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ORIGINAL ARTICLE

Wire-feed additive manufacturing of metal components: technologies, developments and future interests

Donghong Ding [1] · **Zengxi Pan** [1] · **Dominic Cuiuri** [1] · **Huijun Li** [1]

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Abstract Wire-feed additive manufacturing (AM) is a promising alternative to traditional subtractive manufacturing for fabricating large expensive metal components with complex geometry. The current research focus on wire-feed AM is trying to produce complex-shaped functional metal components with good geometry accuracy, surface finish and material property to meet the demanding requirements from aerospace, automotive and rapid tooling industry. Wire-feed AM processes generally involve high residual stresses and distortions due to the excessive heat input and high deposition rate. The influences of process conditions, such as energy input, wire-feed rate, welding speed, deposition pattern and deposition sequences, etc., on thermal history and resultant residual stresses of AM-processed components needs to be further understood. In addition, poor accuracy and surface finish of the process limit the applications of wire-feed AM technology. In this paper, after an introduction of various wire-feed AM technologies and its characteristics, an in depth review of various process aspects of wire-feed AM, including quality and accuracy of wire-feed AM processed components, will be presented. The overall objective is to identify the current challenges for wire-feed AM as well as point out the future research direction.

Keywords Additive manufacturing · Wire · Metal component · Review

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1 Introduction

Over the past 30 years, additive manufacturing (AM) has gained more and more attention in the manufacturing industry, especially to create part models and prototypes. The history of AM has been summarised recently in the report [1]. The original AM techniques include stereolithography apparatus [2] and 3D printing [3]. These AM processes are initially applied to fabricate polymer as communication or inspection tools, and recently even in final production. The capability of producing prototype in a short period directly from CAD models helps to shorten the product development steps. In order to meet the demands from the aerospace [4, 5], automotive [6], and rapid tooling industry [7, 8], the recent focus of AM research has shifted to fabricate complex-shaped metal components, including titanium and nickel alloys that cannot be economically produced using conventional methods.

The competitive position of AM for metal components relative to alternative manufacturing processes is a function of the geometrical complexity and production volume. Figure 1 [7] showed that AM (also referred as layer manufacturing) is suitable to fabricate parts with medium to high geometrical complexity at relatively low quantities.

Compared with the conventional subtractive manufacturing (e.g. CNC machining), AM has several advantages. First, it is possible to automate the AM process completely from part design to fabrication in a CAD/CAM environment. This reduces both the production time and the amount of human intervention needed for each new part. Although the programme for CNC machining can be generated from CAD models automatically as well, for complex geometries multiple re-fixturing is necessary, resulting in time-consuming and expensive re-fixturing and calibration procedures. Second, AM is a cost-competitive approach for fabricating components made of expensive material such as titanium and nickel

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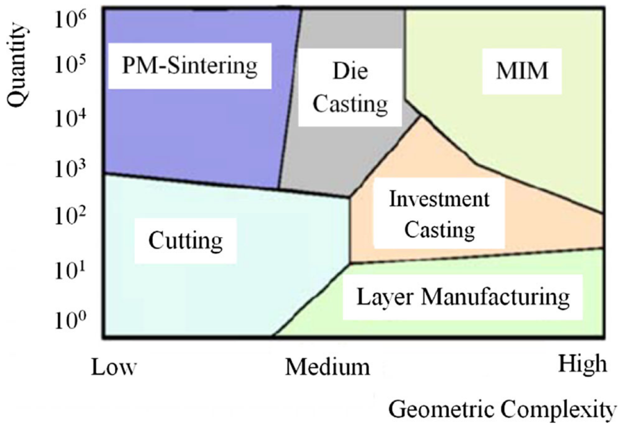

Fig. 1 Qualitative situation of the AM metal components production relative to usual options (*MIM* metal injection moulding, *PM-Sintering* powder metallurgy sintering) [7]

alloys in the aerospace industry, where such components often suffer an extremely low fly-to-buy ratio. In addition, AM is possible to create single-component structures with complex shape that would be impractical or impossible to build with traditional approaches.

1.1 Classification of AM processes for fabricating metal components

According to the standard terminology for AM by ASTM (ASTM F2792), AM technologies for metal components are mainly classified into powder bead fusion, directed energy deposition, binder jetting and sheet lamination as provided in Table 1 [9–20]. Typical additive materials are metal powder and metal wire. With regard to how the additive material is supplied, currently popular AM technologies can be classified as either a powder-feed/-bed process or a wire-feed process.

The majorities of the research in AM have been focused on the powder-feed/-bed AM, where the laser or electron beam equipment is usually used as the power source. Powder-based AM techniques generally involve a complex non-equilibrium physical and chemical metallurgical process, which exhibits multiple modes of heat and mass transfer, and in some instances, chemical reactions. A comprehensive review on the materials design, process control, property characterisation and metallurgical theories for laser sintering, laser melting and laser metal deposition of a wide variety of metallic powders has been reported recently in the reference [21].

Table 2 provides a comparison of the basic features between powder-feed/-bed and wire-feed process [16, 22–27]. The powder-feed/-bed approach is better developed due to its capability of fabricating parts with high geometrical accuracy. The typical layer thickness in powder-feed/-bed technology is 20–100 μm, and the completed components can achieve a dimensional accuracy of ±0.05 mm and surface roughness of 9–16 μm [23–25]. In addition, it is possible to produce parts with functionally graded materials (FGM) [28]. However, the deposition rate of the powder-feed/-bed technology is extremely low, typically around 10 g/min, which limits its application in fabricating median to large-sized components.

In wire-feed AM, a metal wire is used as supply material instead of metal powder. Depending on the energy source used for metal deposition, wire-feed AM can be classified into three groups, namely: laser-based, arc welding-based and electron beam-based [29]. Wire-feed AM has higher material usage efficiency with up to 100 % of the wire material deposited into the component. Therefore, it is a more environmental friendly process, which does not expose operators to the hazardous powder environment. Compared with the powder-feed process, it has a much higher deposition rate of up to 2500 cm^3/h (330 g/min for stainless steel) [27]. It reveals that there is a trade-off between high deposition rate and high resolution while selecting which type of AM process to use for a certain component. As shown in Fig. 2, by using the wire instead of powder materials, the deposition rate increased and large components could be economically produced, while the resolution and complexity

Table 1 Classification of AM for metal components

Classification	Terminologies	Ref.	Material
Powder bed fusion	Direct metal laser sintering (DMLS) Electron beam melting (EBM)	[9] [10]	Metal powder
	Selective laser sintering (SLS)	[11]	
	Selective laser melting (SLM)	[12]	
Directed energy deposition	Electron beam freeform fabrication (EBF^3) Laser engineered net shaping (LENS)	[13] [14]	Metal powder, metal wire
	Laser consolidation (LC)	[15]	
	Directed light fabrication (DLF)	[16]	
	Wire and arc additive manufacturing (WAAM)	[17]	
Binder jetting	Powder bed and inkjet 3D printing (3DP)	[18]	Metal powder
Sheet lamination	Laminated object manufacturing (LOM) Ultrasonic consolidation (UC)	[19] [20]	Metal laminate, metal foil

Table 2 Comparisons of some representative AM processes

Additive materials	Process	Layer thickness (μm)	Deposition rate (g/min)	Dimensional accuracy (mm)	Surface roughness (μm)	Ref.
Powder	LC	N/A	1–30	±0.025–±0.069	1–2	[22]
	SLM	20–100	N/A	±0.04	9–10	[23, 24]
	SLS	75	~0.1	±0.05	14–16	[25]
	DLF	200	10	±0.13	~20	[16]
Wire	WAAM	~1500	12	±0.2	200	[26]
	EBF^3	N/A	Up to 330	Low	High	[27]

of the fabricated parts decreased [16, 22, 26, 27, 30]. Additionally, metal wires are lower in cost and more readily available than metal powders having suitable properties for AM, making wire-feed technology more cost-competitive.

The material properties of parts deposited using either metal wire or metal powder as the additive materials has been investigated [31]. The comparison indicated that the microstructure of samples from both methods is similar, however with some porosity found in the powder-fed deposited parts. Other literatures have investigated the combination of both wire-feed and powder-fed deposition strategy [32, 33]. In [32], it reveals that the deposition efficiency can be increased if these two feeding technologies are combined and the level of porosity was approximately 20–30 % lower than for samples made with powder feeding only. In [33], a combination of Ti-6Al-4V wire feeding and TiC powder feeding was

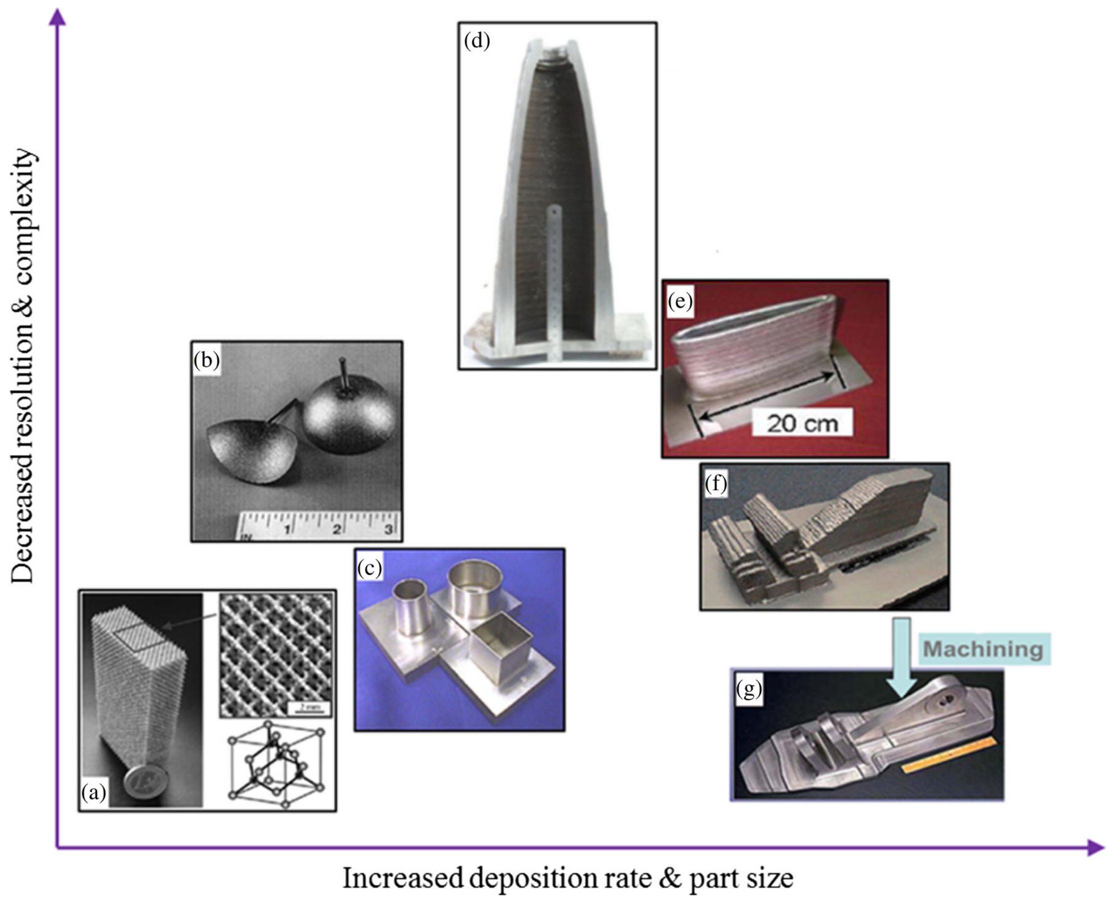

Fig. 2 Comparison of surface finish and deposition rate between powder-feed/-bed and wire-feed technologies. **a** Titanium 3D-micro-framework-structure based on a diamond lattice fabricated using powder bed electron beam melting [30]. **b** A powder-feed-directed light fabrication of 316 stainless steel hemispherical shapes [16]. **c** Three as-consolidated powder-feed laser consolidation IN-625 samples with surface roughness 1–2 μm [22]. **d** A large samples fabricated by WAAM from Cranfield University [26]. **e** 2219 Al airfoil produced by wire-feed EFB^3 [27]. **f** As-deposited sample made by wire-feed LAM (AeroMet) with "stair stepping" surface, and **g** shows the sample after surface machining

investigated. It was found that a uniform distribution of the TiC particles in the new Ti-6Al-4V/TiC composites could be achieved as long as the rates of TiC reach to a certain value.

1.2 Wire-feed AM technology

Wire-feed AM is a promising technology for producing larger components with moderate complexity, such as flanges or stiffened panel. However, there are a few challenges when using wire as the additive material, including residual stress and distortion from excessive heat input, relatively poor part accuracy caused by the "stair stepping" effect and poor surface finish of the produced parts.

While depositing complex and large 2.5 D layers, the geometry-related process parameters (such as deposition width, layer thickness, wire diameter, wire feed rate and welding speed) must be carefully controlled to achieve required part dimension and surface finish. In addition, the residual stresses-induced deformations are a major cause of loss in tolerances in wire-feed AM of large components. The thermal history of the part during the deposition process is related to the process parameters (wire feed rate, welding speed and wire diameter) and the process planning (deposition pattern and sequences). In this respect, significant emphasis should be paid on both part quality (residual stresses and mechanical properties) and part accuracy (surface finish and geometrical accuracy).

Therefore, a review on the wire-feed AM technologies to summarise the state-of-the-art research outcomes and point out the challenges and future research interests is important for researchers in this area. A few existent literature reviews on AM from various aspects could be found [7, 21, 34–39]. With particular emphasis on process control, residual stress and accuracy, this article reviews the current status of research and development in wire-feed AM of metal components, including wire and laser additive manufacturing (WLAM), electron beam freeform fabrication (EBF^3) and wire and arc additive manufacturing (WAAM).

After this introduction session, the rest of the paper is organised as follows. The classification of currently prevailing wire-feed AM processes for metal components are given in Section 2. The current research and challenges of wire-feed AM technology are introduced in Section 3. In this section, an in depth review of various process aspects of wire-feed AM, including quality and accuracy of wire-feed AM-processed components are presented. Section 4 provides a summary and point out the future research interests for wire-feed AM technology. The main issues for wire-feed AM of complex metal components are discussed, including residual stress and distortions, accuracy and surface finish. This review, therefore, seeks to identify the main challenges for wire-feed AM of complex-shaped metal components to achieve good quality and accuracy.

2 Classification of wire-feed AM processes

Depending on the energy source used for metal deposition, wire-feed AM can be classified into three groups, namely: laser based, arc welding-based and electron beam-based. Laser has been the most popular due to its "precision". However, it has very poor energy efficiency (2–5 %) [40]. Electron beam has a slightly higher energy efficiency (15–20 %), but it requires a high vacuum working environment making it suitable for aerospace works [41]. Compared with the poor energy efficiency of laser and electron beam, the energy efficiency of arc welding processes such as gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW) processes can be as high as 90 % in some circumstances [42, 43]. Additionally, the cost of the traditional arc welding equipment is relatively low when compared to the laser or electron beam equipment. More details of WLAM, EBF^3 and WAAM technologies are given below.

2.1 Wire and laser additive manufacturing

Wire and laser additive manufacturing (WLAM) is an AM process to produce metal components with full density using metal wires as the additive material and laser as the energy source. The WLAM system normally consists of a laser, an automatic wire-feed system, a computer numerically controlled worktable or a robot system and some accessorial mechanisms (e.g. shielding gas, preheating or cooling system). As schematically shown in Fig. 3, the laser generates a melt pool on the substrate material, into which the metal wire is fed and melted, forming a metallurgical bound with the substrate [44]. By moving the laser processing head and wire feeder or moving the substrate, a bead is formed during solidification. The relative motion of the welding tool and the substrate could be performed by using a robot arm or a computer numerically controlled worktable.

WLAM is a versatile process that is able to fabricate a wide range of metals and alloys. The performance in terms of surface finish, geometry and quality of the deposit, including the dimension (geometry of the cross-section), the microstructural features (grain size, texture, etc.) and resultant mechanical properties (strength, hardness, residual stress, etc.) are the main concerns of WLAM. These issues are strongly material- and process-dependent and governed by both wire characteristics (e.g. chemical constituents and wire diameter) and processing parameters (e.g. wire feeding direction and angle, wire feed rate, laser power and welding speed).

2.1.1 Materials

A variety of metal alloys, including Fe-based [45], Ti-based [46, 47] and Al-based [48] materials, have been investigated for the WLAM process, among which Ti-

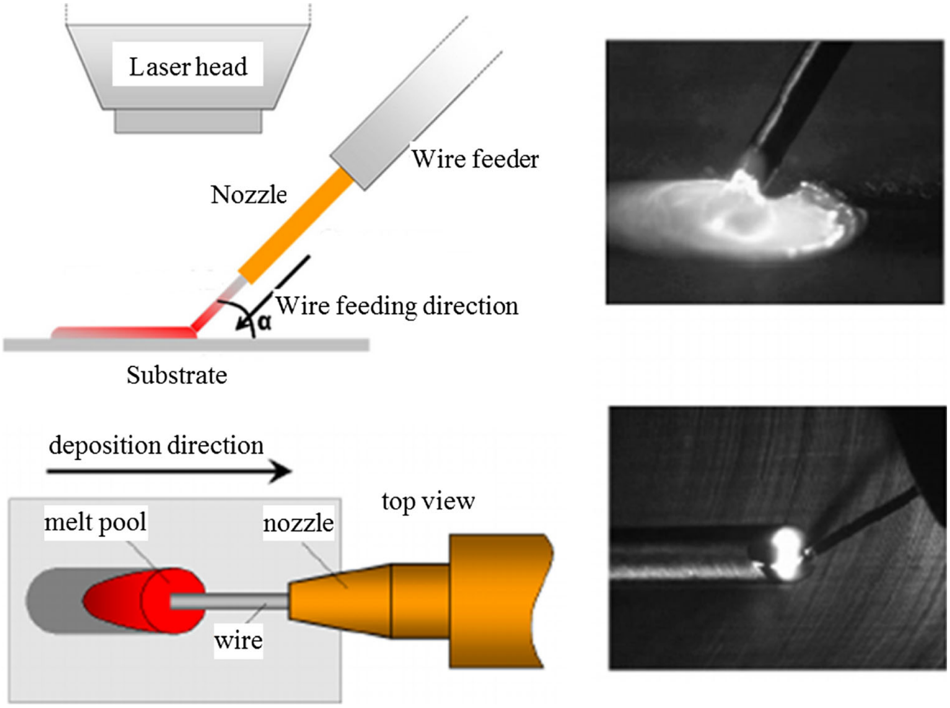

Fig. 3 *Left*: Schematic drawing of the wire-feed process. *Right*: Top-and side view images of the real process [44]

based material (Ti-6Al-4V) gets most wide attention due to its popularity in the aerospace industry. The diameter of the wire for the AM process normally ranges from 0.2 to 1.2 mm.

2.1.2 Wire feed orientation

During the deposition process, wire feed orientation influences drop transfer and the quality of the deposit. Back feeding, side feeding and front feeding, as shown in Fig. 4, have all been reported in the literatures. In order to keep the liquid melted at the end of the wire flow smoothly and continuously onto the workpiece, Kim et al. [49] revealed that for Ti- and Ni-based materials the feed rate is limited for both back feeding and side feeding compared with front feeding. Syed et al. [50] revealed that positioning the wire at the leading edge of the melt pool in front feeding gave the best results in terms of surface finish. Mok et al. [51] also found that the front feeding and side feeding provided smoother surface compared with the back feeding. During the back feeding, a wavy surface with bulbs on the side of the deposit was formed in specimens, this is concordant to the results showed in [50] for deposition with stainless steel wire. However, Xiao et al. [48] measured the influence of direction of the wire addition in CO_2 laser welding of aluminium and suggested that welding with back feeding filler wire is more efficient and stable. Therefore, the optimum wire feed orientation for producing deposits with good shape is material dependent, and good quality could be achieved by adopting appropriate wire feeding direction and position.

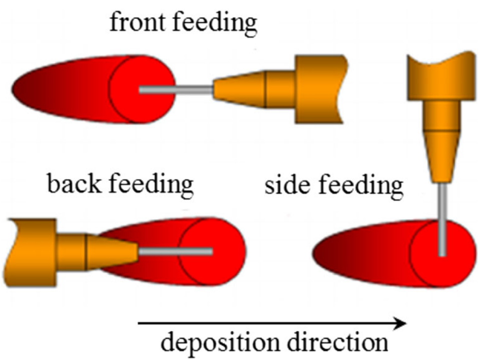

Fig. 4 Three types of feeding directions according to the given deposition direction [44]

2.1.3 Wire feed rate, welding speed and dimension of the deposit

For WLAM processes, wire feed rate is limited by the laser power. When the wire feed rate was set at high levels, wire could not be fully melted. In this case, the wire will be plunged into the melt pool and will be melted partially by the high temperature of the melt pool. Therefore, there is the limitation of the maximum wire feed rate for a certain laser power input. A preferred wire feed rate for the laser power 2.06 and 1.2 kW was chosen as 2 and 1 m/min, respectively, for the deposition of Ti-based alloy in the reference [51]. Deposition rate can be calculated given the wire feed rate and the wire diameter. The

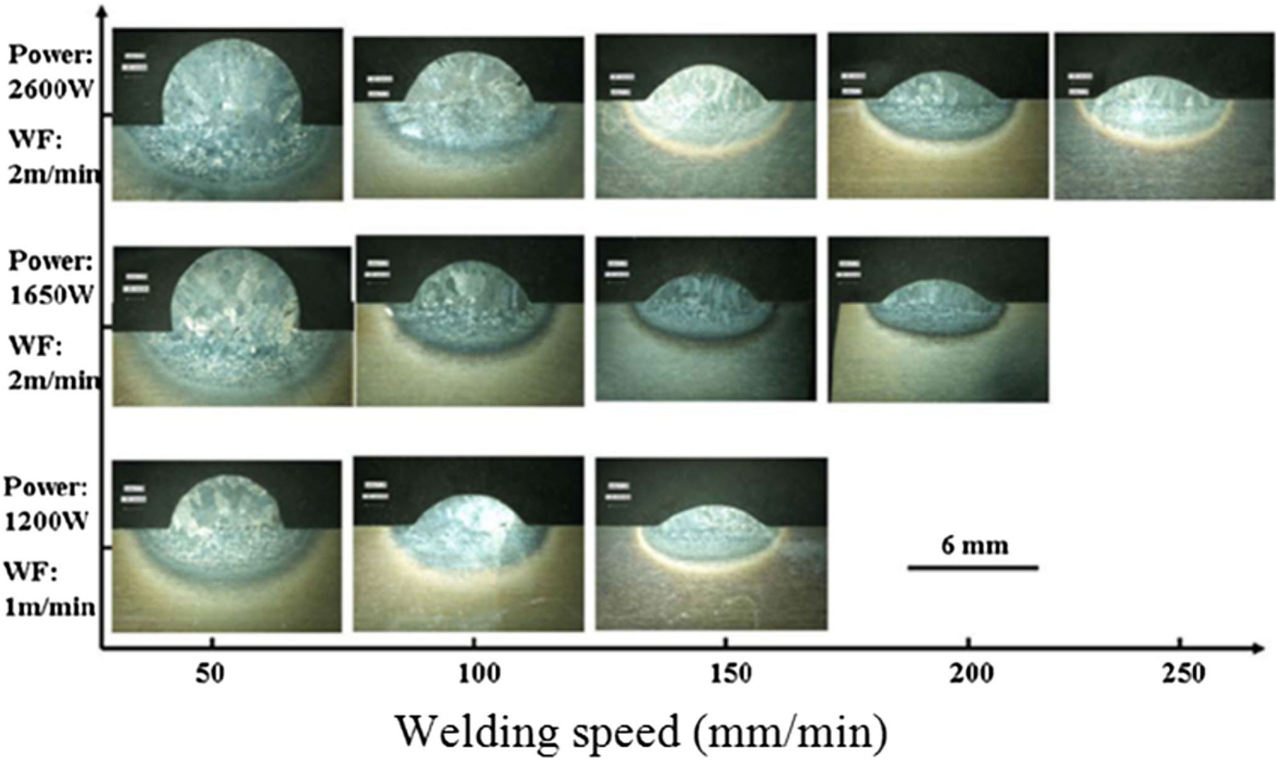

Fig. 5 Cross-section of the single deposit with different set of laser power, wire feed rate, and welding speed [51]

reported deposition rate of WLAM varies from 1.5 to 48.0 g/min. Welding speed normally ranges from 0.05 to 2.4 m/min.

The dimension of the deposit is mainly correlated to the laser power, wire feed rate and the welding speed [51]. As shown in Fig. 5, deposits of the WLAM process were generally free of cracks and porosity, and fully melted to the base plates. The deposition width and height varies with the process parameters. It is revealed that the deposition width is mainly determined by the laser power, while the height is influenced more by welding speed. The influence of process parameters on dimensions of single beads were measured, as summarised in Table 3 [52]. The deposition area is only determined by the wire feed rate, e.g. the ratio of the wire feed rate to the welding speed. With increasing laser beam power, the deposition heights decrease and the deposition widths increase; with increasing the welding speed, the deposition heights increase and the deposition widths decrease; with increasing the ratio λ, both the deposition area and heights increase, but the deposition widths are not significantly influenced.

Table 3 Influence of process parameters on dimensions of single beads [52]

	Deposition area	Deposition height	Deposition width
$P\uparrow$	0	$\downarrow$	$\uparrow$
$V_w\uparrow$	0	$\uparrow$	$\downarrow$
$\lambda\uparrow$	$\uparrow$	$\uparrow$	0

P laser power, V_w welding speed, λ the ratio of the wire feed rate to the welding speed, ↑: significant increase, ↓: significant decrease, 0: no significant influence

2.1.4 Mechanical properties

The hardness and the tensile properties of the fabricated Ti-6Al-4V wall structures from the WLAM processes have been investigated [46]. Figure 6 shows the deposition direction and build direction of a wall structure, and the cross-section of the deposited single bead wall. With the same laser power, the built samples with higher welding speed possess similar or slightly higher hardness than the samples built with lower

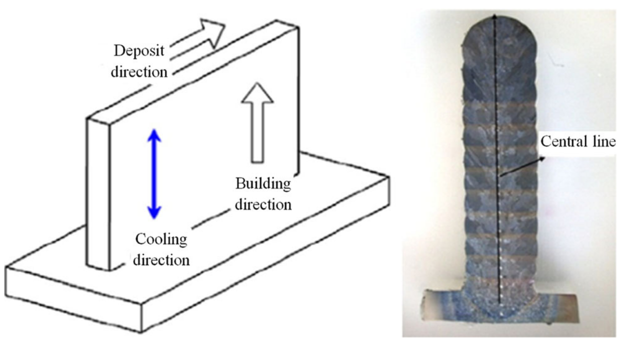

Fig. 6 Schematic of the building direction and deposition direction of the wall structure, and the cross-section [46]

welding speed. The difference of the hardness is less than 10 %. Better tensile properties were observed along the wall building direction than across the wall building direction, due to the anisotropic property of the deposition. The results showed that the post-stress relief process cannot improve the tensile properties of the deposited samples, due to the reduction of the internal residual stress and the coarser microstructure. The mechanical properties of the deposited samples match the properties of as-cast and wrought material. The tensile properties exhibit more significant dependence on the test direction than the process parameters.

Brandl et al. [53] investigated the morphology, microstructure, chemical composition and hardness of additive manufactured titanium (Ti-6Al-4V) blocks, and the effect of heat treatment has been studied. It is found that the hardness of blocks is influenced by the post-heat treatment rather than by the process parameters. The 600 °C/4 h/FC treatment did not significantly influence the morphology and microstructure, but considerably increased the average hardness of the blocks (327 HV0.5→342/343 HV0.5).

In conclusion, with the appropriate wire feed orientation, position and welding parameters, the WLAM process is capable of producing a large variety of metal components without cracking and porosity. The dimensions of single weld bead are mainly dependent on the laser power, welding speed and wire feed rate. Mechanical properties of the additive-manufactured samples can match the properties of as-cast and wrought material. The hardness of the fabricated sample is significantly influenced by the heat treatment rather than by the process parameters. The tensile properties of the additive manufactured blocks are correlated to the deposition direction due to the anisotropic property of the deposition.

2.2 Electron beam freeform fabrication

Electron beam freeform fabrication is a NASA-patented additive manufacturing process designed to build complex, near-net-shape parts requiring substantially less raw material and finish machining than traditional manufacturing methods. Figure 7 shows a schematic of the primary components in an electron beam freeform fabrication (EBF^3) system [13]. The process introduces metal wire feedstock into a molten pool that is created and sustained using a focused electron beam in a high vacuum environment. The electron beam couples effectively with any electrically conductive material, including highly reflective alloys such as aluminium and copper. The EBF^3 process is capable of bulk metal deposition at deposition rates over 2500 cm^3/h as well as finer detailed deposition at lower deposition rates with the same piece of equipment, limited only by the positioning precision and wire feed capability. The diameter of the wire feedstock is the controlling factor determining the smallest feature attainable using this process: fine diameter wires may

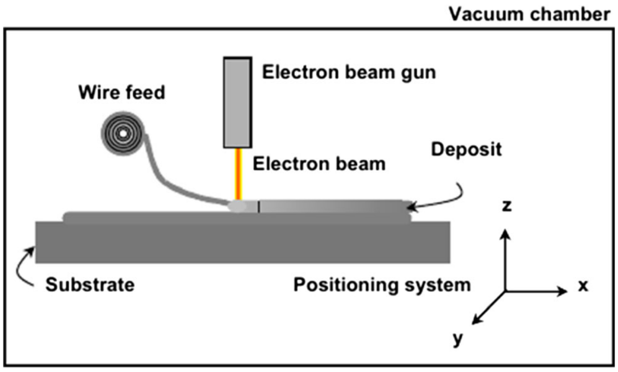

Fig. 7 Schematic of electron beam freeform fabrication (*EBF*) system components [13]

be used for adding fine details, and larger diameter wires can be used to increase deposition rate for bulk deposition.

Taminger et al. [13] reveals that there is a trade-off between the deposition rate and grain size for materials deposited using the BEF process. On the other hand, the tensile properties for BEF^3-deposited 2219 Al and Ti-6Al-4V were very consistent over a wide range of process conditions, indicating that the tensile properties are not sensitive to the variations of heat input. Other researches on EBF^3 could be found [5, 27, 41, 54].

2.3 Wire and arc additive manufacturing

Wire and arc additive manufacturing (WAAM) is another popular wire-feed AM technology. Several research groups have investigated the WAAM process using of gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) or plasma arc welding (PAW) as a heat source, as summarised in Table 4 [4, 26, 55–78].

A schematic diagram of the GMAW, GTAW and PAW process is shown in Fig. 8. GMAW is a welding process in which an electric arc forms between a consumable wire electrode and the workpiece metal. The wire is normally perpendicular to the substrate. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray and pulsed-spray, each has distinct features. Besides, cold metal transfer (CMT), a modified GMAW variant based on controlled dip transfer mode mechanism, has also been widely implemented for AM processes [4, 79], due to its high deposition rate with and low heat input.

GTAW and PAW use a non-consumable tungsten electrode to produce the weld. Different from GMAW, the wire feed orientation in GTAW and PAW is variable and affects the quality of the deposit, which makes the process planning more complicated. The differences between plasma arc and GTAW arc are shown in Fig. 9. The high temperature zone of the plasma arc is narrower than the GTAW arc resulting in relatively narrower weld beads can

Table 4 Different phrases of WAAM from various research groups

Synonyms	Institutions/universities	Energy source	Ref.
3D welding	University of Nottingham	GMAW	[55, 56]
Welding-based deposition	Southern Methodist University	GMAW, GTAW	[57–59]
3D welding	Korea Institute of Science and Technology	GMAW	[60, 61]
Welding-based rapid prototyping	University of Kentucky	GMAW	[62, 63]
Near-net shape manufacturing	Tufts University	GMAW, PAW	[64]
Shape deposition manufacturing	Carnegie Mellon and Stanford University	GMAW, GTAW	[65]
GMAW-based rapid prototyping	Harbin Institute of Technology	GMAW	[66, 67]
MPAW-based rapid prototyping	Xi'an Jiaotong University	Micro-PAW	[68]
Hybrid-layered manufacturing	Indian Institute of Technology	GMAW	[69]
WAAM	Cranfield University	GMAW, GTAW, PAW	[4, 26, 70–72]
WAAM	University of Wollongong	GMAW, GTAW	[73–78]

be deposited [68]. Arc energy in plasma welding can reach three times that of GTAW welding causing less weld distortion and smaller welds with higher welding speeds [80]. An AM system based on micro-PAW was introduced and the effects of process parameters on the mechanical properties of the additive manufactured parts have been investigated [68].

A typical diagram of the robotic WAAM system (GMAW-based) is shown in Fig. 10 [73]. A computer interface (1) is used to programme the experimental processes and collect the experimental results. The robot controller (2) is used to coordinate both the robot motions and welding processes. A programmable GMAW power source (3) is used to control the welding process. A large industrial robot (4) implements the movement of the welding torch (5) for metal deposition, and subsequently a laser profiler (6) to measure the bead profile. An example of weld bead deposits on a work piece is shown (7).

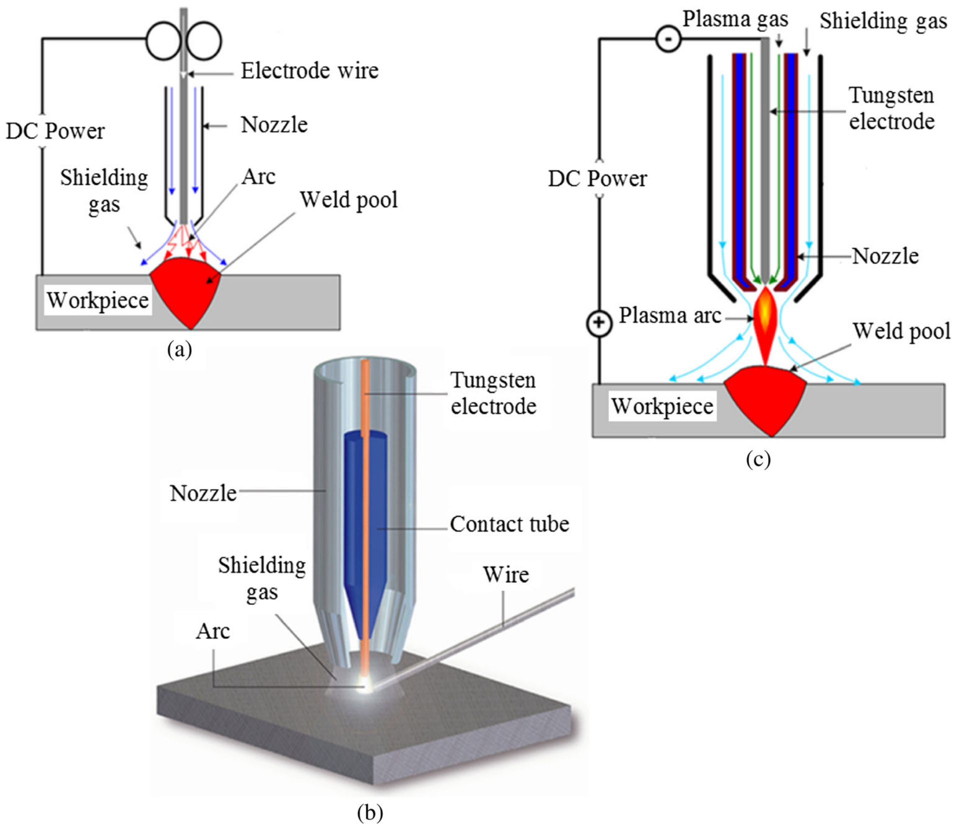

Fig. 8 Schematic diagram of the **a** GMAW, **b** GTAW, and **c** PAW process

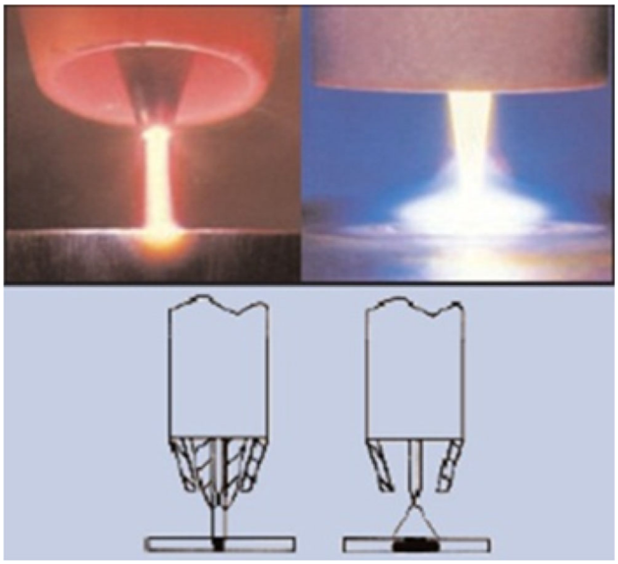

Fig. 9 Comparison between plasma arc and GTAW [80]. *Above diagram* shows a plasma arc on the *left* and a GTAW arc on the *right*. *Below diagram* shows the schematic difference between the plasma arc on the *left* and the GTAW arc on the *right*. Note the cylindrical shape of the plasma arc when compared to the conical shape of the GTAW arc

3 Current research and challenges

While wire-feed AM is a promising technology for producing larger aerospace components with moderate complexity, such as flanges or stiffened panel, there are a few technical challenges yet to be resolved, including the residual stress and distortion from excessive heat input, relatively poor part accuracy caused by the "stair stepping" effect and poor surface finish.

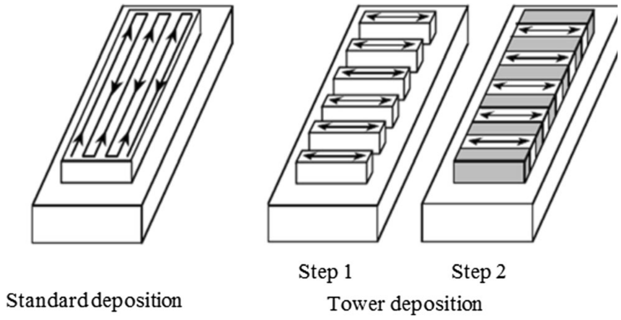

Fig. 11 Schematic of two deposition techniques [81]

3.1 Residual stresses and distortions

The control of residual stresses and distortions especially for the large-scale WAAM process is one of the major concern, as it not only has an effect on the part tolerances but it also cause premature failure. In welding, thermally induced stresses are the result of thermally induced strains during the non-uniform expansion and contraction of the material. The induced strain causes a material or structure to respond by distorting. If it is unable to cause a structure to respond by distorting macroscopically, it will either causes it to deform microscopically

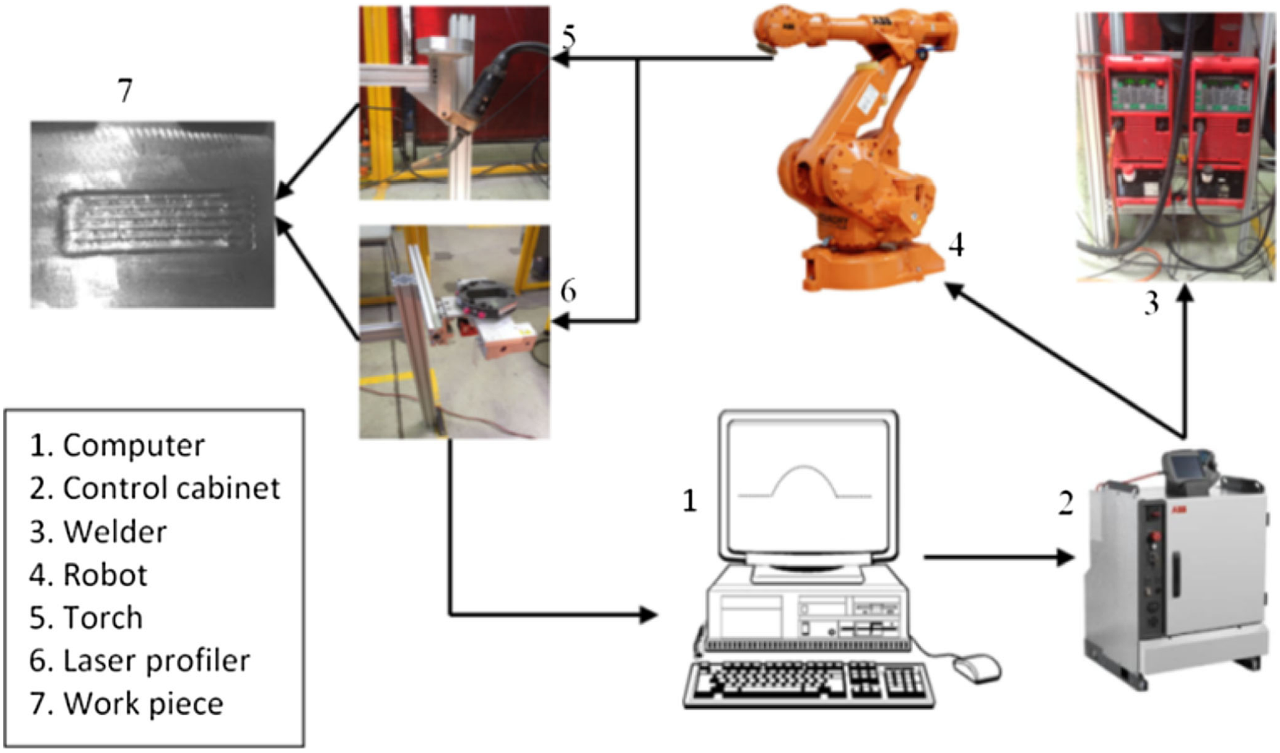

Fig. 10 Schematic diagram of the experimental robotic WAAM system [73]

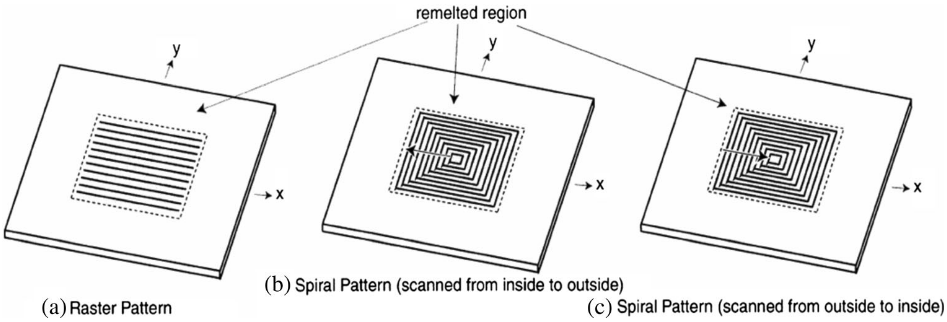

Fig. 12 Deposition patterns for plate substrates [83]

(e.g. yield or crack) or resulting in stress that are “lock in” also called residual stresses. When the fabricated component is unclamped, residual stresses will release resulting in distortion of the component. Although the residual stresses could be minimised by post-processing technologies, residual stresses-induced distortions are a major cause of loss in tolerances. Therefore, the best way to limit distortions is to control the build-up of residual stresses during the deposition.

A lot of research strategies have been investigated on thermal stresses analysis of material deposition of multi-pass single-layer structure by altering deposition patterns, deposition sequences and preheating or interpass cooling. The selective deposition approach, which deposits a series of small patches (“towers”) first and joins them joined together later to form a large patch, has been used to minimise the deformation due to thermal stresses for shape deposition manufacturing [81]. As shown in Fig. 11, these “towers” are only constrained at the bottom and their large surface area to volume ratio allows them to relax significantly as they cool down. Selective deposition can reduce deformation of the final part by allowing much of the deformation produced during cooling to occur before the deposit is fully constrained. The influence of deposition patterns, such as long raster and spiral, on the deflection of the metal part was been studied by Nickel et al. [82, 83] using a combination of finite element analysis and experiments as shown in Fig. 12. It was found that the short raster pattern produced the lower deflection for a beam substrate, but for a plate substrate a spiral pattern scanned from the outside to the inside produces lower and more symmetric deflections. The same result was also obtained in the laser powder deposition process as reported by Foroozmehr [84]. This indicates that the deposition pattern significantly affects the temperature history of the process, and consequently, the stress distribution.

Mughal et al. [85, 86] developed a thermo-mechanical model to predict the residual stress-induced deformations. It has been found that continuous deposition without interpass cooling results in less deformation as it equivalently provides a preheating for the substrate. Chin [87] also reported that uniform substrate preheating reduces residual stresses and deformation. However, continuous deposition may cause excessive heat input in a local area, resulting in high temperature gradients and large remelting of the substrate, which causes poor dimensional tolerances and surface finish [56]. Consequently, a compromise needs to be made between employing interpass cooling to avoid excessive heating and maintaining enough preheating to reduce deformation.

The effects of deposition sequences on residual stresses have also been investigated [85]. It was found that residual stresses are dependent on deposition sequences in continuous deposition. While the maximum stress value does not vary, the highest stresses are always found at the last deposition rows, since latter deposition is a reheating process which relaxes the stresses in the former deposits. However, with enough interpass cooling, the residual stress distribution becomes independent to the deposition sequence as each deposition sequence does not provide any preheating effects to the next sequence.

Thermo-mechanical analysis of material deposition on a single-pass multi-layer wall structure (see Fig. 13) has also been widely investigated [79]. The study from [86] shows that the process using monotonic deposition direction compared with alternative deposition directions provides better heat diffusion condition and the temperature gradient trend. Recently, research works on wall structures [4] showed that the heat from the welding process causes a tensile residual stress along the weld bead due to material contraction during solidification, which causes a balancing compressive residual stress in

Fig. 13 Ti-6Al-4V wall structure deposited by the WAAM process, the deflections along the deposition direction can be observed [79]

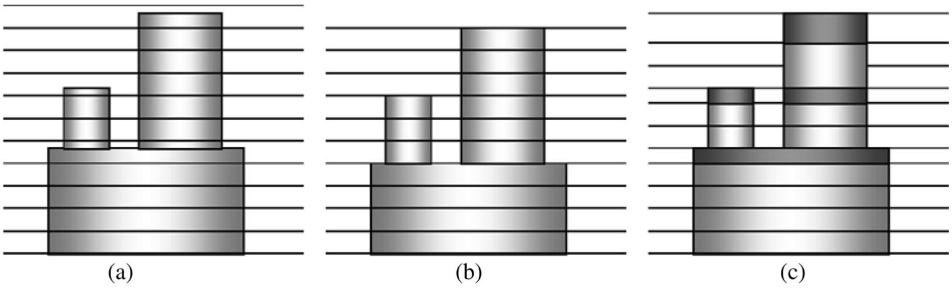

Fig. 14 The principle of layer thickness adjustment: **a** original solid model, **b** sliced model with constant layer thickness and **c** sliced model with adjusted layer thickness [62]

the base plate. A significant distortion of the component and relaxation of the stresses was observed after the clamping was removed. It was also found that the stresses across the deposited wall are uniform with very little influence from the preceding layers. Rolling can reduce residual stresses and distortions on WAAM parts, particularly in the areas adjacent to the baseplate [72]. In addition, rolling also induced grain refinement when the rolled material was reheated during the subsequent deposition pass [72].

Reported experimental research of the effects of deposition pattern, deposition sequences and preheating on the residual stress mainly involves 2D layers or thin wall structures. For real engineering applications, finite element models are commonly used to predict residual stresses and distortions [87]. Currently, the optimum deposition strategy for reducing the residual stresses induced by AM of any given 3D components remains unavailable.

3.2 Accuracy and surface finish

3.2.1 Accuracy

Besides the distortions induced from residual stresses, another main factor that affects the accuracy of the part is the slicing manner that includes the un-match effect and the staircase effect. Normally, a solid model is sliced with a constant layer thickness, as shown in Fig. 14a. The un-match would occur when the sliced model with a constant layer thickness does not match with the original solid model (Fig. 14b). The adaptive slicing strategy which involves non-constant layer thickness is an effective way to address this issue. In the adaptive slicing strategy [62, 63, 88], the layer thickness can be adjusted automatically within a certain range to fit the shape of the model, as shown in Fig. 14c.

The "stair stepping" effect comes from the approximate construction of surfaces using deposition layers with a certain layer thickness. It exhibits dimensional errors normal to the build (deposition) direction as shown in Fig. 15. For a given part surface, the thicker the layer thickness, the larger the error of the produced part would be [89]. Therefore, the accuracy of the part manufactured by wire-feed AM technology is typically 10 times lower than that made by powder bead/feed technology, due to the thicker layer thickness of the wire-feed AM technology (about 1.5 mm), as summarised in Table 2. With high deposition rate, the WAAM process is effective for simpler geometries. However, when high-accuracy parts are desired, a milling process is necessary to be integrated in the WAAM process.

3.2.2 Surface finish

In AM, since a surface is usually fabricated through deposition of a large number of weld beads side by side with/without overlapping and each weld bead is a parabola-similar curve rather than a regular rectangle, the surface finish also refereed as "surface roughness". Therefore, accurate models for single bead geometry as well as the multi-bead overlapping play an important role in determining the surface finish of the fabricated products.

A lot of research has been directed towards developing a correlation between welding parameters and weld bead geometry by using regression analysis [69], artificial neural

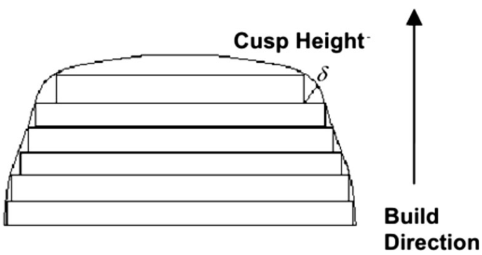

Fig. 15 Approximate surface—"stair stepping" effect [89]

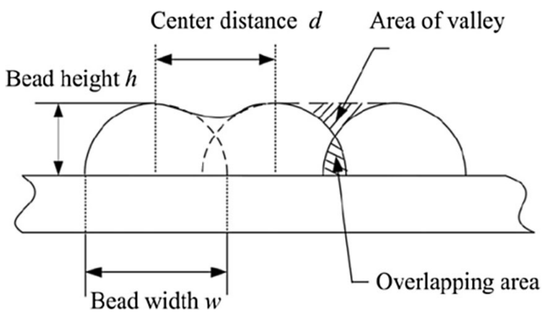

Fig. 16 Sketch of the traditional flat-top overlapping model (*FOM*) [66]

networks or combinations of these two techniques [90]. A symmetric parabola profile of the weld bead has been described by Suryakumar et al. [69]. Cao et al. [91] fitted the weld bead boundary with Gaussian, logistic, parabola and sine functions, and found that the sine function can fit the measured data with highest accuracy. Xiong et al. [66] compared the measured weld beads under different welding parameters to three frequently used profile models, namely circular arc, parabola and cosine function. It was shown that the optimal model for the bead profile is largely dependent on the ratio of wire feed rate to welding speed. Previous research had used measured bead height and width instead of complete cross-sectional profile for the model parameters identification. Nevertheless, the relative errors of bead cross-sectional area predicted by their models were as high as 15–20 % in certain circumstance [66, 69]. Development of more accurate model for bead cross-sectional profile is the first step to reduce the surface waviness.

Some preliminary investigations on multi-bead overlapping models have been made in recent years [66, 68, 69, 91]. A simple flat-top overlapping model (FOM) has been developed in the literature, and is described in Fig. 16. Let a single bead have a height h and width w; and the adjacent beads have a centre distance d. The centre distance d between adjacent beads plays an important role in determining surface quality and smoothness, as schematically shown in Fig. 16. When the centre distance d is greater than the single bead width w, there is no overlap within the two adjacent beads. As the centre distance is decreased, the overlapping area increases, and the area of the valley decreases. As the centre distance d decreases to a certain value, the overlapping area becomes equal to the area of the valley and the overlapped surface will become an optimal plane. With a further decrease of d, excessive overlapping area leads to an increased thickness of the deposited layer and decreasing surface smoothness. Consequently, the optimal centre distance d is determined by the criterion that a flat plane will be obtained when the overlapping area is equal to the area of valley (Fig. 17). However, it has been observed through experimentation that it is impossible to achieve the ideally flat overlapped surface [68, 69]. Therefore, the overlap criterion proposed in these studies is not optimal and produces an undesired wavy surface, as shown in Fig. 18. As a workpiece requires deposition of several layers, uneven layer surface may lead to accumulating errors along the vertical direction, resulting in unstable deposition after several layers. A more accurate multi-bead overlapping model for the determination of the optimal centre distance has been established recently, so that a stable overlapping process can be achieved for mild steel [74]. Overlapping models for other materials are required in the future.

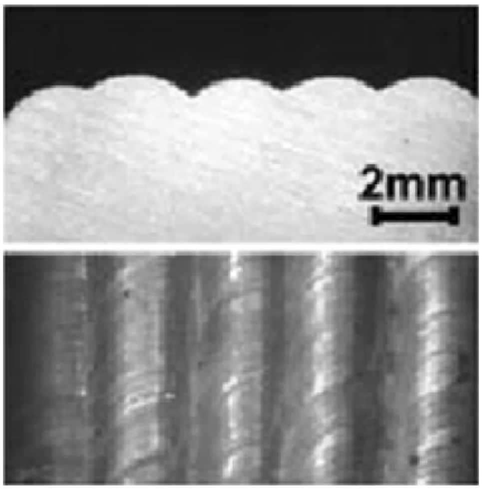

Fig. 18 Cross-section profile of the overlapped part (*top*) and the waved surface (*bottom*) [68]

For the GMAW-based WAAM process, due to the inherent characteristics of the process, the weld bead geometry within a weld pass is not uniform, particularly at the start and end portions. This will lead to the uneven bead geometry, poor surface finish and part accuracy. Figure 19 shows an example of thin walls built by weld deposition where there are significant differences in bead geometry between the start and end of the weld paths [70].

To overcome the issue of uneven surface induced by arc start and arc end, Zhang et al. [62] adjusted the welding parameters at the start and end portions of the weld paths to control the bead geometry. At the start portion of the weld pass, the current and travel speed decrease from higher values to the normal ones, while at the end portion of the pass, the current and the travel speed reduce gradually. Although the shape of the weld pass can be flexibly controlled using this method, the adjustment procedures are empirical and time-consuming. Instead of changing the process parameter, an alternative method was developed to optimise the deposition

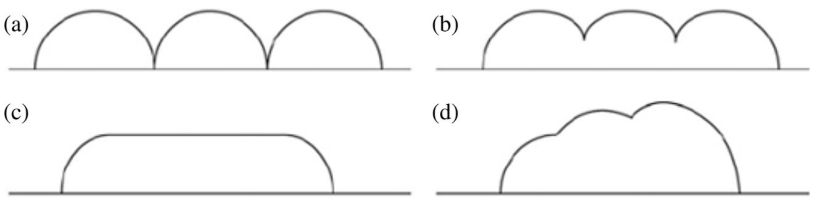

Fig. 17 Patterns of different centre distance d. **a** d more than w. **b** d less than w, overlapping area less than area of valley. **c** d less than w, overlapping area equal to area of valley. **d** d less than w, overlapping area more than area of valley [66]

Fig. 19 Thin walls built by weld deposition showing the changing bead geometry at the start and end portions [70]

tool path pattern. A continuous path has been suggested to minimise the number of weld passes for each layer to eliminate the side effects of the arc starting/stopping [73]. It showed that the surfaces deposited using the continuous tool path planning method (only one starting/stopping) is better than that using multiple starting/stopping. However, the proposed continuous deposition path disregards the side effects from the residual stresses and distortions. Further research should be paid on the optimising of the deposition patterns in terms of reduced residual stresses as well as improved surface finish.

4 Summary and prospective view

4.1 Essentials of wire-feed AM

Additive manufacturing technology, also widely known as rapid prototyping or rapid manufacturing, has a more than 30-year history of development, and has become an important fabrication process for manufacturing custom-made metal components. Wire-feed AM is a promising technology for producing larger features with moderate complexity, such as flanges or stiffened panel, due to its higher deposition rates and better material quality compared to powder-feed/-bed AM technology. A variety of materials are suitable for wire-feed AM, such as steel [45, 50, 56], Ti alloys [46, 47] and Al alloys [48]. Therefore, wire-feed AM is believed by many experts as a cost-effective alternative for manufacturing metal components with median to large size in terms of productivity, cost-competitiveness and energy efficiency.

4.2 Applications

Wire-feed AM technologies have been widely applied in various industries including aerospace, automotive, and rapid tooling, etc. Aerospace components often have complex geometries and are made from expensive materials, such as titanium alloys and nickel alloys, which suffers very low fly-to-buy ratio. The automotive industry has been using AM technology as a useful tool in the design and prototype of automotive components because it can shorten the development cycle and reduce manufacturing and product costs. The tooling industry applies AM to produce functional tool components. Rapid tooling is, therefore, considered as an important subcategory of AM. Examples of metal components produced by wire-feed AM are shown in Figs. 20, 21 and 22. The majority of the components manufactured by wire-feed AM technology have relatively simple geometry, such as cylinder, wall, stiffened panel, etc.

4.3 Future research interests

Researches on wire-feed AM of metal components, as reviewed in the present article, are interdisciplinary, integrating materials science, thermo-mechanical engineering and process planning. Significant research and further understanding are required in the aspects of process control and optimisation control residual stresses and distortions. Combining the opinions proposed by other experts in the AM research field [7, 21, 34–39], the authors have summarised the following issues that are of particular significance for future development of wire-feed AM technology.

4.3.1 Material quality

High deposition is a remarkable advantage of wire-feed AM technology, while it accompany with excessive heat input resulting in residual stresses and distortions. The control of

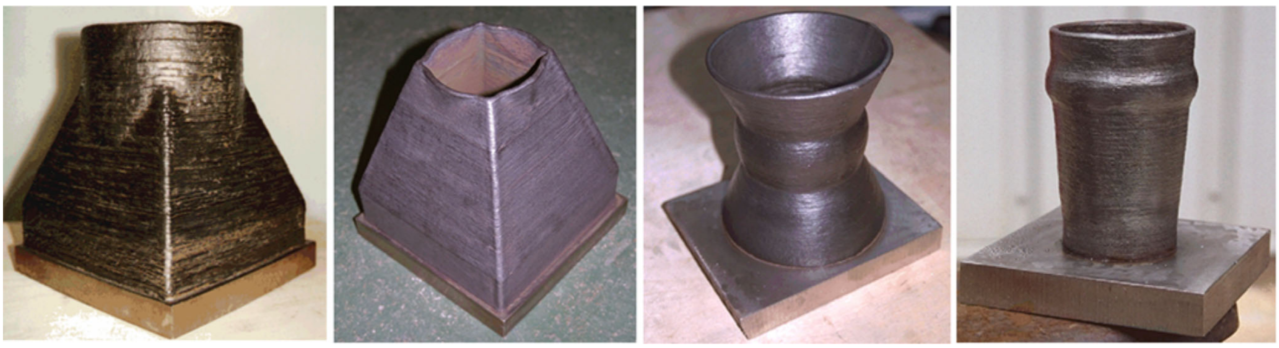

Fig. 20 Various metal components produced by AM using GMAW from Cranfield University [71]

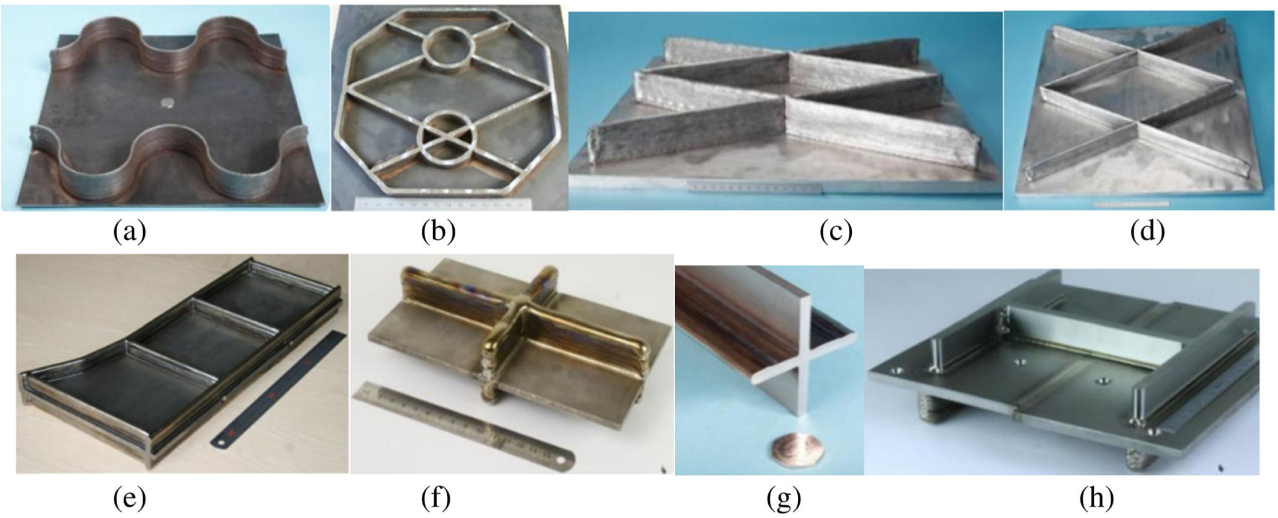

Fig. 21 Intersecting stiffened panels produced by WAAM. **a** and **b** carbon steel. **c** and **d** aluminium. **e** titanium-stiffened panel. **f** Ti thick wall crossover. **g** Ti residual stress balanced cruciform. **h** Ti intersections including machining. All test pieces are collected by [26]

residual stresses and distortions is the main concern especially for a large-scale WAAM process. To identify the optimum strategy for residual stresses and distortions, both experiments and simulations are required. Significant investigations should be spent on the effects of process parameters (e.g. energy power, wire-feed rate, welding speed, wire diameter, etc.), deposition patterns and sequences, cooling or preheating on the stress evolution. Only when the residual stresses and distortions are eliminated or reduced, the components with good quality and accuracy could be achieved.

4.3.2 Design for AM

As shown in Figs. 20, 21 and 22, wire-feed AM are still only applied on simple structures. Real engineering components are more complex. A multi-direction deposition system which enhances the capability of the AM is required. However, the majority of the existing 3D slicing strategies apply only to a subset of possible part geometries. More emphasis should be paid in multi-direction AM to develop robust algorithms capable of automatically slicing any 3D model which satisfy support-less and collision-free layered deposition.

Path planning for wire-feed AM technology is more complicated since special concerns should be paid on the residual stress evolution and the dimensional relationship between the weld bead and the part geometry. The investigation of the evolution of residual stresses could guide the path planning in terms of patterns and sequences. For components with complex geometry, dimension-related issue is another obstacle for automatic path planning.

4.3.3 Monitoring and process control

The capability to achieve predictable and repeatable operations is important for wire-feed AM. Since the deposition process has shown to be extremely sensitive to the process variations, a system for on-line monitoring and control of the deposition process is necessary. Although some preliminary studies have been reported on the control of the deposition process [44, 67, 92], more emphasis is required on this research area to increases the stability of the deposition process.

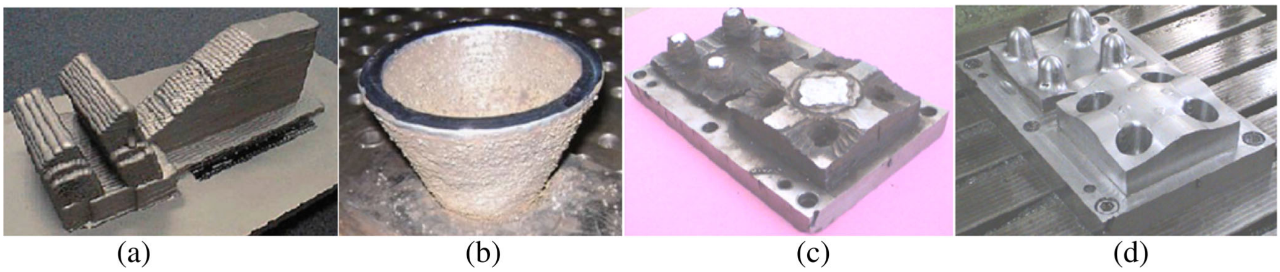

Fig. 22 **a** As deposited sample made by wire-feed LAM (AeroMet), **b** thick wall structure produced by hybrid layer manufacturing (*HLM*), **c** near-net shape of the die pair and **d** finished die pair produced by HLM [29]

4.3.4 From near to net shape

Due to the poor accuracy, "stair stepping" effect and poor surface finish, an integrated 3D milling system is necessary for wire-feed AM when high-accuracy components are desired. For some complex components, 3D milling after the deposition of the whole component would be impossible due to the occurrence of collision. Periodic milling after each layer deposition is possible to produce high-accuracy components; however, it is time-consuming and a wastage of materials. The effective milling strategy is required to be developed from the geometry information of the original 3D components.

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