [63–65].

Figure 7 shows the classification of WAAM, which informs our review. Figure 8 is a schematic diagram of the three methods of wire and arc additive manufacturing, which provides a three-dimensional perspective reference for the subsequent discussion.

The choice of additive manufacturing process has a great influence on the performance of WAAM depositions [67, 68]. Therefore, the performance and quality of WAAM processing obtained by different processing techniques are also different. The following describes the advantages and disadvantages of each processing technology and the processing limitations of the response and introduces some of the latest research progress.

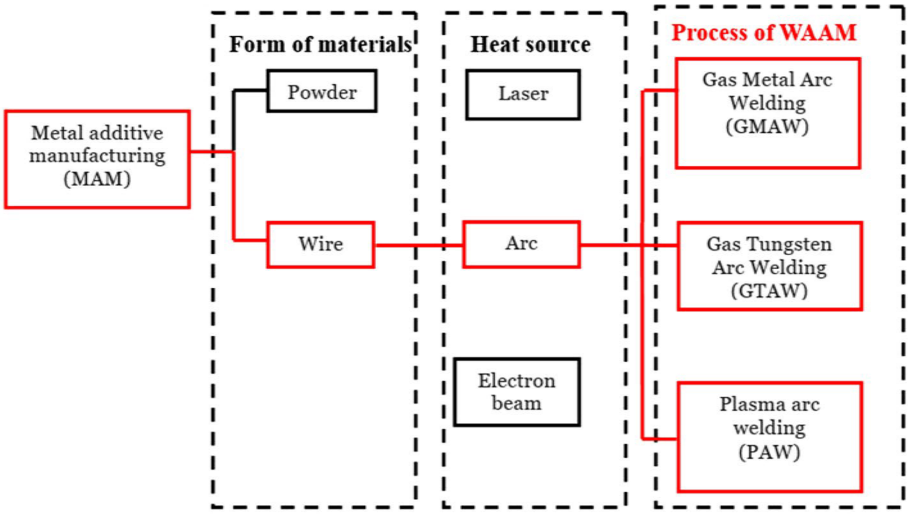


Fig. 7 The classification of WAAM

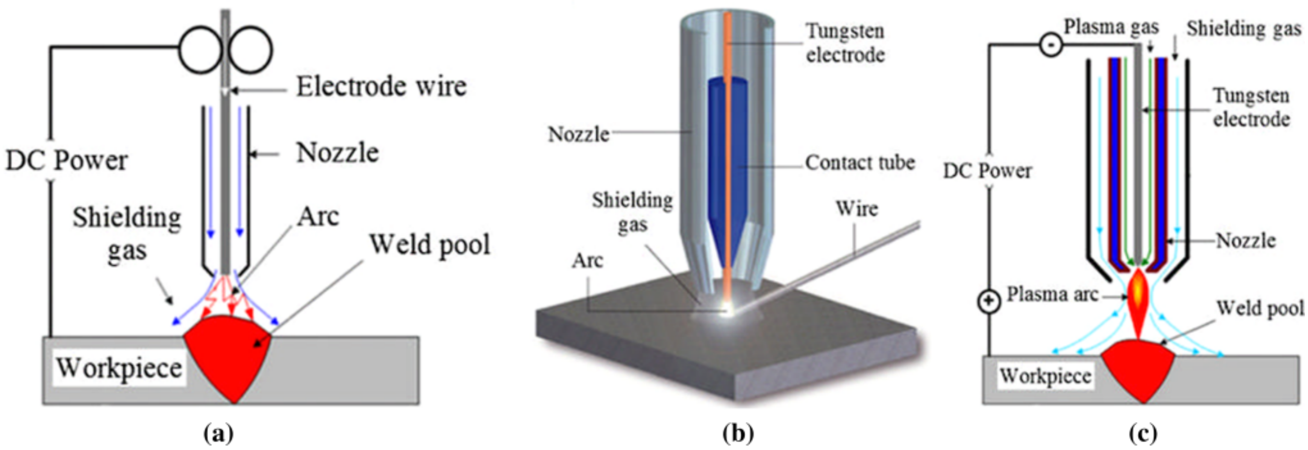


Fig. 8 Schematic diagram of a GMAW, b GTAW, and c PAW processes [66–68]

3.1 Gas Metal Arc Welding Additive Manufacturing

Gas metal arc welding additive manufacturing is a multiple heating and remelting process using an arc as the heat source. It is a complex process with multiple parameters, strong coupling and nonlinearity. It belongs to arc additive manufacturing. In contrast to high-energy beam additive manufacturing, the cost is low, and the efficiency is high. The outstanding advantages of high efficiency show obvious advantages in the rapid prototyping of large-size and complex structural parts. However, the process parameters of GMAW directly affect the heat input and heat accumulation. The heat input is relatively large, and severe heat accumulation will have a certain impact on the molding accuracy and performance [24, 68, 69]. Therefore, the research of GMAW is to improve the deposition efficiency and geometric accuracy, and it is also a major challenge to control the heat input to the WAAM [70, 71].

Therefore, it is necessary to improve GMAW to improve deposition efficiency and geometric accuracy, improve arc stability and round-trip arc additive forming angle research, reduce additive manufacturing time and double-wire manufacturing, and study the difference between different arc modes.

3.2 Gas Tungsten Arc Welding Additive Manufacturing

Gas tungsten arc welding additive manufacturing (GTAM) is an arc welding method that uses nonmelting tungsten electrodes for welding. When performing GTAW welding, shielding gas is used in the welding area to prevent air pollution (inert gas such as argon is generally used), and solder (filler metal) is usually used in combination, but this step can be omitted for some self-fluxing welds. During the welding process, the arc conducted by highly ionized gas and metal vapor (i.e., plasma) serves as a constant current welding heat source to provide energy. GTAW welding is often used for welding stainless steel and aluminum, magnesium, copper alloy and other nonferrous metal sheets. Compared with manual arc welding and gas metal arc welding, it is easier to control the welding position and improve the welding quality. However, GTAW welding is more complicated and difficult to master, and the welding speed is significantly slower than other welding methods. An actual picture of the WAAM is shown in Fig. 9 [20, 50, 72, 73].

3.3 Plasma Arc Additive Manufacturing (PAAM)

Plasma arc-based additive manufacturing technology has the characteristics of arc concentration, high energy density, and high production efficiency. Compared with GMAW, the plasma arc has the advantages of high forming accuracy, no spatter, and a stable arc. At the same time, compared with GTAW, the plasma arc heat input is larger, the manufacturing efficiency is higher, and the arc is more concentrated than the tungsten argon arc, so that the molding accuracy is higher, and the surface quality of the molded part is better. Pulsed plasma arc additive manufacturing (PPAAM), combining pulsed plasma arc welding with AM, is a promising technique that can produce full-density, near-net-shape parts. As a new type of technology, PPAAM has many advantages, such as high forming speed, full density, and low-cost, compared with laser and electron beam additive manufacturing. Therefore, plasma arc additive manufacturing is a process technology that combines the advantages of melting electrodes and nonmelting electrodes and has a wide range of scientific research significance and value. For example, Wang et al. [74] fabricated an Inconel 718 thin wall by PPAAM and found that the temperature gradient and SDA remelting contribute to grain structure transformation, and the morphology of Nb-rich phases is sensitive to the grain structure and cooling rate, as shown in Fig. 10.

The processing method of wire and arc additive manufacturing provides new possibilities for high-end manufacturing. However, each processing method has its advantages and disadvantages. Therefore, we summarize these three methods and list their advantages and disadvantages, as shown in Table 2. The table shows the comparison of the various processing processes of WAAM. According to the comparison and the actual processing technology, the process can be better selected, resulting in excellent performance and a dense microstructure.

4 Challenges of Improving Microstructure And Performance

The deposition formed by arc additive manufacturing technology is composed of full weld metal, which has a uniform chemical composition and high density and has the advantages of high strength compared with integral forged parts. However, because the arc is used as the energy source, the deposited microstructure will have relatively coarse grains, and properties such as hardness and strength may not reach the expected goals. Therefore, there are also many difficulties and challenges in arc additive manufacturing (Fig. 11).

4.1 Grain Refinement

The strengthening of refined grains is one of the many performance improvement methods for arc additive manufacturing. After grain refinement, it can not only promote columnar crystal-equiaxed crystal transformation but also obtain better toughness and strength, improve the overall mechanical properties of the material, and provide a good idea for solving the problems in aluminum alloy

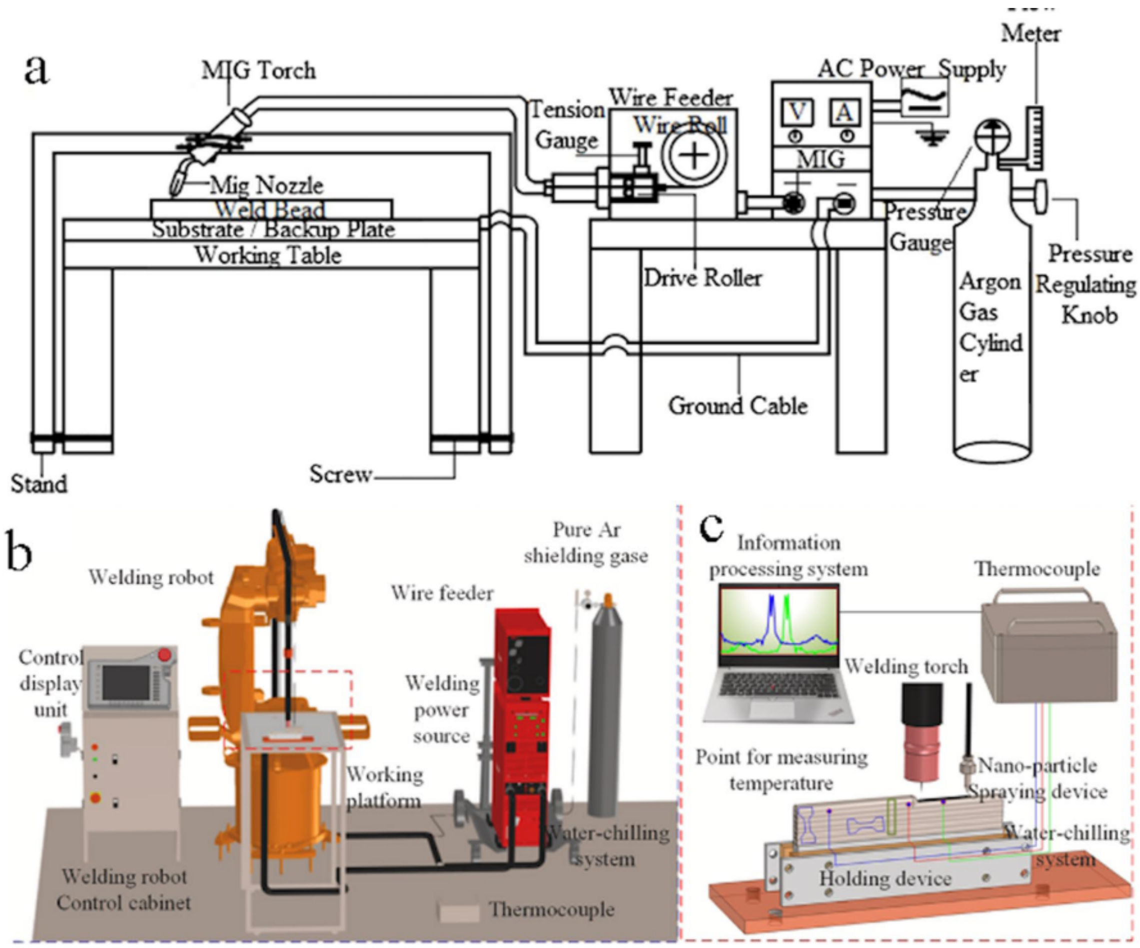


Fig. 9 Schematic diagram for the Gas Metal Arc Welding Additive Manufacturing system **a** 2D schematic diagram, **b** 3D equipment schematic diagram, **c** WAAM 3D processing schematic diagram [73]

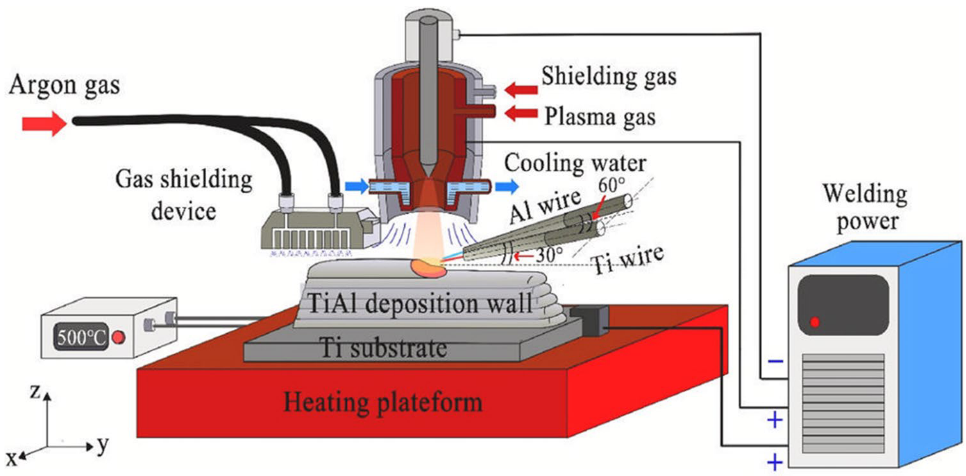


Fig. 10 The schematic diagram of the TW-PAAM system [72, 75]

additive manufacturing. The finer grain size can improve the strength, plasticity and toughness of the material, and the structure and mechanical properties are more evenly distributed. Therefore, grain refinement is an effective way to improve the overall mechanical properties of the material. Therefore, the realization of grain refinement of aluminum alloys or other metal materials can reduce the susceptibility to thermal cracks in the additive manufacturing process and

Table 2 Comparison of advantages and disadvantages of common wire and arc additive manufacturing

Method	Features	Advantages	Disadvantages
Gas Metal Arc Welding Additive Manufacturing (GMAW)	The metal wire is used as a melting electrode	Low-cost and high efficiency, suitable for manufacturing large-sized complex structural parts	Larger heat input will cause severe heat build-up which affects molding accuracy
Gas Tungsten Arc Welding Additive Manufacturing(GTAW)	Tungsten wire is used as a non-melting electrode	Prevent air pollution, suitable for welding nonferrous metal plates such as aluminum, magnesium, copper alloys, etc., easy to automate	The penetration depth is shallow, the deposition speed is slow, and the productivity is low
PAWAM(PAW)	The heat source is plasma	Arc concentration, high energy density, and high production efficiency	The price of inert gas is higher than other arc welding methods, and the production cost is higher

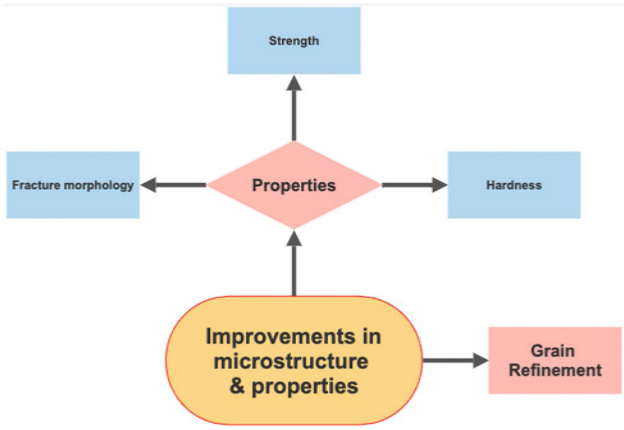


Fig. 11 Summary of Improvements in microstructure and properties

can realize the optimization of the mechanical properties of the additive manufacturing deposition. A changed process is shown in Fig. 12.

Besides, magnetic fields and lasers significantly influence the properties and microstructure of WAAM, and they are external energy sources that substantially impact deposits. Table 3 summarizes the effect of using magnetic fields and lasers on deposited layers for WAAM.

4.2 Properties

Obtaining good properties is the goal of WAAM, which determines the quality and usage scenarios of the deposited products. However, in the actual processing of WAAM, the deposition of the produced WAAM cannot reach the expected performance target or is far below the actual performance target, and poor performance will have important adverse effects in real life. Therefore, the challenge of studying performance improvement needs to be focused on.

Strength is an important index and a monitoring performance indicator of the quality of WAAM deposition. However, in actual production, unqualified strength deposits are often found and cause huge losses. Therefore, it is of great significance to improve the strength of WAAMs. Figure 13 shows a graph comparing the tensile strength and elongation of the new alloys of conventional materials, which can provide a reference for the tensile strength of the deposited layers for WAAM.

For wire and arc additive manufacturing, the control of the processing process is a critical method to determine the performance. Improving the performance can be achieved by introducing a new energy field or changing the processing technology. Table 4 shows the conventional processing methods for enhancing the performance of processing engineering.

5 Online Defect Detection and Improvement

In the process of WAAM, the quality of the deposition will be affected by many aspects, such as poor arc stability and excessive heat input, resulting in defects of additive manufacturing deposition. Defects are manifested as porosity, cracks, residual stress, roughness of manufacturing and other issues. To solve and improve this problem, some technologies and solutions have been introduced, as shown in Fig. 14

5.1 Crack

Cracks seriously weaken the performance of WAAM deposition, reducing the risk of exposure to the machine that often occurs in the actual production process. Therefore, research on cracks can deal with the defects of this crack well. Lei et al. [75, 77] used a high-speed camera for online defect detection, as shown in Fig. 15. The camera can report the crack process of the propagation. This technology can be used to decrease the initiation of the crack.

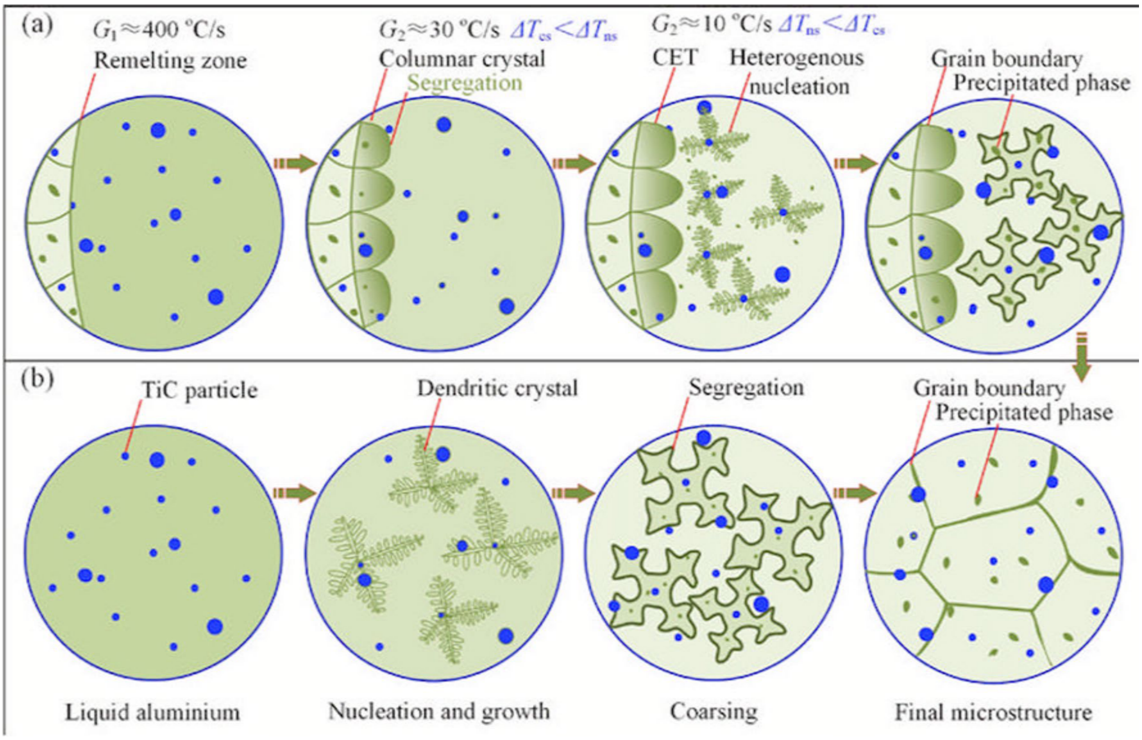


Fig. 12 Microstructural evolution in the deposited samples with the addition of 1.5 wt% TiC particles **a** inner-layer zones, **b** inter-layer zones [54]

Table 3 Influence of external energy on the properties and microstructure of WAAM

Tool	Effect on properties	Effect on microstructure
Magnetic Field	Enhances the fluidity of the molten pool and controls the performance of the deposition	A suitable magnetic field can refine the grains
Laser	Improves the problems of high laser reflectivity of aluminum alloys in laser additive manufacturing, easy to produce spatter, and rough structure of arc additive manufacturing samples	In pursuit of higher precision and finer grains

5.2 Porosity

Porosity is a defect that easily occurs during wire and arc additive manufacturing. Its existence reduces the compactness and corrosion resistance of the weld, reduces the effective load-bearing area of the deposit, and easily forms as a concentration, thereby reducing the strength and plasticity of the joint. Therefore, the pores must be strictly controlled. Several characterization techniques were applied at this time, for example, the line elemental map, area map and electron microprobe analysis (EPMA).EPMA has an essential application in the study of the metal interface of the substrate and deposited metal manufactured by wire and arc additive manufacturing such as Liu D et al. [76, 78] used electron probe to test the element distribution of the WAAM deposition, and results showed that the eutectic contained aluminum, zinc, magnesium and copper, and the distribution were uniform.

5.3 Microscopic Deformation

It can be seen from the figure that when cracks were formed, the molten metal in the molten pool exchanged elements with the surrounding environment, such as water and carbon-containing powder. During the solidification of the molten pool, the solidification cracks also continuously expanded [68, 79]. To investigate the effect of wire feeding speed on solidification cracks, EDS tests were performed on welded joints at each wire feeding speed. Three groups of representative results were selected for the tests, as shown in the following Fig. 16.

5.4 Low Precision of Deposition

Accurately calculating and controlling the macroscopic dimensions (layer width, layer height) of deposition are very difficult. There are many factors that affect the stability of

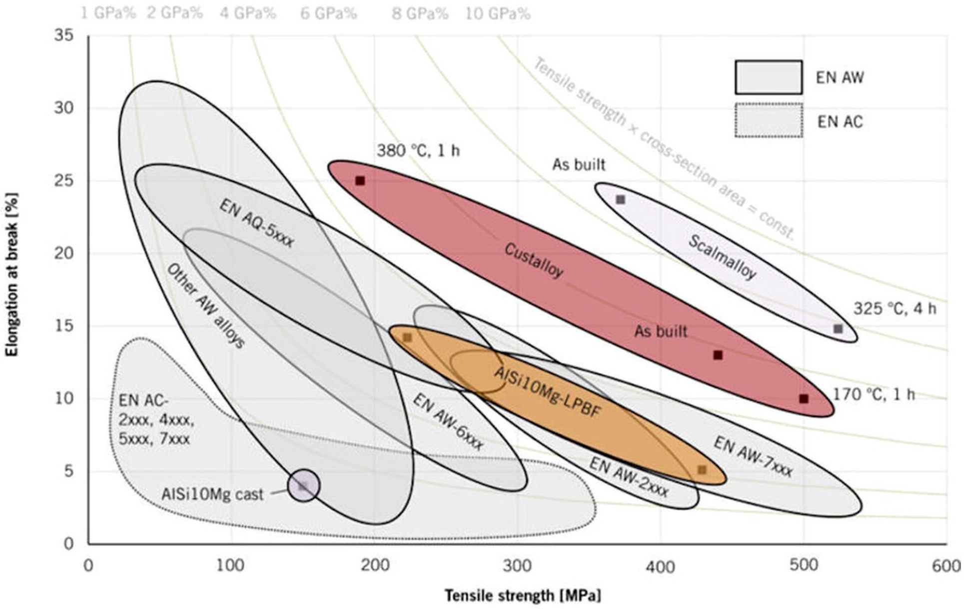


Fig. 13 Comparison of the new alloy with conventional materials [76]

Table 4 Properties and Common Processing Methods of WAAM Deposition

Properties	Common method
Strength	Increase strength by controlling process parameters, choice of materials, adding laser/magnetic fields, etc
Hardness	Increase hardness by controlling process parameters, choice of materials, adding laser/magnetic fields, etc
Fracture morphology	Improve the quality of fracture morphology through alloy strengthening and grain refinement

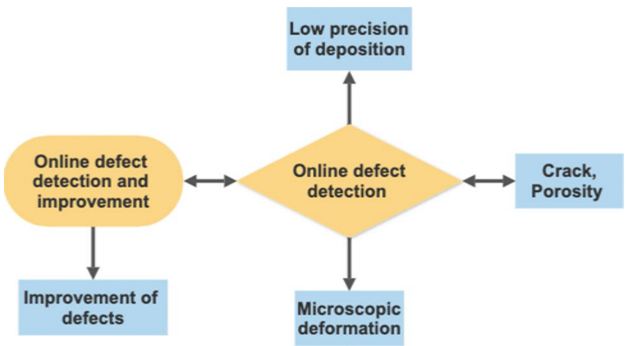


Fig. 14 Diagram of online defect detection and improvement

the arc in the WAAM process, such as the volume of the molten metal and the welding heat input. In addition, heat input during the WAAM process will also cause substrate deformation, which brings more challenges to dimensional accuracy control. In addition, the forming path of WAAM is different, and the thermal cycle, stress, deformation, microstructure and performance of the obtained deposition are also different, as shown in Fig. 17.

The defect detection methods of wire and arc additive manufacturing are extensive, and there will be some limitations in actual testing for these detection methods. Table 5 summarizes the five inspection processing methods and points out the defect types, advantages, and disadvantages of inspection, which provides a reference for speeding up inspection efficiency.

6 Application of New Technology Introduced to the Processing of Wire and Arc Additive Manufacturing

With increasing wire feeding speed, the solidification crack rate of the aluminum alloy welded joints changed greatly. With EDS detection analyzing the welded joints at the solidification cracks, the influence of wire feeding speed on solidification cracks was better understood. Figure 18 shows the diagram of new technology introduced to the processing of WAAM.

6.1 Application of Simulation Technology in Wire and Arc Additive Manufacturing

In the actual manufacturing process, wire and arc additive manufacturing, because the shape of the deposition needs to be predicted in advance, the deposition is obtained in advance using simulation technology. As shown in Fig. 19,

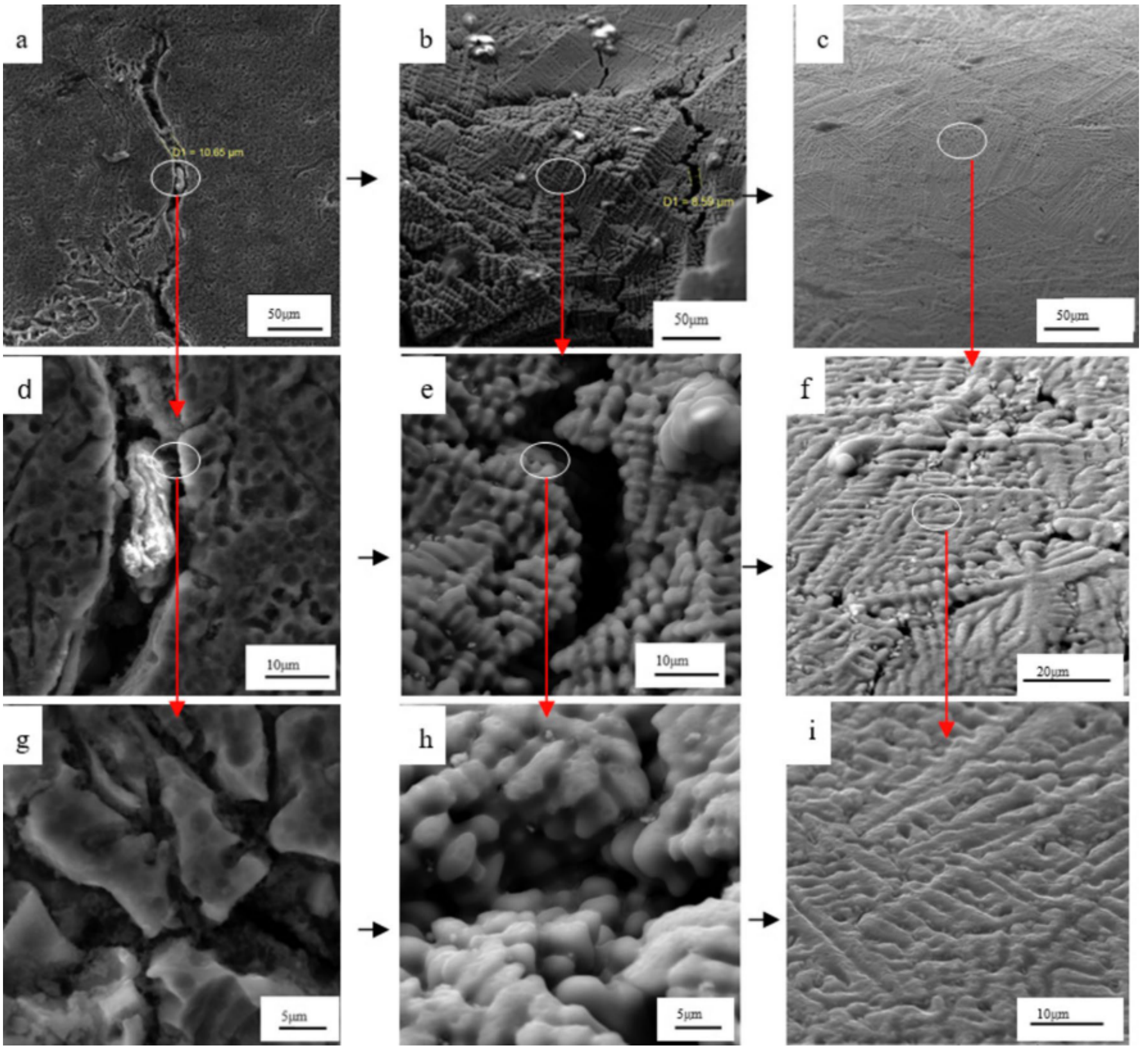


Fig. 15 Influence of wire feeding speed on the microstructure near the solidification cracks: (**a**, **d**, **g**) 4.5 m/min; (**b**, **e**, **f**) 6 m/min; (**c**, **f**, **i**) 7 m/min [77]

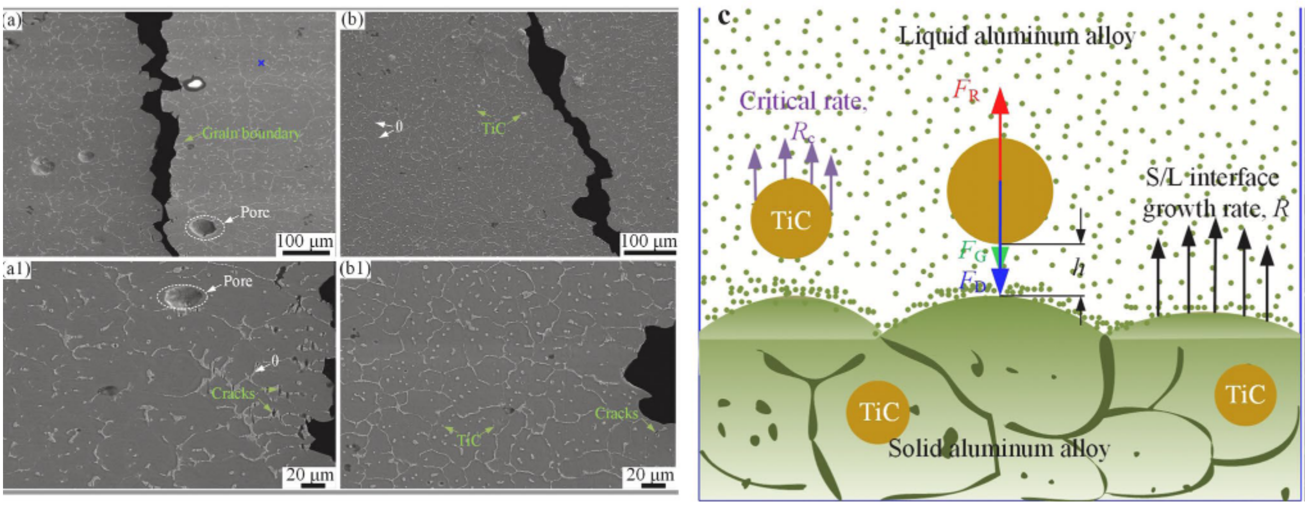


Fig. 16 **a** Microstructure of the crack, **b** Schematic drawing of the forces acting on the TiC particle in front of the solid/liquid interface [72]

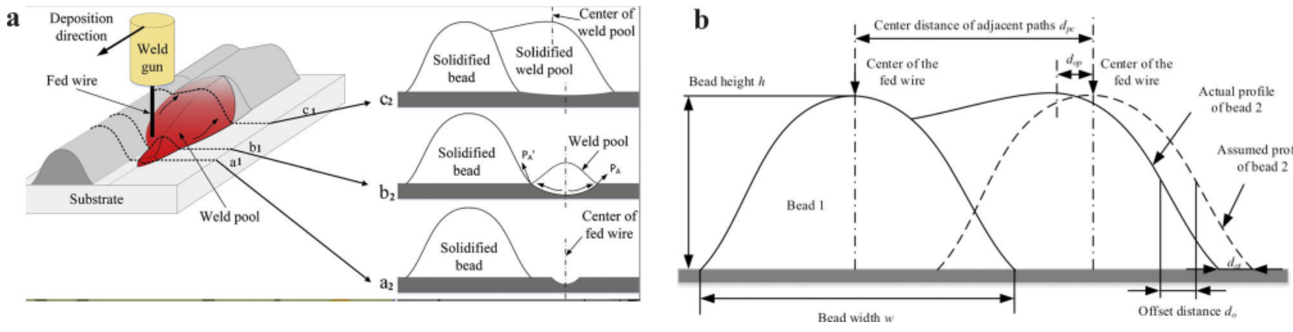


Fig. 17 Surface fabrication defects of arc additive manufacturing. **a** Step effect of additive manufacturing. **b** Sketch of the traditional flat-top overlapping model [80]

Table 5 Advantages and disadvantages of detection methods for WAAM

Detection method	Defect	Defect location	Advantages	Disadvantages
X-ray	Crack;	Surface Defects—Internal Defects	Strong detection penetration, high detection efficiency, high detection flexibility, not affected by the shape and structure of the material	Radiation hazard;
Machine vision method	Porosity;	Surface defects	Wide detection range, high precision, and easy automation;	Only surface defects can be detected
Magnetic powder detection	Micro deformation;	Surface and Near-Surface Defects	Defect visualization; simple detection process; high precision	Only suitable for ferromagnetic materials; detection range is affected by size and difficult to automate
Ultrasonic detection method	Low precision of deposition	Surface Defects—Internal Defects	Strong detection penetration, high precision;	Low detection efficiency

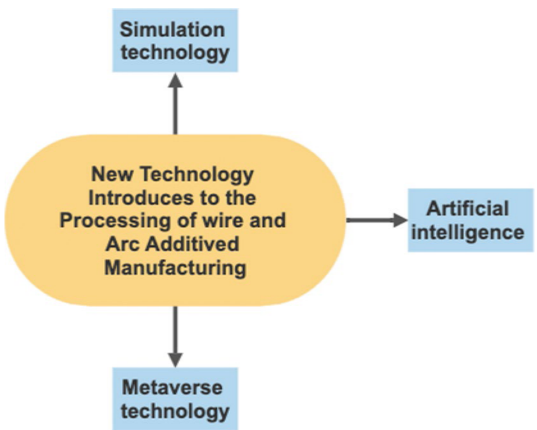


Fig. 18 Diagram of new technology introduced to the Processing of wire and Arc Additive Manufacturing

the deposition is drawn in three dimensions, the simulated deposition is obtained by finite element analysis, and the deposition is finally processed. This approach reduces material waste and enables overprediction of manufacturing geometries and possible defect regions.

6.2 Application of Artificial Intelligence (AI) in Wire and Arc Additive Manufacturing

In recent years, artificial intelligence has been widely used in the field of advanced manufacturing and has gained a lot of attention. Intelligent arc additive manufacturing has also become a hot development direction. Further, intelligent wire and arc additive manufacturing includes the application of complex informatization, digitization, networking and intelligent technology in the whole process of product manufacturing, which involves a wide range of materials, structures, processes, equipment and systems, products and markets. Therefore, the research and development demand for intelligent wire and arc additive manufacturing technology is very urgent.

In view of the above-mentioned needs, artificial intelligence is gaining more and more applications in wire and arc additive manufacturing. For example, as shown in Fig. 20, Francisco uses a combination of finite element simulations and artificial neural networks to predict interlayer temperatures in arc additive manufacturing, which can help manufacturers improve productivity (lower idle time) and part behavior (e.g., microstructure and mechanical properties) to strike an appropriate balance.

Wire and Arc additive manufacturing has been widely used in AI, and the design technology and strategies are outstanding. Table 6 summarizes the application strategies and goals of WAAM in the field of AI, which provides a basis for the subsequent application of artificial intelligence technology and WAAM technology.

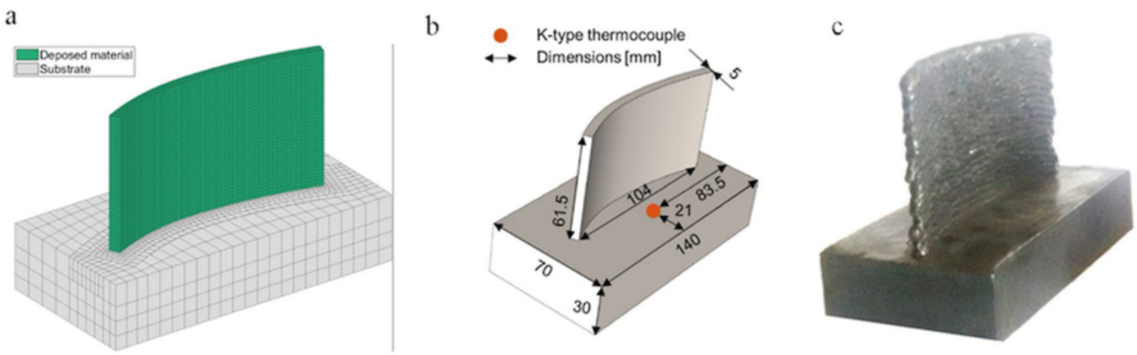


Fig. 19 Application of computer simulation technology in path planning of WAAM. **a** Simulated molding of the deposition. **b** Three-dimensional molding of the deposition **c** Final molding of the deposition [81]

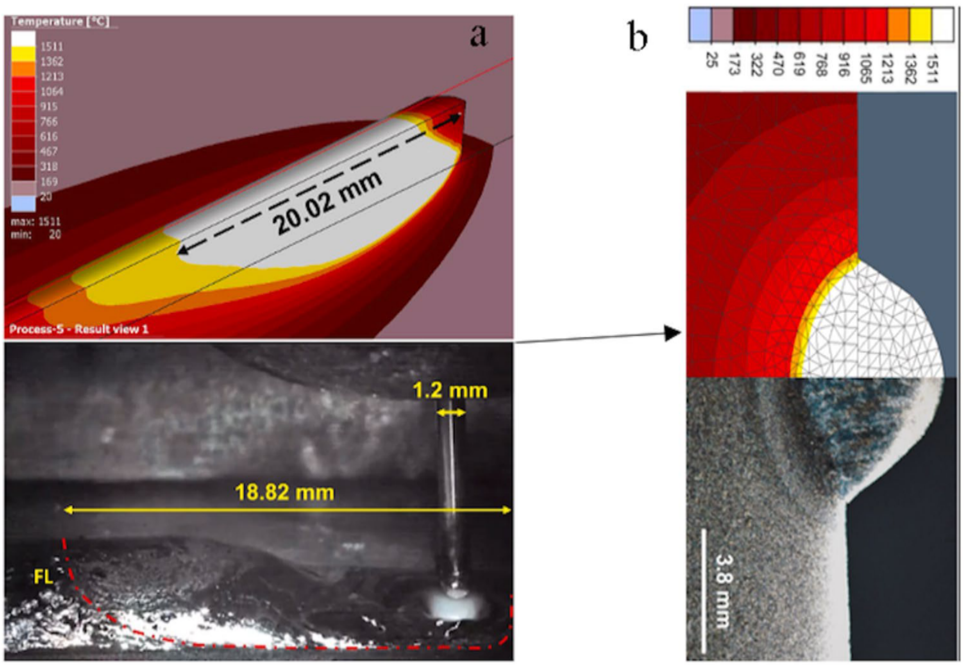


Fig. 20 **a** FEM simulation of the thermal profile for the bead-on-plate (top) and high-speed image obtained during deposition of the bead-on-plate (bottom). **b** Simulated thermal profile (top) and macrograph of the bead-on-plate (bottom) [82]

Table 6 Applications of AI in WAAM

Advanced technology category purpose	Advanced technology category purpose
Simulation techniques	Predict mechanical properties, temperature changes during manufacturing
Path planning	Optimize deposition geometry
Neuron mathematical algorithm	Control the geometry of deposition
Deep learning	Melt pool temperature prediction

7 Future Perspectives and Conclusions

WAAM technology can manufacture larger-sized structural parts, with a material utilization rate of nearly 100%. However, due to the low arc energy density, the heat input required during the forming process is relatively large. A larger heat input increases the temperature of the molten metal, which reduces the surface tension of the molten metal, enhances fluidity, and makes forming accuracy poorer. At the same time, there are also problems such as unstable arcs and coarse structures of formed parts. In summary, defects such as coarse columnar crystals, pores and cracks are prone to appear in the arc additive manufacturing process, which has a significant impact on the mechanical properties and microstructure of the deposit. The problems in the microstructure and mechanical properties of arc additive manufacturing need to be resolved.

8 Conclusions

1. For metal materials, the difficulties mainly come from the selection of materials and the connectivity of dissimilar material processing. For these difficulties, it is necessary to use the selection of optimized materials.
2. A variety of WAAM process methods significantly impacts the performance of deposition. Therefore, the material properties and the processing characteristics of WAAM are the basis for selecting the processing method.
3. In terms of structure and properties, the difficulties we face are improving the properties and refining the microstructure.

Future aspects

4. For online detection and improvement of manufacturing defects, the main difficulties come from the discovery of defects, how to characterize them. Further, in future WAAM industry, there is a massive demand for online deposition detection and further acquisition of defect-free deposition layers, which determines the stability and high product quality performance.
5. For the application of simulation technology and artificial intelligence in the field of WAAM, many factors are hindering their application. The biggest problem is that the technology is not very mature, resulting in the reliability of manufacturing cannot be guaranteed. Therefore, for artificial intelligence and simulation technology to enter our WAAM, the insistence on development and R&D using advanced technology must be insisted on to improve the technical gold content.

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