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Topical Review

Towards quality controllable strategies in wire-arc directed energy deposition

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Abstract

Wire-arc directed energy deposition (wire-arc DED) enables the fabrication of large-scale metal components with rapid manufacturing ability and diverse material selection, making it a compelling technology in industries and defenses. However, challenges in both macroscale and microscale defects still limit printed component widespread applications. Recent advances in automatic and intelligent technologies have brought a range of quality controllable strategies to the forefront. This review covers these new strategies for the printing component, including path planning, process monitoring, auxiliary processes, and post processing, while discussing the expectation for structure and quality improvement. In addition, the work brings new areas of intelligent wire-arc DED development, including advances in digital twin, visualization, and human-processing interaction to promote its performance. It is anticipated that a focus on intelligent system will be key to smart and high-quality manufacturing for future wire-arc DED.

Keywords: wire-arc DED, current challenges, quality control strategies, intelligent fabrication technology

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1. Introduction

The increasing demand in various industry sectors calls for advanced manufacturing technologies for products application. In recent years, additive manufacturing (AM) has become a viable technology for manufacturing 3D components and rapid prototypes. From American Society for Testing and Materials (ASTM), AM often deposits material layer-by-layer using a computer-controlled travelling mechanism[1], and it provides tremendous advantages in fabrication products with saving raw materials, improving work efficiency, increasing design freedom and enabling load-optimized design possibilities[2]. This technology can also produce components with higher precision and more complex structures without relying on molds, cutting tools, fixtures, or complex processes[3], which has been employed in diverse applications such as shipbuilding, aerospace, aesthetics, and architectural design[4,5]. At present, additive manufacturing categorizes process into seven types, including powder bed fusion (PBF), direct energy deposition (DED), material extrusion(MEX), binder jetting(BJ), material jetting(MJT), vat photopolymerization (VPP) and sheet lamination(SHL)[6]. Wire arc directed energy deposition (wire-arc DED) belongs to a subtype of DED where components are produced through layer-by-layer overlay using welding arc as energy source and welding wire as feedstock material. The defining feature of wire-arc DED technology lies in its distinct heat source and feedstock, setting it apart from laser-based and electron-beam DED methods. Compared to traditional metal 3D printing technologies like Selective Laser Melting (SLM), wire-arc DED offers significant advantages. It demonstrates higher manufacturing efficiency, lower production costs, and reduced environmental impact, making it particularly promising for lightweight, large-scale applications. These attributes position wire-arc DED as a compelling choice for advancing sustainable and cost-effective manufacturing[7,8]. Additionally, due to insensitivity to metals, which enables application across a wide range of metal materials, wire-arc DED finds diverse industries[9]. A typical wire-arc DED product will experience four stages: CAD modelling, path planning, fabrication, and post processing as illustrated in Figure 1. Once the AD model is established, printing path planning is necessary, entailing 3D slicing and parameter configuration. Upon completion of model configuration, the fabrication process can commence. Process monitoring and auxiliary techniques employed during the fabrication process provide substantial research value and developmental potential, thereby constituting the focal point of this study. Subsequently, post processing is conducted to refine the product's form following the fabrication process. Ultimately, products meeting practical production requirements are achieved. Raw materials suitable for wire-arc DED encompass a wide array of welding-compatible materials, including steel[10], nickel-based alloy[11], titanium alloy[12], aluminum alloy[13], etc.

The initial wire-arc DED was proposed terming as shape welding during the 1930s, and it was performed for large metal component in the 1970s and 1980s[14]. In specific, the earliest wire-arc DED dates back to 1925, when Baker applied for a patent entitled 'the use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers. During the 1990s, wire-arc DED was constrained to manufacturing products with rudimentary shapes. Until 2013, a notable shift occurred as product structures began to embrace greater complexity. In the ensuing years, wire-arc DED technology facilitated the sequential fabrication of intricate components such as propellers, rocket tubes, rocket connection loops, and pressure vessels, as shown in Figure 2. Notably, by 2023, wire-arc DED had reached a significant milestone, especially that Relativity space corporation used the world's largest wire-arc DED printer to produce the world's first fully 3D printed rocket. The rocket's successful maiden flight represents a fundamental simplification of the supply chain through the company's fusion of wire-arc DED printing, artificial intelligence, proprietary software, and autonomous robotics, and signals that the history of the aerospace industry over the past 60 years has been transformed. After recent decades of development, wire-arc DED has become one of the most promising technologies to produce large-size and low-cost metal components for aerospace, defense and marine industries[15].

The rapid advancement of wire-arc DED technology has attracted numerous manufacturers to enter the market, offering stable equipment and technological resources, as shown in Figure 3. Most wire-arc DED printers are focusing on medium-to-large parts fabrication. For example, MX3D corporation creates a M-Metal closed-system printer, which can print fully customized and qualified metal parts, weighing up to 10 000 kg. An increasing number of printers are integrating more sophisticated technologies. Gefertec specially developed a CAM software with Siemens control system into wire-arc DED printer, which could simplify the manufacturing and quality monitoring process. The RoboWAAM system from WAAM3D corporation is equipped with various shielding solutions, automatic fume management system, automatic purification of inert atmospheres, and additional safety system, which considerably increases the safety of the entire printing system. There are also companies dedicated to the production of hybrid additive and subtractive manufacturing systems. For example, the ArcMan M500 developed by Enigma corporation is currently one of the world's most advanced additive and subtractive composite additive devices for the integrated molding of complex structural parts, with the direct production of near-net-shape parts and even finished parts. Details of wire-arc DED printer manufactures currently on the global market, and product features are summarized in Table 1. Here it is found that wire-arc DED systems will become increasingly intelligent and automated, by integrating sensors, control systems, and software for more efficient operations and production processes. They also need to be more versatile and flexible to cope with different types and sizes of component requirements. Moreover, the print speed and accuracy of wire-arc DED have also been significantly improved to achieve more efficient production and meet more stringent product quality requirements. To face these challenges, various printers are constantly being updated to inject new vitality into the wire-arc DED market.

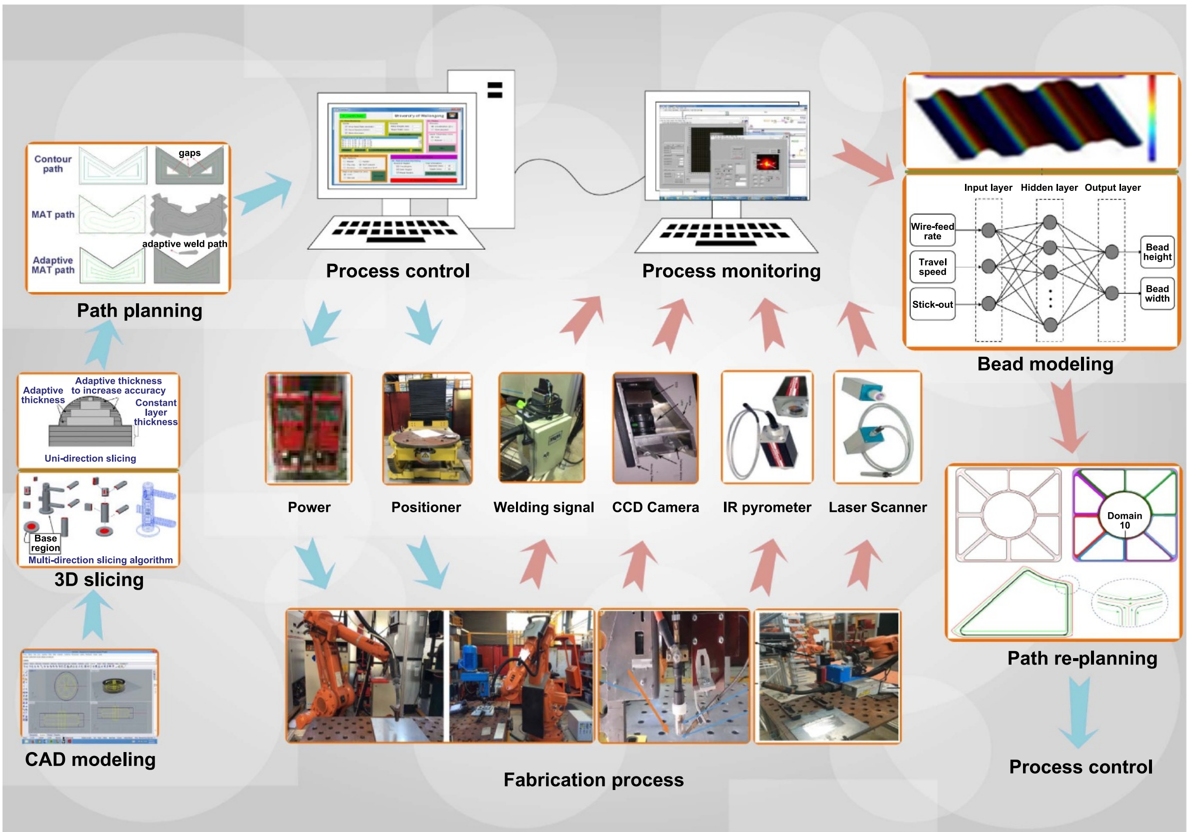

Figure 1. Wire-arc DED process.

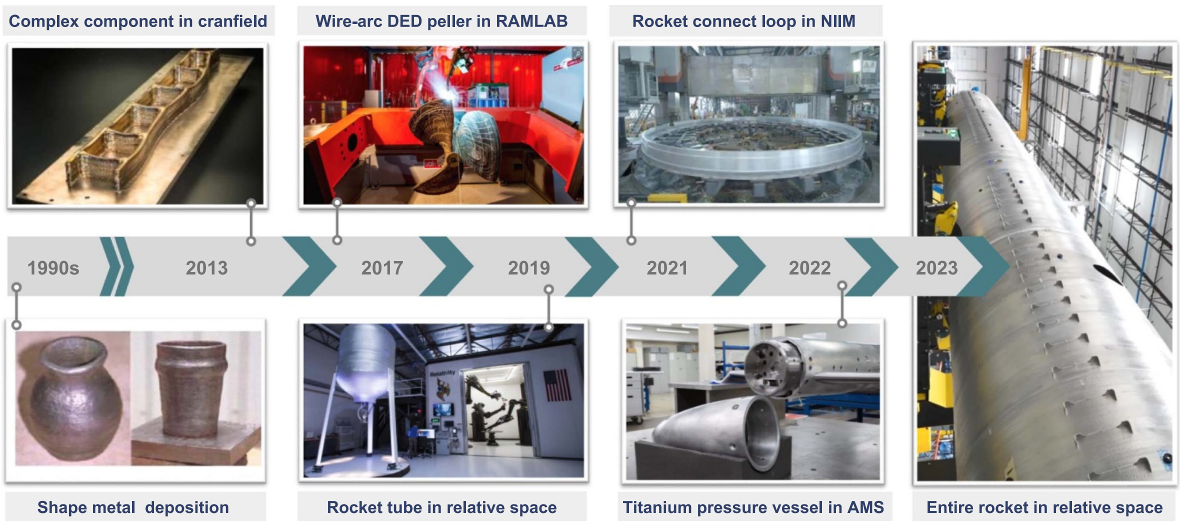

Figure 2. Wire-arc DED development timeline.

Increasingly, researchers are directing their efforts towards developing comprehensive wire-arc DED production systems, which encompass smart path planning strategies, intelligent process monitoring systems, and other automated auxiliary processes. Furthermore, many innovative approaches have been developed, progressively enhancing wire-arc DED produced components from the entire additive manufacturing process. For example, recent reviews focus on selection of materials[16], process parameters influences[17], printing component properties[18], path planning strategies[19], and process monitoring and control[20]. These articles have been synthesized from a specific aspect, and they have few comprehensive reports of quality commonality issues among the wire-arc DED processes. Currently, implementing an effective quality controllable strategy in the entire wire-arc DED is still a challenge.

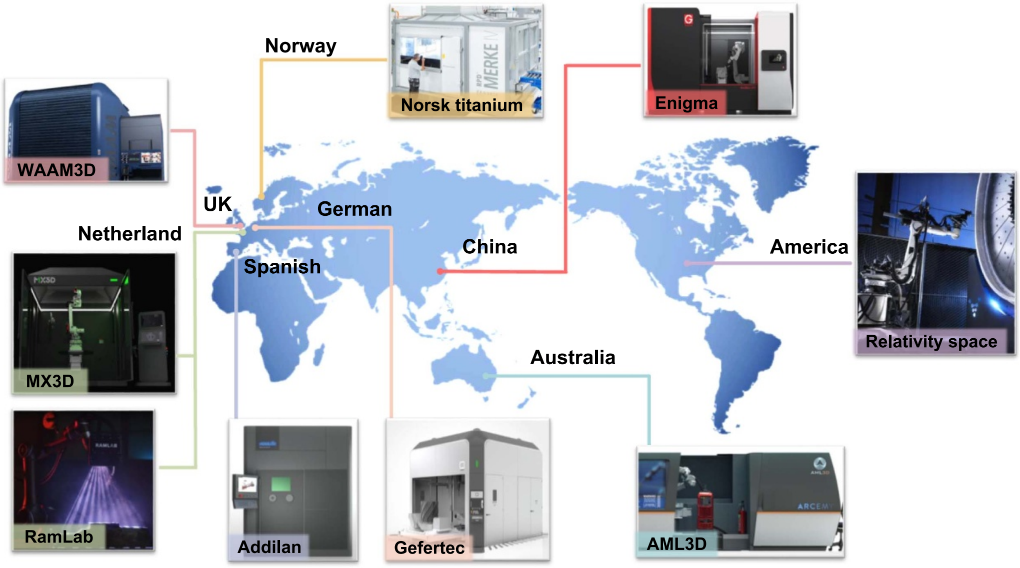

Figure 3. Wire-arc DED printer manufacturer distribution.

Table 1. Details of main wire-arc DED printer manufacturer in global market.

Company name	Nation	Product Series	Product Feature	Areas of application
AML3D	Australia	Arcemy	A variety of technologies including welding science, robotic automation, materials engineering and proprietary software	Aerospace; defense; marine industries
WAAM3D	UK	RoboWAAM	Kuka robotic motion system; power sources selected to match material and process requirements; end effectors equipped with sensor kits and proprietary software	Simplification of operator controls; upgrading of safety systems
Gefertec	Germany	3DMP	Temperature tracking; cooling systems; automatic welding gun cleaning systems; independent titanium modules	Simplification of manufacturing and quality control processes
Norsk Titanium	Norway	MERKE IV	Development of titanium alloys in wire-arc DED technology; reduction of machining times	Aerospace and defense industry
MX3D	Netherlands	M-Metal	Use of interchangeable tool attachments; transformation of existing equipment into hybrid additive/subtractive manufacturing systems	High-quality in-house production of medium-to-large metal parts
Addilan	Spanish	ARCLAN 1000-5X	Performance of titanium, superalloy and aluminum alloy parts is maximized.	Aerospace, defense, and marine industries
RamLab	Netherlands	MaxQ	Automation of production, quality inspection, and certification processes for robotic welding and repairs	Large parts for marine industry
Relativity Space	America	Stargate	World's largest robotic metal 3D printer	Manufacture of rockets for orbital flight
Enigma	China	ArcMan M500	One of the most advanced additive and subtractive composite additive equipment in the world	Rapid manufacturing replacement of perishable parts in production lines; rapid repair of parts in outdoor and mobile scenarios; replacement of traditional processes that cannot meet manufacturing needs

The uniqueness of this review lies in the complete critique of innovative quality control processes in the recent wire-arc DED field. From perspective of solving existing challenges of component structure and quality, innovative technologies from printer manufacturers and academic researchers are reviewed and summarized, which involves the four most critical aspects

Figure 4. Current development of wire-arc DED.

of manufacturing process, including path planning, process monitoring, auxiliary process, and post-processing, as shown in Figure 4. Here, the development direction of each process is also provided. The structure of this paper follows: the second chapter presents current challenges of structure and quality from both macroscale and microscale perspectives. The third chapter outlines current stage of wire-arc DED innovations in path planning, process monitoring, auxiliary process, and post processing respectively. Finally, the fourth chapter outlooks the future direction of promising wire-arc DED.

2. Wire-arc DED product issues

Although wire-arc DED technology has been rapidly developed, the obtained components still have various types of defects and also face many challenges in terms of structure and quality. Metallic materials for wire-arc DED often exhibit diverse physical and mechanical properties, which consequently lead to various manufacturing processes and defect issues[21]. The repeated melting and layering of metal materials also lead to various types of defects in the produced parts. This chapter will categorize the defect types in wire-arc DED products from both macroscale and microscale, as depicted in Figure 5, and will further explain these defect generation reasons, as shown in Table 2.

2.1. Macroscale issues

Wire-arc DED has the advantages of high adaptability and rapid molding, but it also exhibits disadvantages of high energy consumption and low molding accuracy that bring various defects including crack, porosity, oxidization, and distortion[22]. To be specific, cracks are among the most critical defects in wire-arc DED parts, as they are challenging to repair and can significantly reduce the mechanical properties of the printed components. Cracks are typically classified into two types: hot cracks and cold cracks. Another common defect is porosity, which weakens the part by creating areas with reduced strength and fatigue life[23]. Oxidation, caused by entrapped oxygen, can lead to internal defects that diminish the mechanical strength and corrosion resistance of the component. Moreover, oxygen-induced defects may compromise the stability and reliability of the printing process, resulting in surface irregularities and uneven product quality. Distortion is another prevalent defect that can cause severe deviations in geometry and accuracy, impacting the functionality and durability of the part while also increasing post-processing costs[24,25].

2.2. Microscale issues

From inherent characteristics of wire-arc DED, the component often experiences significant anisotropic microstructure. Microstructural anisotropy mainly brings about directional inconsistency in material properties, which can increase the risk of part failure[26]. As wire-arc DED uses arc as an energy source, the deposition easily generates coarser grains that lead to undesirable properties compared to fine grains[27]. Segregation is also a common defect. Uneven cooling rates during solidification and remelting during heating all can

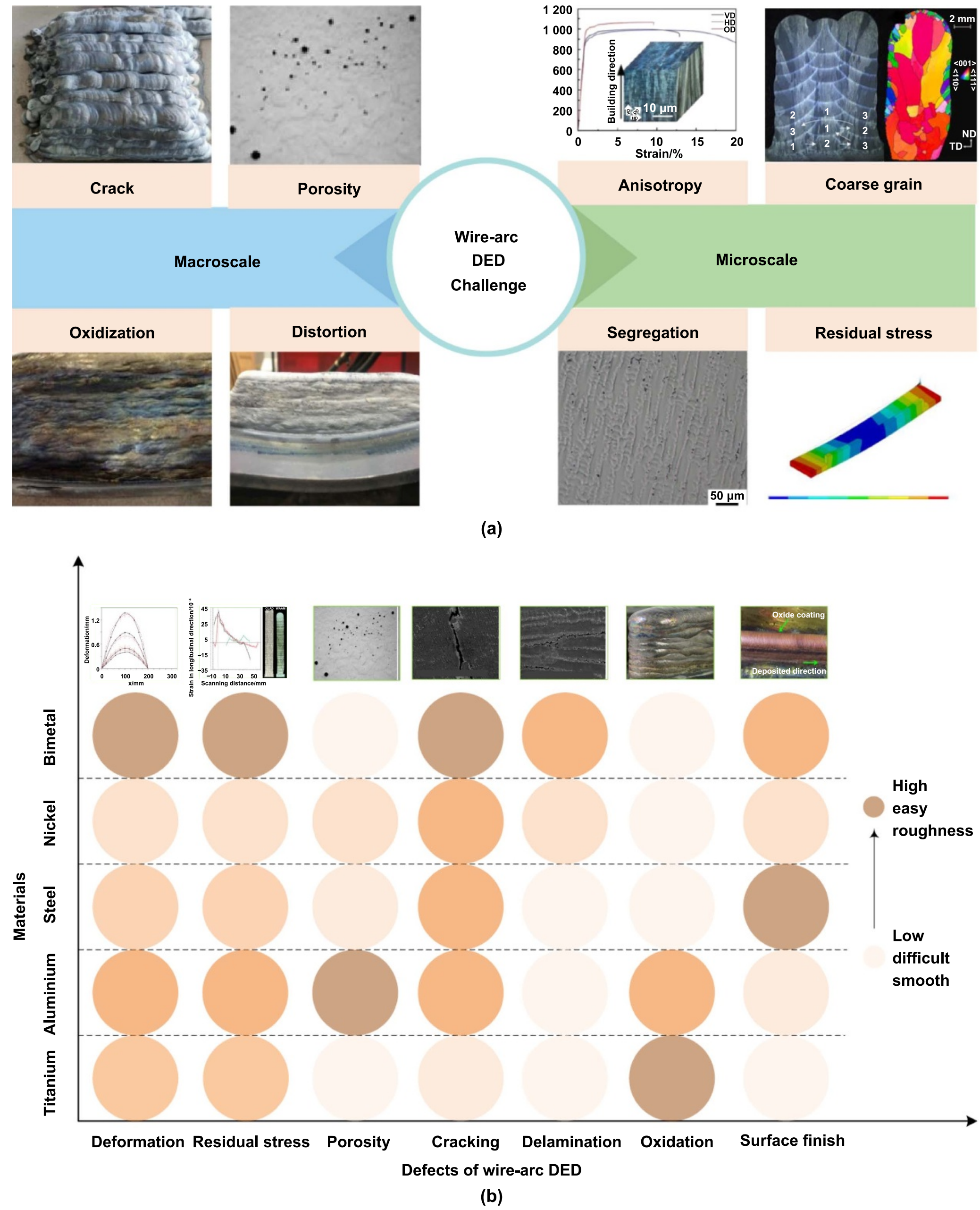

Figure 5. Defects challenges in wire-arc DED: (a) typical defects; (b) susceptibility of defects to common materials.

cause segregation. Segregation leads to localized inhomogeneity of material properties, in particular decreasing in tensile strength and fatigue properties. Areas of segregation are more susceptible to galvanic corrosion, which reduces service life. During wire-arc DED process, molten metal will be hot-worked and then rapidly cooled, resulting in a temperature gradient within component. These uneven thermal expansion and contraction can cause thermal residual stress that may result in deposition distortion and further component in a dimensionally and geometrically unstable state, as well as may increase the risk of cracking failure. The mechanical properties of produced component sometimes fail to meet expected or practical standards, hence, improving the comprehensive mechanical properties of material still needs to be paid increasing attention[28].

3. Innovative strategies for controllable quality for wire-arc DED

This chapter responds to the challenges of wire-arc DED outlined in the second chapter by reviewing innovative processes developed to defects response. According to the entire additive manufacturing process, the section mainly divided into four

Table 2. Common defects in wire-arc DED.

Type	Name	Cause	Solution
Macroscale	Crack	Hot crack: thermal stresses exceeding material's ability Cold crack: residual stresses or shrinkage	Path planning process; process monitoring; preheating and cooling aids, as well as appropriate post treatment
	Porosity	Gases dissolve or remain in material; inadequate melting and welding; insufficient gas protection; factors such as humidity, temperature, and air pressure	Optimizing path planning; Real-time monitoring of temperature, melt pool morphology; post treatment such as heat treatment or heat welding
	Oxidization	Entry of oxygen reacts with molten metal.	Sufficient flow and rate of shielding gas; post treatment methods such as chemical cleaning and heat treatment
	Distortion	High heat input results in uneven cooling, causing thermal and residual stress.	Real-time monitoring and feedback control system; post treatment; preheating, pre-cooling, and appropriate cooling methods
Microscale	Anisotropy	Deposition is in continuous layers, resulting in inhomogeneous temperature gradients and cooling rates.	Monitoring processes accompanied by algorithms such as machine learning; auxiliary processes such as ultrasound; post treatment
	Coarse grain	Fast cooling rate, high heat input, and thermal cycling; elemental segregation between solid and liquid phases	Rapid cooling; high heat input and thermal cycling; elemental segregation between solid and liquid phase
	Segregation	Uneven cooling rate; multiple remelting of heat-affected zone	Appropriate post treatment; optimization of process parameters
	Residual stress	Temperature gradient due to rapid addition and cooling	Monitoring techniques and detection instruments; optimizing print path

subsections path planning, process monitoring, auxiliary processes, and post processing. The roles of each area will be briefly introduced, and followed by a review of recent innovative approaches and research results.

3.1. Path planning

In wire-arc DED manufacturing process, the critical initial task is to generate printing path that will control the movement of welding torch to fill each 2D layer geometry[29]. During deposition, the bead geometric features, including height, width, and the distance between two adjacent layers, are critical to component, which will determine final geometric accuracy and surface quality[30]. Compared to conventional single-wire and single-torch welding methods[31], innovative single torch and twin wire or multiwire mothed brings more opportunities in material and component diversity, as shown in Figure 6. This approach can produce an interwoven strategy of different materials, bring a functional as well as gradient component. As a result, the path planning for these manufacturing conditions will be greatly changed.

In wire-arc DED, the employed path planning strategy fundamentally influences deposition quality[32]. Ideal path planning strategies can achieve continuous and uniform deposition and further produce commercially compliant parts[33]. Presently, path planning strategies will integrate various algorithms to enhance their functionality, such as predicting droplet shapes, rational part division, and automating path planning. The utilization of computer algorithms has accelerated the development of path planning in wire-arc DED. According to component geometries, current path planning strategies can be classified into single bead, block, wall, topology and component, as displayed in Figure 7. The specific innovative path planning strategies within each type are summarized in Table 3. It needs to be noted that some strategies can be applied to multiple geometries simultaneously. Different path planning strategies can help to reduce deposition defects, such as holes, deformation, etc. This section highlights the development of innovative path planning strategies in wire-arc DED under different geometrical characterizations.

At the beginning of wire-arc DED development, some path planning strategies, including unidirectional path, reciprocal path, zigzag path, were widely used because of their simplicity and convenience. It is found that the simplest path planning is the unidirectional path. However, there are obvious drawbacks of this path, including anomalous stacking at the beginning and termination of each path, as well as low efficiency due to the long time required, and large gaps between neighboring paths. As a result, the unidirectional path is gradually deprecated. The reciprocal path is often used to save time in the movement of welding torch. The path is also effective in achieving well-bonded deposition layers with a smooth surface. However, this path still has stacking issues at the beginning and termination of deposition, and it cannot be applied to various as well as complex component shapes. Therefore, zigzag path

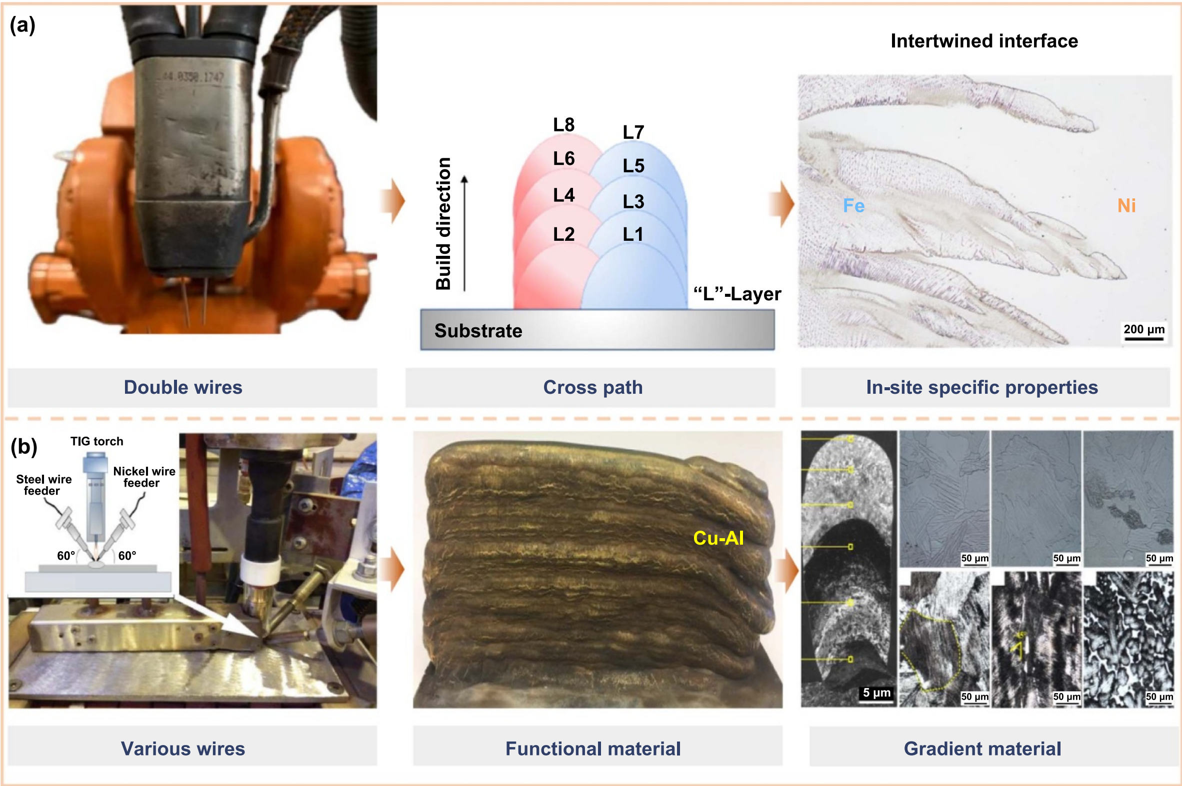

Figure 6. Single torch and twin wire deposition: (a) tandem torch for in-site specific material; (b) TIG torch for functional and gradient material.

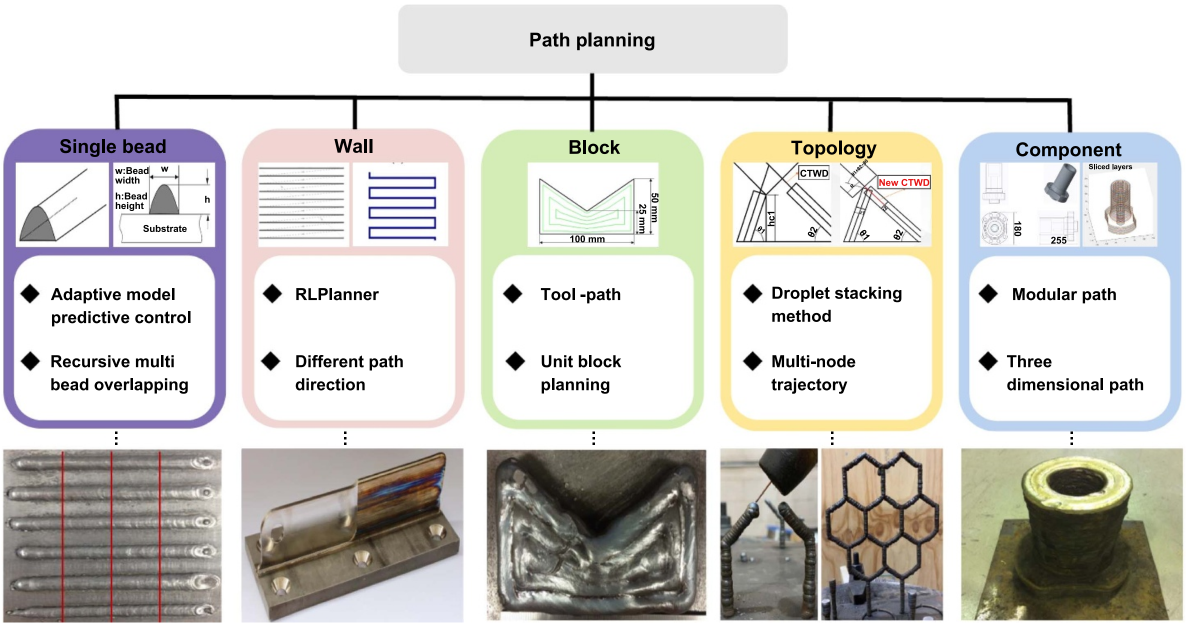

Figure 7. Path planning for different structures.

occurs, allowing for uninterrupted operation. This path can not only reduce the stacking issue, but also fill interior regions, eliminating pores, voids, and other undeposited regions that are created by traditional path. However, zigzag path easily leads to uneven stacking, as illustrated by the sequential path-planning method proposed by Wang et al.[60], which uses a water-pouring rule as an example. Here, it is noted that the developed zigzag path at present has superior densification and higher deposition efficiency. In recent years, path planning methods for complex structures have emerged. These methods involve altering torch travel path, employing algorithms to predict optimal paths and adjusting parameter selection.

Table 3. The summary of innovative path planning strategies in wire-arc DED.

Term	Geometry	Advantage	References
Modular Path Planning (MPP)	Component; wall structure	Adaptation to targeted geometry	[33]
Composite path planning of sharp corner correction	Component; wall structure	Pores between geometric center and sharp corner in lap joints are eliminated.	[34]
Adaptive path planning for thin-walled structures with different thickness	Wall structure	Thin-walled structures with varying thicknesses are filled.	[35]
Adaptive model predictive control (aMPC)	Single bead	Control latency is reduced and manufacturing accuracy for varying geometry beads is improved.	[36]
Model using recursive multi-bead overlapping for profile transformation	Single bead	Forming accuracy of components is improved	[37]
Process control adaptation for thin-walled and overhang features	Overhang component	Thin walls featuring inclined elements exhibiting overhang angles ranging from 0° to 37.5°	[38]
Machine-learning-based adaptive void filling in continuous Eulerian tool path for rib-web structures	Component; wall; topology	Reducing probability of welding defects	[39]
Continuous path planning for optimization of thermo-mechanical	Block	Thermo-mechanical property improves and average residual decreases.	[40]
Continuous three-dimensional path planning (CTPP)	Component	Manufacturing of closed components with method to ascertain optimal closing area	[41]
Corner path optimization strategy of gap-free shapes	Component	Gap defects at corners can be controlled.	[30]
Energy control strategy for curved path along L-shaped wall and variable amplitude waveform	Wall structure	Consistent metal-allographic beading on both straight and curved sections	[42]
Slicing method for cylindrical surfaces utilizing conformal slicing	Component (propeller)	Mechanical properties of propeller components are superior to casting components with the same composition.	[43]
Integration of zigzag and contour-offset path planning method	Wall structure	Improvement of residual stress distribution and shape outline accuracy	[44]
Automated processing planning algorithm and automated robot offline programming (AOLP] engine	Overhang component	Planning multi-directional wire-arc DED process automatically	[45]
Multi-beads model by calculating overlapping volume	Wall structure	Samples with overlapping intervals exhibit a uniform profile.	[46]
Multi-input multi-output model-predictive control (MPC) algorithm	Component	Enhancing real-time control performance by augmenting the complexity of implemented control algorithm	[47]
Deep learning-based technology to control droplet transfer modes based on collected data	Wall structure	Enhancing real-time process stability has led to improved deposition quality.	[48]
Task-priority based kinematic online coordinated motion control	Wall structure	Welding torch adheres to a predefined trajectory outlined in positioning table for deposition framing.	[49]
Algorithm to define optimal printing position	Component; wall structure	Algorithm can improve the expected dimensional accuracy of components.	[50]
ML algorithm for process-Informed Segmentation of Dense Point Clouds	Wall structure	Algorithm facilitates rapid and precise layer segmentation for geometric assessment	[51]
RLPlanner	Wall structure	Manufacture for thin-walled structures automatically; different welding speeds with wire feed rate	[52]
Region-based path planning for CL-wire-arc DED	Wall structure	Surface waviness and thickness exhibit consistent attributes across arbitrary region of complex surfaces.	[53]
Double electrode micro plasma arc welding (DE-MPAW)	Wall structure	Capability to resist interferences is improved and deposition paths concerning metal part's layer heights are streamlined	[54]

(Continued.)

Table 3. (Continued.)

Term	Geometry	Advantage	References
Support-free method utilizing surface and interior separation along with surface segmentation	Component; wall structure	Density of component with interlaced passes increases.	[55]
Multi-node trajectory planning method integrated T-GMAW	Wall structure; topology	Production time, energy consumption, and material wastage are decreased while minimizing the number of interruptions.	[56]
Scalar Thermal Field for Continuous Toolpath	Component	Superior reliability and restitution capacity	[57]
Unit block–based path planning strategy	Component; wall structure; block	Achieving optimal process output that harmonizes surface precision, deposition rate, and material efficiency	[58]
Process planning strategy utilizing hybrid heat input	Component; wall structure	High production efficiency and simultaneous quality	[59]

Subsequent sections are detailed to describe the suitability of path planning for different component geometries.

3.1.1. Path planning for single bead geometry. The single bead is the most basic wire-arc DED welding geometry. Only by improving a single bead can be guaranteed the quality of product formed by subsequent layer-by-layer stacking. For example, Li et al.[36] demonstrated a non-autoregressive dynamic model for predicting single bead geometries. For this purpose, an adaptive model predictive control (aMPC) method was formulated to optimize welding parameters for enhanced deposition precision. The disadvantage of method was that the method did not take into account the arc impingement and extinguishing phases, which can result in products that will be partially defective. Chen et al.[37] demonstrated a recursive model that employs coordinate transformation for forecasting single-layer multi-bead superposition profiles, and they also obtained a high accuracy in the model simulation. To improve single-bead geometry, many academic researchers have developed large number of algorithms to predict bead shapes for better tuning of the deposition process.

3.1.2. Path planning for block geometry. When materials in a wire-arc DED process are deposited using a multi-layer, multi-bead path, and the first and last layers are aligned parallel to each other, the resulting structure is referred to as block geometry. The block geometry is a stack of single-bead geometries. Therefore, to improve the product quality of block geometry, more factors need to be considered and more complex processes need to be developed. Because block geometry is simpler geometry, it is suitable for planning and testing continuous paths. For improving thermo-mechanical properties, Zhou et al.[40] proposed a method that can provide continuous tool trajectories and good thermo-mechanical properties. The critical operations of this method, including crossover and mutation, were designed according to the characteristics of component. Meanwhile, to ensure planning process efficiency, path fitting would be evaluated within a few seconds under the fast thermo-mechanical field prediction model. It was found that the method can improve the thermomechanical properties of manufactured product and further reduce the average residual Von Mises stress. Block geometry can be not only a geometry for testing continuous paths, but also a method for planning weld paths. Zhao et al.[58] illustrated a unit block-based path planning strategy. The unit block here was termed as a block deposited in a unit time and block size would be changed with process parameters variation. This strategy could divide the part with complex structure into blocks with different layer thicknesses, achieving high material utilization, surface accuracy and deposition rate. However, this method required different segmentation calculations for parts with different structure, which would reduce the general applicability. Due to the limitations of the applicability of blocks as a geometry, not much research has been done on block geometries. With in-depth study of related research, the application value of path planning for block geometry will be continuously developed and utilized.

3.1.3. Path planning for wall geometry. The wall geometry described here is not confined to weld paths resembling fences. Instead, it is broadly defined as a geometry formed by multi-layer, multi-bead deposition without complex structures. Consequently, wall geometry encompasses the fabrication of curved surfaces and accommodates various path planning methods. A common optimization of path planning strategy is to alter motion path of welding head. Michel et al.[33] developed a method called modular path planning (MPP), which employed the division of each layer into separate parts. The path planning could be modified by the user according to the target geometry as a way to produce products with complex structures. Combining a layer-by-layer deposition strategy with a feature-based modular design, the approach saved time in developing paths for each new geometry and also improved suitability for diverse materials and deposition techniques. Petrik and Bambach[52] proposed a path planning framework called RLPlanner. This framework allowed fully automated deposition path planning and also had thin-walled structure adaptability. An additional advantage was that the welding speed can be adjusted as wire feed speed changes. In this way, the weld seam size is controlled

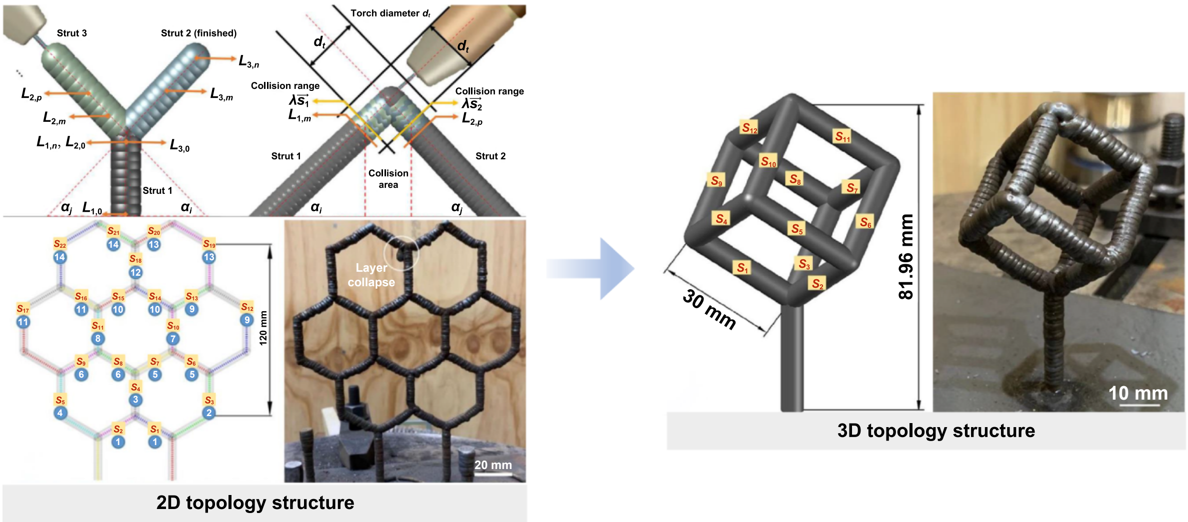

Figure 8. Topology geometry transition from 2D to 3D.

so that a wide range of geometries can be adapted. The whole framework combined many algorithms to compensate for the shortcomings of existing path planning methods, such as poor geometric adaptation. However, the framework did not take into account the optimization of uniform temperature distribution during welding process.

To optimize motion path of welding head, the contact angle between welding head and workpiece can also be changed. Due to the drag phenomenon generated by gravity, different melt pool behaviors and bead shapes at different locations during the deposition of surfaces can cause inconsistent molten layer morphology. To address this phenomenon, Hu et al.[53] presented a region-based robot surface layer strategy. This strategy employed an adaptive head overlap model that could be controlled according to the local tilt angle, which could achieve horizontal weld positions and consistent forming appearance. Therefore, the produced product could mitigate the step effect that occurred in the conventional isoperimetric method and flat surface layer wire-arc DED fabrication. There are many other ways to improve the product quality of wall geometry, such as controlling the bead transfer mode. Qin et al.[48] introduced a deep learning method for managing bead transfer pattern. This technique utilized a long short-term memory neural network as a classification model for core transfer pattern. The fabrication could have high deposition accuracy and process cleanliness, indicating process stability and component quality improvement.

It is evident from the path planning strategies in recent years that most of the methods involved in wall geometry are related to algorithms. The interrelationships between process parameters and processes in complex structures can be better handled by algorithms. Thus, more and more researchers are opting for better results through automated path planning.

3.1.4. Path planning for topology geometry. Topological geometry often indicates wire structures in the form of a mesh. The geometry typically exhibits complex geometries and internal features, which traditional path planning may not effectively address. Therefore, improving the product quality of topological geometry needs to be made in several ways. For example, the wire structure can be fabricated using a point-by-point manner[61], and thus topological deposition quality can be ultimately controlled by predicting the bead shape on a bead-by-bead basis[62]. Yu et al.[63] proposed a process strategy suitable for machining free-form parts consisting of a wire structure with multiple stubs, as shown in Figure 8. The approach devised a bead modeling procedure capable of forecasting and establishing the optimal process parameters for bead geometry. A height control system and slicing algorithm that could generate an adaptive slicing model were also proposed. In wire-arc DED, if the number of beginning and termination increases, material stacking and defect possibly occur to a large extent. However, for topological geometry, it does not allow for a continuous path. To address this issue, Nguyen et al.[39] developed an optimal tool path for generating lightweight rib-web structures. This path plan transformed the non-Eulerian path into Eulerian path, realizing continuous and improvement for underfilling of the vertices of rib-web structure. This strategy was not only applicable to individual parts, but could also be capable of generating tool path corrections for arbitrary joints using a neural network trained on an experimental database. As a result, it enabled more efficient welding and shorter delivery times compared to paths generated by the single weld bed strategy. However, its efficiency decreased when faced with variant-rich production. Additionally, many other innovative methods exist for wire-arc DED. Shi et al.[56] reported an innovative multi-node path planning method for fabrication using Tandem Gas Metal Arc Welding based wire-arc DED. This strategy could generate multi-node and multi-bead continuous forming paths with a large number of meshed reinforcement plates. The combination of this strategy and T-GMAW resulted not only the realization of topological structures, but also the reduction of production time and waste of material and energy by reducing the number of interruptions.

There is still a lot of room for the development of topological geometry, which will be the focus of development in the field of wire-arc DED. Researchers work on developing reliable algorithms to fabricate stable skeleton structures or to reduce the mass of the products. It is also important to incorporate thin-walled and solid structures, to form more complex and diverse part structures.

3.1.5. Path planning for component geometry. The component geometry is close to the final product that wire-arc DED hopes to obtain. Diourt´e et al.[41] introduced a "Continuous Three-Dimensional Path Planning" (CTPP) strategy that could minimize arc start and stop phases. The main effect of the CTPP method was to generate continuous spiral paths for closed-loop thin-walled produces, which used an adaptive wire feed speed combined with a constant travel speed to adjust deposition shape. This approach exhibits the ability to produce new geometry with good geometrical recovery and complexity beyond the capabilities of the currently used 2.5D wire-arc DED technology. Because of the presence of excessive self-overlap and underfill, corners manufactured by conventional contour paths are prone to leaving fill gaps. To improve this shortcoming, Ding et al.[30] investigated a path planning strategy for corner path optimization, which generated multi-channel paths with different center distances and seam filler paths in corners. Based on this innovative path, an Artificial Neural Networks (ANNs) bead model is developed to determine the appropriate welding parameters for improving the corner path. The surface uniformity of deposited produces can be very fluctuating without effective control, especially for large products with complex structures[64]. Thus, improving the control strategy can also improve the product quality. Mu et al.[47] proposed a layer-by-layer online control method that integrates offline process planning with the real-time control system. The strategy utilized an online adaptive model predictive control (MPC) controller based on a linear autoregressive (ARX) modelling process, which allows for continuous updating of welding parameters between adjacent layers. By increasing control algorithm complexity and adaptivity, real-time control of deposition can be achieved.

Component geometry also has many special structures such as overhang and propeller structure. Hence, multi-directional wire-arc DED technology is seen in development. Yuan et al.[45] reported an automated planning algorithm that could connect with the robotic offline programming and wire-arc DED hardware to print overhang structures. Propellers are important parts of ships, and their special structure lies in the constant bending of the blade cross section in space. Since propeller structure cannot be achieved by ordinary plane slicing, He et al.[43] developed a cylindrical slicing strategy according to conformal slicing principle. The propeller hub could be produced via offset filling and plane slicing. In contrast, the blade could be created through an alternating sequence of cylindrical slice, cylindrical axial filling and cylindrical circumferential filling. This alternative strategy could reduce dimensional tolerance, enhance microstructural homogeneity and further promote mechanical properties for deposited propeller. Despite the growing complexity of component geometries, there are numerous opportunities to enhance path planning. As research progresses, component geometries will become increasingly sophisticated, enabling the creation of more intricate structures.

Path planning plays an important role in final component quality. Well-developed path planning strategies can help prevent defects during the manufacturing process. Existing path planning strategies are divided into five types based on geometric shapes: single bead, block, wall, topology, and component. The advantages of improved path planning are demonstrated by comparing it with traditional path planning. These methods not only enhance the travel path of the welding head but also optimize the partitioning of component regions and improve bead shapes. Various types of algorithms have also been developed in wire-arc DED to assist in the prediction and execution of path planning.

3.2. Process monitoring in wire-arc DED

Wire-arc DED technology has experienced rapid development both in theoretical research and practical production processes, with an increasing focus on refining the wire-arc DED system. However, numerous challenges persist, impeding the widespread adoption of this technology. In additive manufacturing, process monitoring and feedback control play crucial roles in ensuring product quality[65]. Similarly, wire-arc DED, as an emerging technology, faces similar challenges. During deposition, repeated cycles of heating and cooling can result in non-uniformities in the microstructure[66]. Heat input during welding can lead to residual stresses and deformations[67]. Defect generation can also be influenced by random factors and environmental perturbations[68]. Consequently, the challenge in wire-arc DED development predominantly stems from the absence of an integrated process monitoring system and real-time feedback control capabilities.

Throughout the entire wire-arc DED fabrication, heat distribution and dissipation will fluctuate with various process parameters, which are critical factors that affect the final part quality[69]. Therefore, to enhance geometric accuracy and deposition quality, process monitoring and feedback control are highly recommended. Effective feedback control for wire-arc DED system relies on a robust monitoring system. Implementation of an online monitoring system in wire-arc DED can lead to reduced product defect rates, cost savings, and increased productivity. Online monitoring has laid a solid foundation for control and automation in the welding industry[70].

Traditional monitoring methods have been developed more maturely, but process monitoring for wire-arc DED still has many problems. With the continuous efforts of researchers, many new monitoring methods have appeared in recent years. As displayed in Figure 9, the incidental defects during deposition include porosity, cracks, distortion, etc. The main role of monitoring system is to detect the occurrence of these defects and further give feedback. In addition to

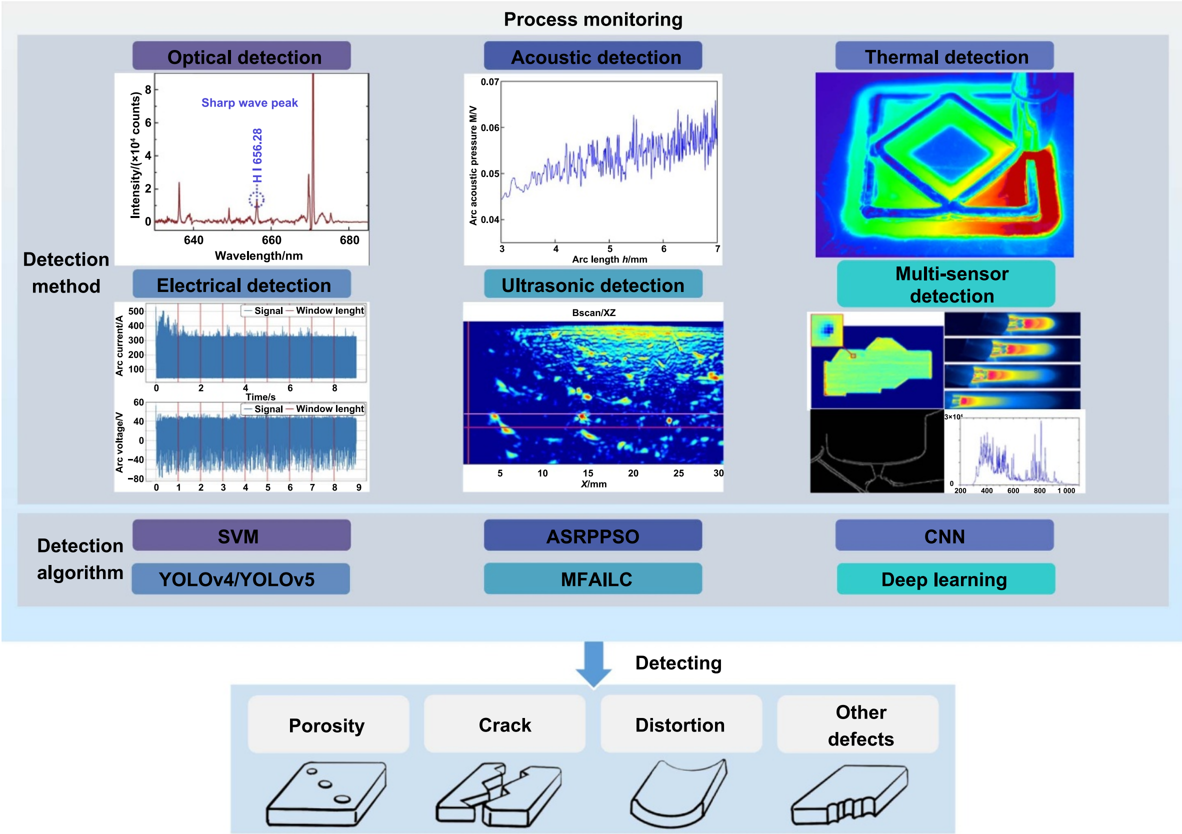

Figure 9. Detection methods and algorithms and defect types[9,71–74]. Reproduced from[9], with permission from Springer Nature. Reproduced from[71], with permission from Springer Nature. Reproduced from[72], with permission from Springer Nature. Reprinted from[73], © 2019 Elsevier B.V. All rights reserved. Reproduced from[74], with permission from Springer Nature.

the emergence of more innovative and effective monitoring methods, various types of algorithms have been incorporated into the monitoring process to improve detection efficiency. Table 4 lists process detection methods and algorithms from recent years. In this section, the innovative means of process monitoring in wire-arc DED will be analyzed from four perspectives: single-sensor monitoring, multi-sensor monitoring, process monitoring method, process monitoring algorithm.

3.2.1. Single-sensor monitoring. Based on similar principles, the basic monitoring methods in AM can be applied to wire-arc DED. The mature sensing methods in the existing field of wire-arc DED include electrical sensing, thermal sensing, acoustic sensing, spectral sensing and vision sensing[20]. Vision sensing belongs to an intuitive sensing method, which can be employed to detect surface appearance, melt pool morphology, size, and dynamics in real time. However, visual sensing is not suitable for a feedback control system because of its long processing time and relative lag. Spectral sensors are mainly used for product composition analysis, including information on metal vapors, shielding gases and arc gases. Thus, they are used to understand the deposition physical mechanism and to monitor process conditions. The advantages of spectral sensors are wide measurement range and high sensitivity, while the disadvantages of high cost and non-intuitive information obtained[112]. Acoustic sensors, which are non-contact and do not require destruction of the product, can be applied to acquire the arc state, melt pool dynamics and internal material changes such as internal cracks and porosity during deposition. However, it is susceptible to external interference such as noise in the environment. During the printing process, heat distribution affects the formation of phases and microstructures in the component, which makes thermal sensors a convenient and fast monitoring method. It can be used to detect hard-to-reach parts of the product surface and produce quick results. Thus, thermal sensors can detect the profile characteristics of beads and defects in the deposited layer[113]. Electrical sensors are used to detect the state of bead molding[114], as both bead transfer and arc ignition can be reflected by the arc power signal.

Several of the above sensors were only used independently in the previous research, so that good results could not be achieved. Although they have their own advantages, they cannot improve the recognition rate because of the single information obtained. As a result, research in recent years has been devoted to the development of multi-sensor monitoring systems to analyze the generation of defects from a variety of information pathways to improve production efficiency. Ultrasound and other monitoring approaches are gradually

Table 4. The process monitoring methods and algorithms.

Monitoring methodology	Effect	References
Multiple sensor (CCD camera, acoustic sensor, 3D scanner, spectrometer, and electrical sensor)	Various welding conditions and certain imperfections can be identified.	[20]
Multiple sensor (liner laser, camera, spectrometer, thermal imager, and hall sensor)	A viable approach to guarantee quality and enhance deposition efficiency amidst intricate manufacturing scenarios	[9]
Acoustic emission (AE)	94% classification accuracy on all tasks	[75]
Vision sensing system	Satisfactory control accuracy of melt pool width is guaranteed.	[76]
Identification of arc length through analysis of arc acoustic signals	Arc length identification is effective.	[71]
An outlier detection method based on adaptive switching randomly perturbed particle swarm optimization algorithm (ASRPPSO)	Superiority of convergence rate and solution quality	[77]
A method employing cost-sensitive convolutional neural network and remanence/magneto-optical imaging	Highly accurate and automated diagnostic results for low-carbon steel components	[78]
Feedback control system utilizing multiple model approach	Geometric errors compensation; enhancing deposition productivity by circumventing the need for low interlayer temperatures	[79]
A passive vision sensor monitoring layer heights	Deposition height of thin-walled components can be precisely controlled.	[80]
Resonant Ultrasound Spectroscopy (RUS) testing part integrity at different locations	Variations at different regions could be identified quickly.	[81]
Phased array ultrasound testing (PAUT) roller probe in high temperature	Detection of artificial point defects in diameter of as small as 1.0 mm	[82]
Automatic defect detection solution driven by deep learning based on YOLOv4	High detection capability for small and dense defects in objects	[83]
Acquiring arc spectral and image signals in real time	Features of spectral and image signals corresponding to typical defects are determined.	[84]
A microphone-based acoustic sensing approach	Effects of contamination can be identified.	[85]
Distance-based multivariate anomaly detection	Addressing key challenges in real-life industrial data sets, including varying signal sample rates, synchronization issues, and concept drift	[86]
Monitor of evolution of geometry and molten pool size	Estimating heat input reduction coefficient of wall structure based on geometry and height of molten pool	[87]
Arc voltage sensing control system using height adjustment and iterative learning dual control method	High height stability and material and energy utilization	[88]
Dual-vision sensors real-time acquisition system	This method decreases the frequency of arc initiation and extinction, enhancing production efficiency while conserving materials and energy	[89]
Digital image correlation (DIC)	Viability of in-situ DIC for the assessment of strain fields	[90]
Virtual Source Aperture (VSA) in ultrasonic roller-probe inspection	A nearly 50% reduction in data size allowed for a doubling of inspection speed	[91]
Monitoring set-up combining structural Acoustic Emission sensor, condenser microphone and current sensor	High accuracy in distinguishing between process-related and contaminant-related porosity	[92]
Interrupted fatigue testing accompanied by periodic X-ray computed tomography (CT) scanning	Cyclic plasticity model parameters are determined and employed to compute reduction in mean stress at pore root.	[93]
Passive Vision	Width monitoring is successfully carried out, even in the presence of a highly noisy deposition process.	[94]
Laser opto-ultrasonic dual (LOUD) detection	Compositional information is derived from optical spectra, while residual stress distributions and structural defects are obtained from ultrasonic signals.	[95]

(Continued.)

Table 4. (Continued.)

Monitoring methodology	Effect	References
A novel multi-channel monocular vision sensor	Maximum errors in height and width are reduced.	[96]
Teh-Chin chain approximation algorithm and K-means clustering method of Thermal camera	Teh-Chin chain approximation is used to detect thermal light regions.	[97]
Multi-input and multi-output (MIMO) model-predictive control (MPC) control strategy	Reduction in fluctuations of both component's height and bead width along single weld seam	[98]
Model Free Adaptive Iterative Learning Control (MFAILC) algorithm	This algorithm improves forming accuracy and automatic level.	[99]
Non-Destructive Testing (NDT) systems of Eddy Current Testing (ECT)	EC probes can detect artificial defects at depths of up to 5 mm and with thicknesses as small as 350 µm, while also addressing challenges posed by surface roughness and high temperatures.	[100]
Control model for Contact-Tip-to-Work Distance (CTWD) in sound monitoring utilizing spectral analysis	Evaluation of work distance with a precision of 0.5 mm	[101]
Multi-layer ultrasonic imaging of as-built manufactured components	Capability for layer-specific or volumetric inspection of components in as-built	[102]
Near-infrared camera	Detection of heat accumulation-induced width deviation	[103]
Closed-loop controller utilizing Fuzzy-PID system for arc voltage	Strategy is effective to eliminate peaks in cross structures.	[104]
Full Matrix Capture data acquisition using Laser Induced Phased Arrays (LIPAs)	Imaging defects at depths up to 10 mm below inspection surface	[105]
Non-contact in-situ 3D laser profilometer inspection (3D-LPI) system	This method can identify extensive bulges and collapses as well as small pore defects with pixel-level precision.	[106]
Phased array ultrasonic testing (PAUT) technique	PAUT method allows for detection and sizing of defects ranging from 0.6 to 1 mm in components.	[74]
Internal defects detection method using phased-array ultrasound	Phased array ultrasound multi-angle scanning pattern is capable of probing the same location within a material using ultrasound beams from multiple angles.	[107]
Vision-based defect monitoring system for inter-layer inspections	Enhanced precision in surface anomaly detection and improved accuracy in identifying location of fabricated components	[108]
Microstructure pore defect detection model based on YOLOv5s	High detection accuracy and detection speed	[109]
Deep learning in visual monitoring for diagnosing various anomalies	Classifying different types of melt pool images	[110]
Molten pool visual acquisition system	This system can predict changes in molten pool shape in advance, with an average weld reinforcement regression precision better than 0.3 mm	[111]

employed to build the monitoring system for wire-arc DED, and due to their superior performance, they may gradually replace the traditional monitoring method. With the development of Industry 4.0 and intelligent trend, all kinds of recognition algorithms are also introduced into the field of wire-arc DED.

3.2.2. Multi-sensor monitoring. With the rapid development of automation and intelligent technology, a multi-sensor based wire-arc DED monitoring system has been proposed. By installing multiple sensors around the deposition equipment, each deposition layer can be monitored online from multiple angles. Identification of defects from multiple dimensions can substantially improve the accuracy of the monitoring system. It should be noted that for multi-sensor monitoring systems, the number of sensors does not represent the accuracy of monitoring. Employing multiple sensors will provide a comprehensive insight into the deposition, and if additional sensors exist, it will cause information redundancy problem and reduce the processing efficiency. Xia et al.[20] proposed a process monitoring system based on multi-sensor

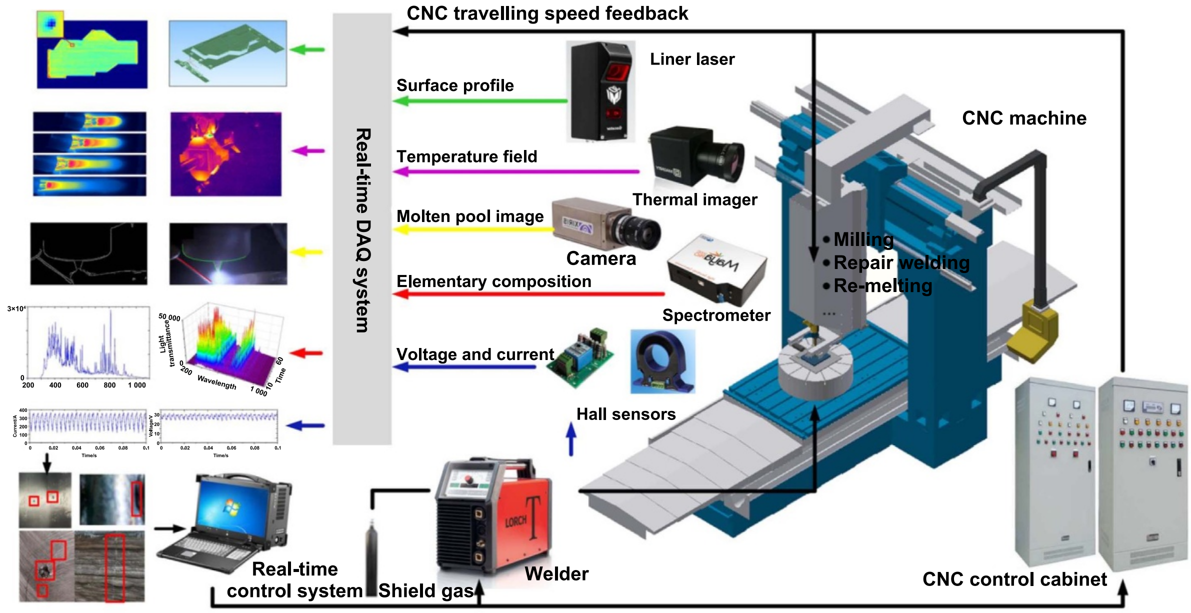

Figure 10. Multi-sensor monitoring model[9]. Reproduced from[9], with permission from Springer Nature.

in where laser scanner, CCD camera, acoustic sensor, spectrometer and electrical sensor were employed to monitor different targets. The raw data collected by these sensors did not provide useful information directly, and algorithms were required for data processing, feature extraction, and decision-making. Consequently, the monitoring system enabled online diagnosis of defects. Chen et al.[9] proposed a closed-loop control model for data fusion from multi-sensors including linear laser, thermal imaging camera, video camera, spectrometer and Hall sensor, as shown in Figure 10. The system improved the efficiency and quality of manufacturing through online inspection and promoted the green transformation of traditional forging methods, consuming only 35% of the energy of conventional methods.

With wide application of wire-arc DED, traditional and single sensors cannot meet the detect requirement for defect details in deposition, so multi-sensor monitoring system will become an important trend in future development. After fusing multiple data, the detection will include overall signals, which can reduce information redundancy brought from the separate processing of multiple data. Hence, the development of a multi-sensor monitoring system is conducive to improving monitoring efficiency and fully enhancing the deposition quality.

3.2.3. Process monitoring method. Due to complex thermal stacking and various defect performance, it is somewhat difficult to establish both online and offline non-destructive testing (NDT) system[100,115]. Even though, a desired on-line NDT system can identify defects in component in real time and can be a quality assurance for wire-arc DED produced part[116]. An ideal approach would be to perform on-line inspection of the deposited layers to obtain the quality of each layer in real time. If an anomaly occurs, all machines involved in deposition in the closed-loop feedback control system can be adjusted based on the monitored information to eliminate defects quickly.

Among the innovative process monitoring methods of recent years, ultrasonic inspection exhibits a promising position in wire-arc DED. This inspection method has a highly sensitive ability that can detect small defects. Therefore it is used to accurately locate and judge defects of different shapes and sizes[117]. Zimermann et al.[102] first proposed the concept of ultrasonic phased array volumetric imaging, which is arranged on the surface of the part of components and can be used to inspect the non-planar surfaces of the component. By employing the multi-layer adaptive Total Focusing Method (TFM) and Synthetic Aperture Focusing Technique (SAFT), the detection system could achieve fully focused imaging of as-built component. The resulting TFM image of the component has a sufficient signal-to-noise ratio and can be used for defect detection. Wang and Guan[107] also proposed a phased array ultrasound based internal defect detection method. The method employed phased array ultrasound to scan the component from multiple angles, allowing for identification of the same location in deposition through a multi-angle ultrasound beam to significantly improve detection accuracy. In combination with the multi-angle ultrasound data fusion algorithm, the raw data from each phased array channel could be coalesced. However, this method had to reset the parameters in materials prepared with different process parameters. Instead of singly using ultrasonic detection, Ma et al.[95] proposed a laser opto-ultrasonic dual (LOUD) detection method in which a pulsed laser beam was employed to motivate sample surface to generate ultrasonic spectra. Here, by analyzing compositional information from these ultrasonic spectra and signals, local residual stress and defects will be obtained. The LOUD method is highly efficient and can replace the traditional single inspection method.

In addition to ultrasonic detection, a variety of detection methods have been proposed. Reisch et al.[86] proposed a modular anomaly detection system that includes multivariate time series. This detector was used to solve the problems of real data sets in industrial production, such as lack of synchronization, concept drift and miscellaneous signal sample rates. By using this approach, industrial applications save time and cost on artificial defects generation in machine tool. In addition, eddy current testing (ECT) is another good nondestructive testing method that possesses ability including contactless and fast detection in both ferromagnetic and non-ferromagnetic materials. Bento et al.[100] explored an inspection system in which a customized ECT probe was used to monitor real-time deposition. The probe could locate parts up to a depth of 5 mm and went beyond the limitations of commercial ECT that only inspects for surface and sub-surface defects.

The monitoring system not only increases productivity and product accuracy, but also reduces production costs[118,119]. Due to the length and complexity of the production process, inspectors are unable to visually monitor deposition in real time accurately, making the use of appropriate monitoring methods essential. However, the monitored data is characterized by high volume and complexity and cannot exist singularly. Therefore, it also needs to be coupled with an inspection algorithm to achieve effective defect detection. Detection algorithms will be explained in detail in the next part.

3.2.4. Process monitoring algorithm. The large amount of monitoring data obtained through various types of sensors is very inefficient and poorly accurate based on the observation of the experimenter. In order to achieve an integrated industrialized and efficient wire-arc DED defect monitoring system, detection algorithms that can monitor the machining process need to be established. In recent years, machine learning techniques in wire-arc DED process have been developing rapidly[120]. Especially, machine learning algorithms, including Artificial Neural Network (ANN), Convolutional Neural Networks (CNNs), Support Vector Machines (SVMs), clustering algorithms and decision trees have been utilized to correlate sensor data during deposition. Ding et al.[62] reported a system strategy which presents various algorithms, including head modelling[121], 2D path planning[29], and multidirectional slicing algorithm[122].

Machine learning currently dominates the field of detection algorithms. However, for wire-arc DED, there are many problems of complex inspection environments and diverse defect types. Hence, classical machine learning algorithms are not applicable. Researchers have proposed a variety of improved algorithms, as shown in Figure 11. Most of these algorithms are used to detect the creation of defects or to monitor melt pool state with the aim of predicting printed geometry. Li et al.[83] developed an automatic defect detection scheme through deep learning model of YOLOv4 algorithm. This scheme could detect four types of defects: weld seam, surface porosity, groove, slag inclusions and the proposed model could be widely used in detection system for real-time defect observation. However, the algorithm used in proposed scheme requires numerous samples for learning and training. Because of this shortcoming, the development of incremental learning methods appeared. Li et al.[123] introduced a process monitoring system using integrated intelligent algorithms. From a support vector machine (SVM) learning method, the system could identify welding signals in which welding current and voltage could be used to monitor defect generation. Subsequently, an incremental machine learning model could be employed to improve detection rate. Another machine learning approach is the convolutional neural network (CNN), which can be applied in visual sensing technique to monitor melt pool stability. For example, Zhang et al.[124] developed a monitoring system for observing different melt pool states. By using different convolutional neural networks, the melt pool characteristics for liquid region, semi-solidified region, and solidified region could be captured accurately. However, this monitoring system was committed to the relationship between melt pool and macro defects, and is not yet able to find micro defects, such as porosity and cracks. Although mainstream research emphasizes the application of machine learning algorithms for defect detection, several studies are concurrently exploring alternative strategies to enhance the efficacy of monitoring systems. For instance, Diao et al.[88] devised a deposition process monitoring system that leverages arc voltage sensing. Given the inherent random noise within the raw arc voltage data, their system implemented empirical mode decomposition (EMD) as a filtering method to mitigate this interference. Additionally, they proposed a composite control strategy that integrates height-lifting control (HLC) with iterative learning control (ILC).

Process monitoring is essential for ensuring the reliability of wire-arc DED system. Traditional monitoring methodologies, although relatively mature, often fall short in providing comprehensive defect information management during deposition. To mitigate these limitations, multi-sensor monitoring systems have been developed to integrate diverse information sources, thereby facilitating a more holistic surveillance of defect occurrences. Moreover, innovative detection methods and advanced algorithms have been introduced, leveraging novel technologies and artificial intelligence (AI), to enhance the accuracy of defect identification and enable effective corrective actions. The integration of AI, particularly deep learning-based recognition algorithms, promises significant advancements in melt pool monitoring and defect detection within the wire-arc DED process. In tandem with the progression of Industry 4.0, the incorporation of Internet of Things (IoT) technologies is anticipated to automate wire-arc DED further. Enhanced data sharing and processing capabilities made possible by big data analytics will contribute to improved process optimization and quality assurance in wire-arc DED applications.

3.3. Auxiliary process

Auxiliary processes are introduced to enhance the performance of the entire wire-arc DED system without altering its fundamental structure or primary functions. These processes can be incorporated into various components of wire-arc DED

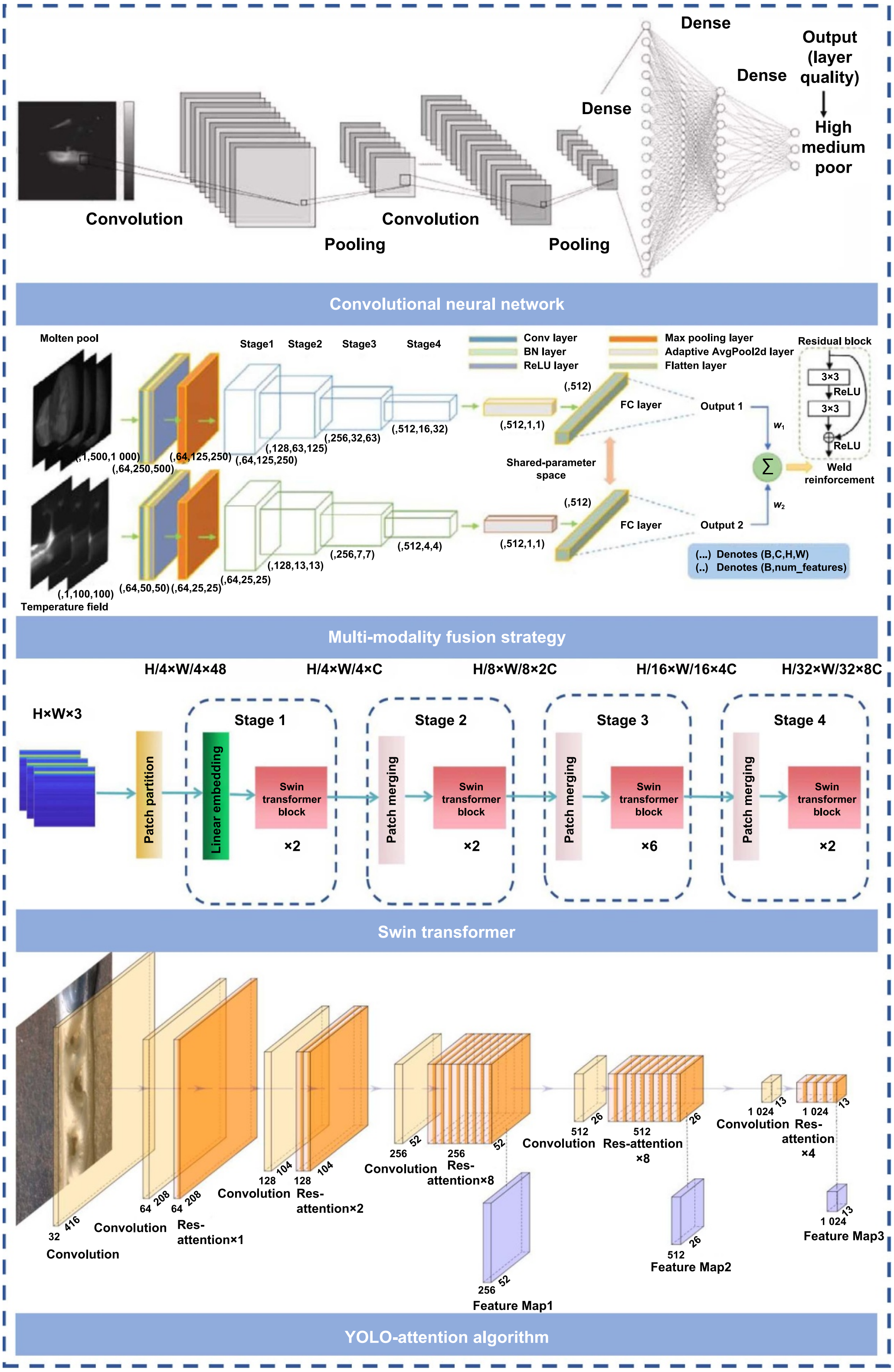

Figure 11. Multiple monitoring algorithms[83,125–127]. Reprinted from[83], Reproduced with permission from[125]. Reproduced with permission from[126]. Reproduced with permission from[127].

system and are crucial for improving material properties, reducing thermal stress and distortion, increasing forming accuracy and quality, and automating the process, as shown in Figure 12. A detailed list of the methods of auxiliary processes and the results achieved in recent years is given in Table 5. This section aims to analyze the current research status of

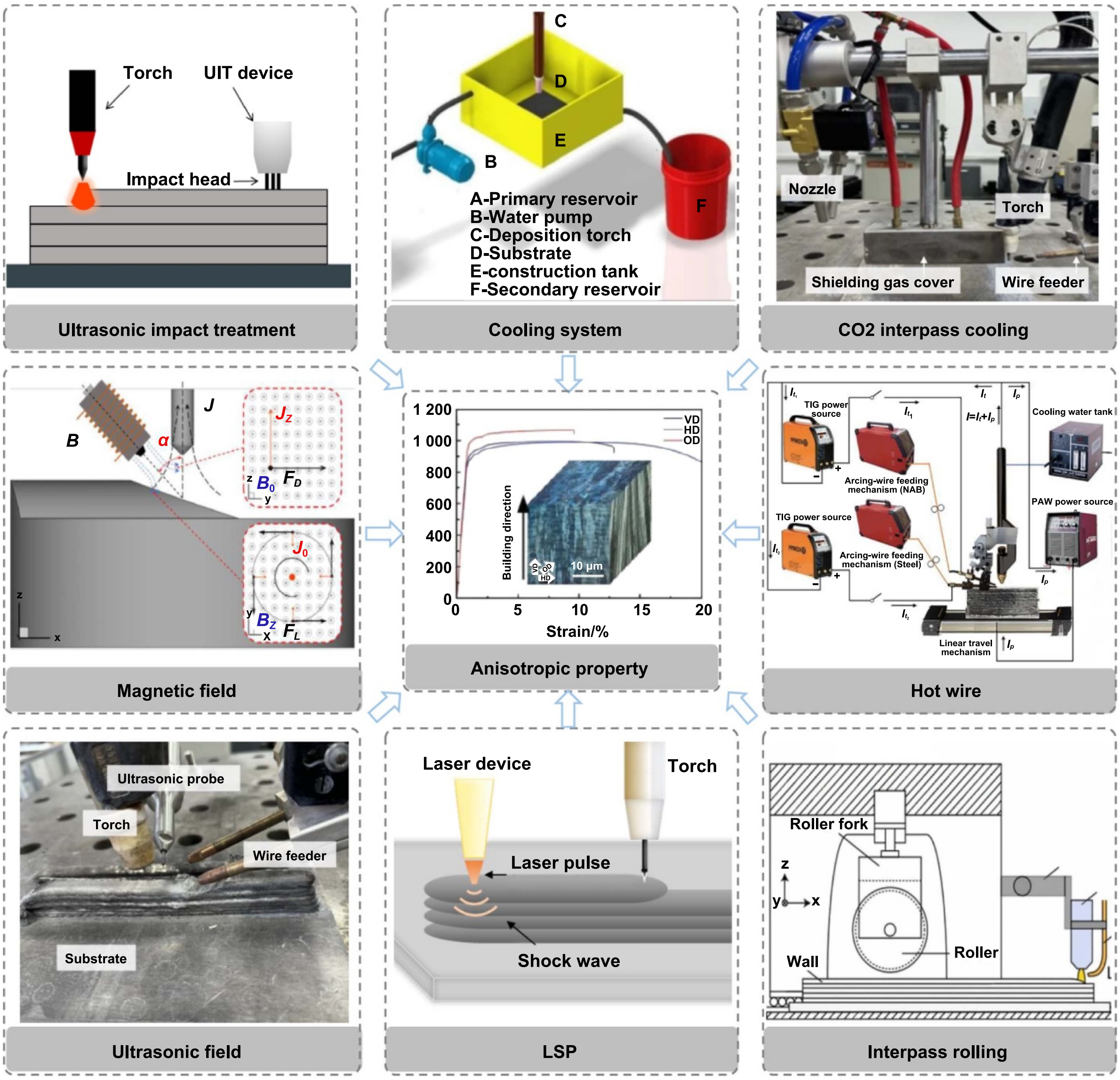

Figure 12. Wire-arc DED auxiliary processes[128–130]. Reprinted from[128], Reproduced from[129], with permission from Springer Nature. Reproduced from[130]. CC BY 4.0.

auxiliary processes within the context of wire-arc DED. By classifying and discussing these processes, we hope to illuminate the development and potential future directions of auxiliary techniques in wire-arc DED.

3.3.1. Ultrasonic process. Since the heating, cooling, melting, and solidification conditions during the deposition of wire-arc DED differ in different orientations, the microstructure of the product is mostly oriented growth and weaving in the preferred orientation[150–152]. Material anisotropy is a serious defect that significantly impacts the product's service life and mechanical properties, limiting its industrial application. Therefore, the development of wire-arc DED relies on improving mechanical properties, refining microstructure, and reducing anisotropy.

Ultrasound has been used as auxiliary processes due to its ability to enhance the structure of materials without altering their original composition. Sun et al.[132] introduced interlayer ultrasonic impact (UI) strengthening in the fabrication of mild steel. After UI treatment, the component exhibited a transformation from a distinctly oriented columnar structure to a homogeneous and fine equiaxed microstructure. As a result, this approach effectively enhanced the microstructure and mechanical properties of the material. Ji et al.[136] explored the effects of assisted ultrasonic vibration (UV) on the melt pool behavior and appearance of deposited layer, and they found that intense ultrasonic vibrations could alter the frequency and amplitude of the melt pool pressure, significantly impacting the grain size and evolution during deposition. Ultrasonic vibrations also facilitated higher flow velocities and thermal diffusion within the melt pool, reducing the thermal

Table 5. The auxiliary processes methods.

Process method	Effect	References
Hybrid magnetic field and deposited manufacturing (HMDM)	The morphology of bead can be altered by the application of an auxiliary longitudinal magnetic field.	[131]
Inter-layer ultrasonic impact (UI) strengthening	Reduction in grain refinement, local misorientation, and texture orientation strength	[132]
Hot forging wire arc additive manufacturing (HF-wire-arc DED)	Refinement solidification microstructure; enhancements in ultimate tensile strength and yield strength; lower porosity	[133]
Electron beam irradiation of surface	Increasing microhardness and decreasing friction coefficient	[134]
Hybridization of wire-arc DED with pre-surface treatment using Laser-marking	The feature size of wire-arc DED can be reduced, and used for the fabrication of complex components with thin structures.	[135]
Assisted ultrasonic vibration (UV) of metal additive manufacturing	Even distribution of temperature and minimized thermal gradient; alteration in surface condition of molten pool	[136]
Indirect arc formed between two non-consumable tungsten electrodes within a confined space	The shape of arc and droplet transfer process can be enhanced, leading to significant improvements in both forming characteristics and metallurgical bonding strength.	[137]
An alternating current (AC)-assisted wire-arc DED method	AC affects flow of molten pool and changes its microstructure.	[138]
Synchronous-hammer-forging-assisted wire-arc DED technology	The area ratio between intra-layer and inter-layer regions diminishes, leading to a notable equiaxed grain refinement effect.	[139]
An ultrasonically assisted (UA) wire-arc DED process	A low number of porosities, refined solidification structure, and minimal agglomeration of nanoparticles contribute to enhanced mechanical properties.	[140]
A manufacturing method using pulsed arc plasma (PAP- wire-arc DED)	Compact molten pools, rapid cooling rates, and little heat accumulation; precise geometric features, refined microstructures, and excellent tensile strength	[141]
Mechanism of corrosion protection using magnetic arc oscillation	Superior corrosion resistance owing to refined grains	[142]
Magnetic arc oscillation (MAO)	Reduction in solidification time, enhancing surface accuracy of the as-built alloys	[143]
Workpiece vibration in conjunction with variable polarity cold metal transfer arc	Grain refinement; removement of fine grain zone at interlayers; increasement of ultimate tensile strength (UTS)	[144]
Interpass cooling conditions	This process achieves consistent layer height, uniform wall thickness, and absence of oxidation in the parts. Additionally, effective forced cooling ensures desirable mechanical properties are obtained within short dwell times.	[145]
Forced interpass cooling	High hardness values and increased strength; forced interpass cooling improves deposition properties and manufacturing efficiency, and promotes geometrical repeatability.	[146]
Interpass temperature control and forced cooling	Productivity is improved. Small objects are allowed to be printed at near-net shape.	[147]
Active interpass cooling	Build times have been reduced; significant distortion reduction; good mechanical performance	[148,149]

gradient and promoting a more uniform temperature distribution. Additionally, these vibrations could induce the formation of capillary waves on the surface of the melt pool to potentially modify the solidification appearance. Wang et al.[140] investigated the preparation of metal matrix nanocomposites using ultrasonically assisted (UA) wire-arc DED.

Compared to conventionally prepared samples under identical deposition parameters, those processed via UA-wire-arc DED exhibited superior properties, including finer solidification structures, lower porosity, and reduced nanoparticle agglomeration. These improvements in microstructure led to enhanced mechanical properties of the materials. Some researchers have attempted to implement ultrasonic auxiliary processes at locations such as the substrate, but no significant effects have been observed thus far, and in-depth investigations remain limited. Recent studies indicate that ultrasonic auxiliary processes can take various forms; however, they consistently enhance the quality and performance of components in wire-arc DED.

3.3.2. Magnetic arc oscillation. In recent years, magnetic arc oscillation (MAO) has been introduced into wire-arc DED to enhance product quality. MAO can improve the mechanical properties of materials by aiding in the stirring process to refine grain size. Additionally, the addition of MAO can increase deposition efficiency by reducing molten pool spillage[153], and can also minimize undesirable microsegregation, thereby reducing thermal cracking[154]. Shao et al. investigated the corrosion properties of Ti-6Al-4V alloy fabricated under magnetic arc oscillation[142]. The specimens produced with MAO exhibited stronger corrosion resistance compared to those created with a stable arc. The underlying mechanism involved the refined α grains, which generated numerous grain boundaries and provided abundant ionic locations or reaction sites. This refinement facilitated the rapid formation of a passivation film on the material's surface, making it less susceptible to localized attack by chlorides. Qiu et al.[143] examined the mechanical properties, microstructure, and surface finish of materials deposited using different frequencies of MAO for Ni-base alloys. Compared to samples without MAO treatment, the results demonstrated that MAO reduced arc density during the deposition process, thereby shortening the solidification time and improving the surface accuracy of the samples. Moreover, the dendrites of the material exhibited a higher diversity of growth orientations, contributing to improved mechanical properties. The MAO-assisted process holds significant potential for further development and warrants additional research efforts.

3.3.3. Shielding gas. The wire-arc DED system necessitates an inert shielding gas environment during operation to protect the metal from oxygen, preventing oxidation. Different shielding gas and flow rates significantly influence the quality performance of wire-arc DED produced component. da Silva et al.[155] evaluated the effect of oxygen content in argon-based shielding gas on arc cathodic emission behavior and layer formation. They found that when the oxygen content was 200 $mg \cdot L^{-1}$, there was no discernible impact on layer formation. However, at 20 000 $mg \cdot L^{-1}$ oxygen content, the shielding gas contained sufficient oxide levels to prevent cathodic emission from occurring along the wall height. Instead, cathodic emission was confined to the weld pool, resulting in a more compact arc with higher pressure, which contributed to improved layer formation. Derekar et al.[156] explained the formation of pores due to the dissolution and subsequent consumption of hydrogen in solid aluminum. They also found that Pulsed-MIG specimens exhibited higher hydrogen content compared to those prepared using CMT. Under varying heat input and interlayer temperature settings, pulsed-MIG samples displayed a greater number and volume fraction of pores relative to CMT-prepared samples. However, CMT samples contained a higher concentration of dissolved hydrogen within the solid solution compared to pulsed-MIG samples. Given the critical role of shielding gas in wire-arc DED, ongoing research is expected to increase to achieve a deeper understanding of its effects on the process and structure quality.

3.3.4. Interpass auxiliary process. Heat accumulation during wire-arc DED is a common issue. Predicting the thermal state or internal stress changes during deposition can help address this challenge. Drawing parallels with welding practices, interpass cooling has been introduced into wire-arc DED[157]. This auxiliary process offers multiple benefits, such as improving part quality, reducing residual stresses, enhancing mechanical properties, and shortening production times. Wu et al.[146] used compressed CO_2 forced interpass cooling to fabricate Ti6Al4V thin-walled structures. This process not only resulted in a higher surface finish and reduced surface oxidation, but also increased the hardness and mechanical strength of the material. Additionally, the fabrication period was also improved due to a significant reduction in dwell time between deposited layers. Wu et al.[148] also utilized an active interpass cooling technique involving compressed CO_2 to enhance heat dissipation and minimize heat accumulation during deposition. To improve the cost-effectiveness and reliability of wire-arc DED, Kozamerni et al.[147] developed a system incorporated interpass temperature regulation and enforced cooling techniques. The interlayer temperature control used an infrared pyrometer to remotely measure the temperature of the most recently deposited layer, ensuring stable and reproducible deposition shapes even under changing heat transfer conditions. Stable temperature control allowed for consistent interlayer deposition heights and the desired final deposition size.

In addition to interpass cooling methods, other auxiliary processing techniques are used for the interlayers during wire-arc DED. Hönnige et al.[158] investigated the impacts of vertical interpass rolling and post-deposition lateral rolling on aluminum alloys. Vertical interpass rolling altered the residual stresses within the material and through work hardening, it also increased mechanical yield and tensile strength, meanwhile eliminating deformation. Conversely, post-deposition lateral rolling was highly effective in mitigating residual stresses and deformation. However, the rolling process is not applicable to components with complex geometries. Fang et al.[159] explored the influence of interlayer hammering on the microstructure evolution of 2319 aluminum alloy. Interlayer hammering was found to significantly refine the grains and further deform the recrystallized grains, thereby increasing the ultimate tensile strength. The hammering process also significantly improved the mechanical properties of the alloy when the deformation was 50.8%. Niu et al.[139] proposed synchronous-hammer-forging-assisted wire-arc DED technology. The synchronous hammer-forging (SHF) technique enabled the material to be forged at elevated temperatures, facilitating significant plastic deformation with minimal forging force. Experimental results indicated that this method promotes equiaxial grain refinement. Furthermore, the SHF method could reduce porosity while enhancing both ultimate tensile strength and yield strength of the specimen.

3.3.5. Other auxiliary process. Beyond the aforementioned auxiliary methods, researchers are continuously developing new processes to enhance the wire-arc DED system. Duarte et al.[133] introduced a hot forging wire and arc additive manufacturing (HF-wire-arc DED). This approach involved localized forging of material immediately after deposition, resulting in in-situ viscoelastic deformation at elevated temperatures. As a result, recrystallisation of previously solidified grains occurred, providing microstructural refinement. The method not only reduced the weaving effect and refined microstructure, but also closed pore defects and reduced porosity. Additionally, it increased yield strength and ultimate tensile strength, as well as improved surface roughness and enhanced geometric precision. Huang et al.[138] developed an alternating current (AC)-assisted wire-arc DED technique for preparing functionally gradient materials titanium alloys. The addition of AC to the Ti6Al4V filled wire during deposition caused the tungsten inert gas arc to oscillate. This oscillation altered the distribution of temperature and electromagnetic field, which in turn affected melt pool flow. Moreover, the material hardness increased with the intensity of AC current. Duan et al.[141] developed a novel fabrication method using pulsed arc plasma wire-arc DED. The heat source for this process was a pulsed arc plasma generated using a pulsed voltage, which reduced the total heat input required for material deposition and minimized heat transfer to the deposited material. Consequently, the deposited material could cool more rapidly, suppressing the adverse effects of heat accumulation. The component fabricated by the PAP-wire-arc DED exhibited finer microstructural and geometrical features and higher tensile strength.

These auxiliary systems complement the functionality of wire-arc DED systems. Introducing more innovative methods into the field of wire-arc DED will accelerate its development. The incorporation of auxiliary processes improves the microstructural properties of materials and geometry precision during deposition, thereby reducing post processing work and minimizing energy and material waste.

3.4. Post processing

Components produced by wire-arc DED often require post processing to meet the application specific requirements. These requirements are influenced by product specifications, budget constraints, process capabilities, and time considerations. Post processing not only enhances component

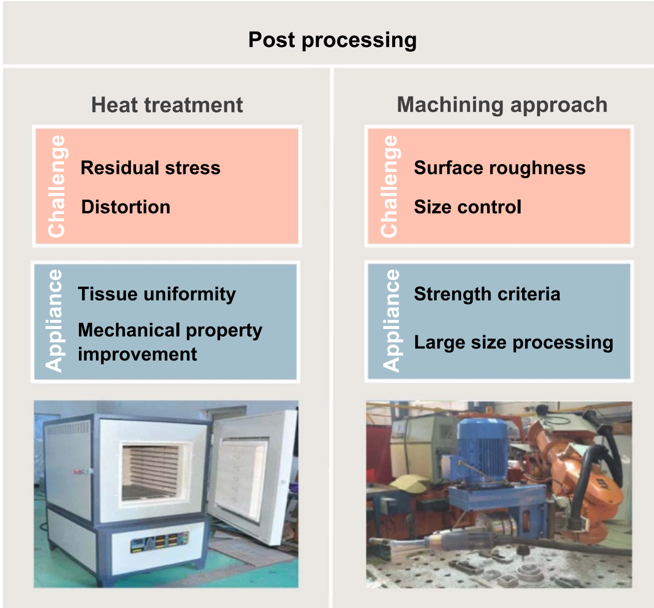

Figure 13. Post treatment process.

quality and performance but also addresses certain types of defects[160]. It improves material properties and strength, particularly for titanium alloys, aluminum alloys, and high-temperature alloys[161], and aids in grain refinement. Therefore, advancing post processing techniques is crucial for improving the quality of wire-arc DED products.

Various simple post processing methods have been developed. For instance, if the component surface exhibits roughness or geometric inaccuracies, surface treatments like polishing, grinding, or sandblasting may be necessary. In some cases, further machining operations such as milling, drilling, or turning are required to achieve specific dimensions, shapes, or accuracies. Support structures used during the manufacturing process can also be removed through mechanical or chemical means during post-processing. This section summarizes recent innovations in post processing techniques, as illustrated in Figure 13. Common post processing methods include heat treatment and machining, each with its own set of challenges and applications. Table 6 provides detailed information on these methods and their respective roles. Understanding these post-processing techniques can inspire advancements in wire-arc DED technology.

3.4.1. Heat treatment. Heat treatment is a common post-processing step in wire-arc DED. It alters the mechanical properties, hardness, strength, toughness, and other characteristics of components to improve their performance and reliability. Heat treatment can also enhance the mechanical properties of components, reduce residual stresses, and promote uniform microstructures[172,173]. Although heat treatment processes have been established for wire-arc DED, handling large-size components remains a significant challenge. The Ipsen company has addressed this issue by

Table 6. The post processing methods.

Process method	Effect	References
Mechanical rolling and annealing	Mechanical properties of texture and elastic anisotropy surpass minimum values.	[162]
T6 heat treatment	Netlike precipitated phases dissolve, giving way to the precipitation of nano-sized θ″ and θ′ phases. Mechanical properties are improved.	[163]
Interlayer hammering	Microstructure refined grain. Recrystallized grains can be deformed leading to an increase in dislocation density and contributing to an increase in ultimate tensile strength.	[159]
Post-heat treatment involving both sensitization and solution treatment	Low ferrite fraction; excellent corrosion performance	[164]
Post heat treatment	Strength and hardness under room temperature can be increased.	[165]
Post-deposition heat treatments	This new heat treatment significantly enhances mechanical properties and substantially mitigates the anisotropic effect.	[166]
Post heat treatments	High mechanical strength is achieved due to extensive precipitation of strengthening phases, but this comes at the expense of elongation rate and toughness.	[167]
Heat treatments and hot isostatic pressing	Hot Isostatic Pressing is highly effective in eliminating porosity.	[168]
Post-build thermomechanical processing	The material exhibits high yield strength, ultimate strength, and elongation to failure, with properties that are equal to or surpass those of typical wrought or cast alloys of similar composition.	[169]
Electro-discharge machining (EDM)	EDM can be utilized to machine thin and hard surfaces with low-surface quality	[170]
Post-heat treatment	The ultimate tensile strength, yield strength, and ductility significantly exceed the mechanical properties of standard wrought P91 steel used in industry	[171]
Vertical inter-pass rolling combined with post-deposition side rolling	Vertical inter-pass rolling enhances tensile strengths and yield, while post-deposition side rolling effectively controls distortion and residual stresses and increases hardness through work hardening.	[158]

introducing the DS series of heat treatment furnaces specifically designed for large components, as depicted in Figure 12. These furnaces accommodate a broad range of part sizes, from small batches to high-volume production, enabling controlled grain morphology changes through heat treatment.

Despite heat treatment being a mature post-processing method, its underlying mechanisms and specific effects are not fully understood. Most research focuses on its impact on microstructure and mechanical properties. Zhou et al.[163] studied the microstructure and mechanical properties of 205A high-strength aluminum in both as-deposited (AD) and T6 heat-treated (T6) conditions. T6 heat treatment significantly improved the mechanical properties of 205A aluminum. While the AD condition showed intergranular fracture, the T6 condition exhibited predominantly transgranular fracture. Chen and Soh[167] explored methods to enhance the mechanical properties of Inconel 718 through optimized solution annealing and single-step age-hardening processes. An alternative heat treatment process was proposed, differing from the standard Aerospace Materials Specifications (AMS) protocol, resulting in components with high strength, ductility, and toughness. Bermingham et al.[168] examined the effects of Hot Isostatic Pressing (HIP) and post-build heat treatments on the strength and ductility of Ti6Al4V alloys. While HIP effectively eliminated spherical porosity, it did not significantly improve strength or ductility. Li et al.[171] analyzed the mechanical and microstructural properties of P91 steel before and after heat treatment. They developed a new heat treatment process to replace the conventional one for deformed materials. By optimizing homogenization and aging treatments, they achieved excellent mechanical properties, including improved plasticity, yield strength, ultimate tensile strength, and ductility, surpassing those of standard deformed P91 steel. As research continues to elucidate the mechanisms of heat treatment processes, a better understanding and application of

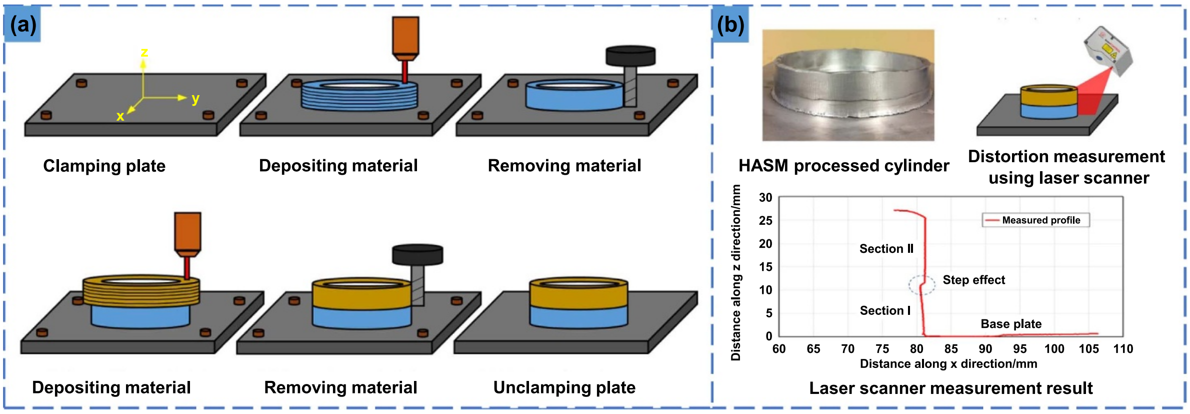

Figure 14. Hybrid additive/subtractive manufacturing process: (a) simultaneous additive and subtractive materials; (b) surface finish morphology.

these methods will lead to improved quality in wire-arc DED processes.

3.4.2. Machining approach. To improve deposition geometric accuracy, in-situ subtractive materials are proposed in the additive manufacturing process, as shown in Figure 14. During deposition, additive process is initially employed to stack layers, and then followed by subtractive process to obtain the desired surface finish. This cyclical production continues for the remaining portions. However, upon inspection with a laser scanner, an obvious step is observed at the boundary between the additive and subtractive materials, indicating an area for future improvement. Machining in wire-arc DED process serves as a post-processing or hybrid solution to enhance component quality and is essential in transforming fabricated parts from near-net-shape to final function components. In general, machining improves surface finish and refines dimensional accuracy to meet stringent geometric and tolerance requirements, as well as removes surface defects such as porosity and oxidation layers. Additionally, hybrid systems that integrate machining with wire-arc DED enable seamless processing in a single setup, significantly increasing production efficiency. Elmer et al.[169] introduced a post-build thermomechanical processing technique. This method combined post-build rolling with thermomechanical processing to improve overall material properties and reduce the anisotropy in component. Additionally, electro-discharge machining (EDM) is an unconventional machining method primarily used for harder conductive alloys. It allows the machining of components with thin-walled features and complex contours. Motwani et al.[170] proposed a novel EDM machining method as an alternative post processing technique. Experiments demonstrated that this method could machine thin and hard part surfaces with low surface quality effectively. Post processing is an essential step in completing a wire-arc DED component with practical performance. Not only does post processing modify component's geometric size, shape, and accuracy at a macroscale level, but it also improves overall quality and mitigates anisotropy at a microscale level.

4. Conclusion and future wire-arc DED

4.1. Brief summary

There is huge potential for wire-arc DED to revolutionize manufacturing sectors by integrating intelligent technologies into critical markets on a global scale, but it still meets many technical challenges for expected component structure and quality. This review outlines recent innovations in the entire wire-arc DED process, including path planning, process monitoring, auxiliary process as well as post processing, aiming to offer a highly practical mentality to improve structure and quality defects at both macro and micro levels. The main summaries include:

(1) Desired path planning strategies can reduce generation of defects such as cracks and pores at deposition, which thus is critical to the final component. To improve wire-arc DED flexibility, development of highly designable and optimal algorithms for complex structures is warranted, ensuring deposition performance, meanwhile, material savings. This encompasses enhancement in structural design, path optimization as well as other related process to attain good surface finish and geometric consistency.
(2) Current real-time process monitoring system can easily discover macroscale defects, however, it is still formidable to find correlatively detectable features that can exhibit abnormal microscale defects. Hence, intelligent online monitoring and adaptive control system, which integrates multi-sensor technologies, is a critical development direction. Certainly, intelligent algorithms, especially capable of real-time adjustment and compensation based on observable data, will be paid increasing attention to enhance process automation and stability.
(3) Efficient and advanced auxiliary technologies for wire-arc DED can significantly enhance the entire deposition process, reducing defect formation, particularly oxidation, porosity, distortion, and anisotropy, while ensuring improved final material properties. Continuous understanding of various auxiliary technologies as well as their inherent operating mechanisms will benefit further process

improvement, which will offer a complete and efficient wire-arc DED system and expected fabrication of high precision and upgrade quality products.

(4) The various post processing can cope with most of macro and micro defects. However, it still needs an optimization in material microstructure during deposition, aiming to reduce manufacturing cost. In fact, increasing attention is gradually paid to find in-situ auxiliary process to replace post processing, which benefits both material and manufacturing time savings.

4.2. Future wire-arc DED

Achieving desirable quality and longevity of printed component is facing a series of challenges in wire-arc DED field. Following a comprehensive review and discussion, a quality-focused framework designed to achieve a high-quality, defect-free wire-arc DED process is proposed, as displayed in Figure 15. To address component defects at both the microscale and macroscale, the entire deposition process, including path planning, process monitoring, auxiliary process, and post processing should be considered. Path planning can find optimal ways to reduce defects occurrence at an early stage of component design and manufacturing. Here, printing path design for different component geometries requires consideration of the relationship between structure, slicing, parameters, and path types. In combinational algorithms with adaptive paths and optimal parameters, path planning will have an accurate and reliable data process. Process monitoring can detect and reduce defects during manufacturing, so that real-time performance, including droplet transfer behavior, dynamic melt pool, temperature profiles, welding signals as well as deposition geometric features, is a key focus. Auxiliary processes can improve microstructural evolution, material properties, and surface finish, which are often achieved through magnetic field, thermal field, acoustic field, mechanical field, and other fields. Post processing methods can be chosen relying on material and component requirements, with attention to geometric features, grain profiles, and phase information. Hence, it is fully acceptable that the entire process involves numerous and multi-source data that can be eventually collected to generate a dedicated and complete database where physics-based models and data-driven models can be established to achieve component quality in artificial intelligent control. In near future, new-type artificial intelligence algorithms will revolutionize the wire-arc DED process, which will further create smart 3D printer and digital twin system to realize product quality improvement.

In the industry 4.0 era, wire-arc DED system has also undergone a comprehensive upgrade toward intelligent and

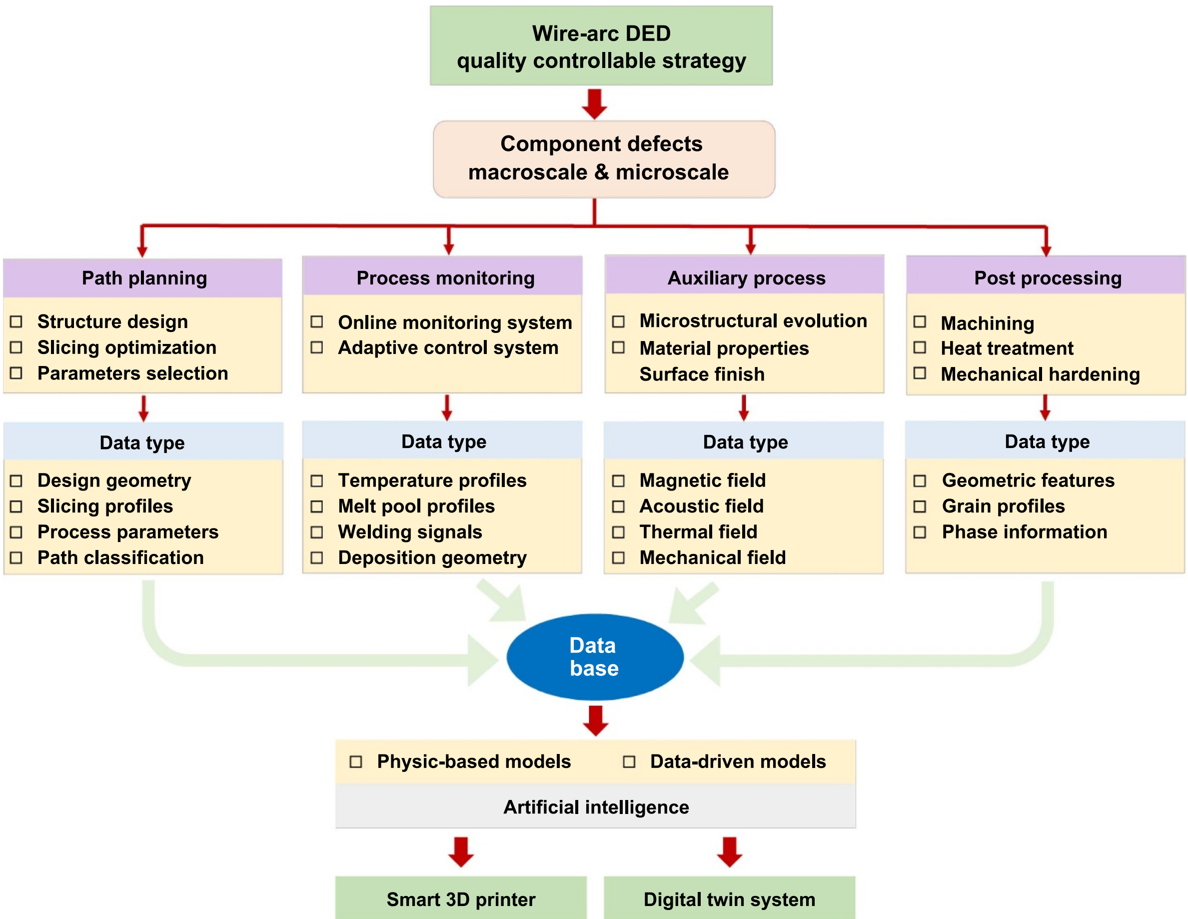

Figure 15. Framework of quality controllable strategy for wire-arc DED.

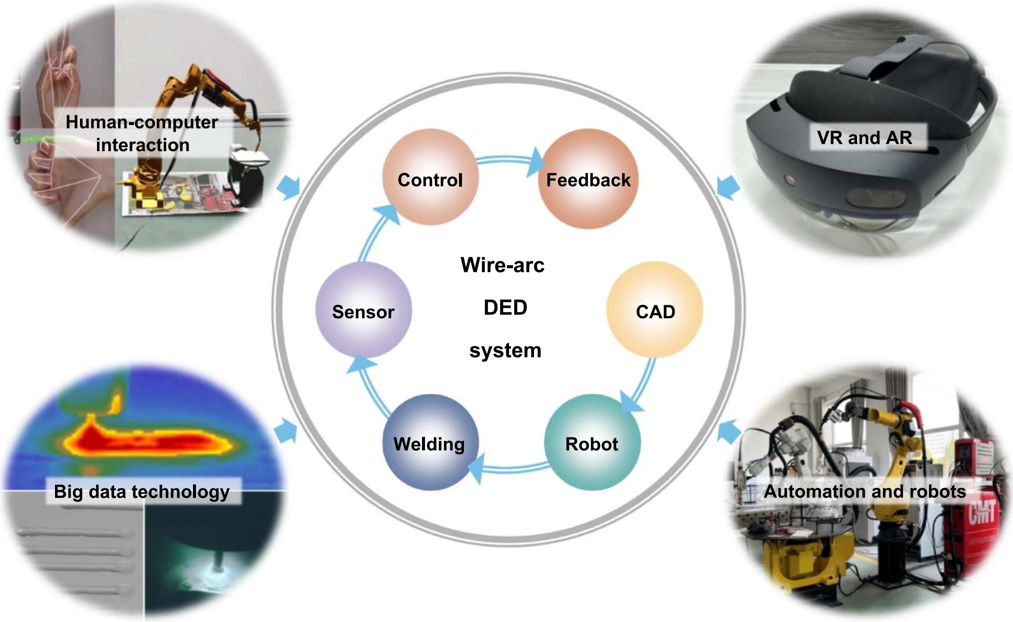

Figure 16. Future wire-arc DED system.

automated direction, as illustrated in Figure 16, and they are paid more attention to material utilization, energy consumption, and environmental friendliness. Extensive process data that are generated during wire-arc DED can be managed using artificially intelligent algorithms and models to build potential correlations, trends, and anomalies in deposition. Digital twin technologies can be used to visualize the optimization of wire-arc DED design and manufacturing process, potentially offering an interactive space. Human-computer interaction technology can be employed for remote monitoring and fault diagnosis, enhancing real-time capabilities in production. Also, robotic production lines can be integrated to realize ultra-size component fabrication with high production efficiency and consistency. Despite facing many challenges for wire-arc DED, continuous technology development will offer flexible and sustainable solutions and then promote manufacturing levels for wide applications.

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