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WAAM process for metal block structure parts based on Mixed Heat Input

Junyi Cui
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**WAAM process for metal block structure parts based on
Mixed Heat Input**

By

Junyi Cui

**This thesis is presented as part of the requirement for the conferral of the
degree:**

**Master of Philosophy
(Mechatronic Engineering)**

From

**University of Wollongong
Faculty of Engineering and Information Science**

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Abstract

Additive manufacturing based on robotic welding is used for the manufacturing of metal parts by applying an arc as a heat source and wire as feedstock. The process is known as Wire Arc Additive Manufacturing (WAAM). However, the current WAAM process has a limitation in fabricating block structure components with high geometry accuracy and consistent welding due to the process complexity and lack of appropriate process planning method. Furthermore, common defects such as voids, gaps and collapse decrease the mechanical properties of the final product. This thesis presents a novel process planning method based on a Mixed Heat Input(MHI) strategy to minimise voids and collapse defects that occur in fabricating large block structure components while maintaining a high manufacturing efficiency. By dividing each layer into a boundary layer and multiple inner layers, the MHI method applies various heat input conditions at different positions of the layer allowing the construction of defects-free components. The performance of this method is shown by the fabrication of a simple structure component. To evaluate the mechanical properties of the deposited sample, the hardness and microstructure are exhibited and compared with the conventional WAAM process. Finally, the MHI strategy is applied to the manufacturing of a real-life large block structure component with a dimension of $670 \times 465 \times 154\text{mm}$. The results show that such strategy succeeds in achieving production efficiency and quality simultaneously.

Keywords: *robotics; WAAM; large block structure components; heat control*

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Certification

I, Junyi Cui, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Master of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

Junyi Cui

August 2020

List of Names or Abbreviations

1. Abbreviations

AM	Additive Manufacturing
WAAM	Wire - Arc Additive Manufacturing
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
CMT	Cold Metal Transfer
CAD	Computer-Aided Design
WFS	Wire Feed Speed
TS	Travel Speed
HI	Heat Input

2. Notations

ρ	The density of the molten pool
γ	The surface tension of the molten pool
H_t	Actual height
h	Target height
I	Welding current
R	Resistance of the welding arc
η	Heat input efficiency
U	Welding voltage

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Chapter 1 Introduction

1.1 Overview

Since the 1980s, Additive Manufacturing (AM) has gradually evolved from rapid prototype applications to end-use production in the aerospace industry, automotive industry and shipbuilding industry[1, 2]. The metal AM process uses either a laser beam, electron beam or arc as the power source and either wire or powder as feedstock material to deposit material layer by layer[3]. Among metal AM technologies, Wire Arc Additive Manufacturing (WAAM) stands out as a variation of Direct Energy Deposition (DED) techniques due to the high deposition rate and lower costs for equipment.

The WAAM process contains feeding filler wires into a molten pool melted by using an electric arc as the heat source, which is a highly -efficiency process for the fabrication of large-sized block structure components. Compared with other AM methods, the deposition rate of WAAM can reach to 5 to 6 kg/hour, which is five to ten times faster than the Laser Metal Deposition (LMD)[4]. At the same time, it is demonstrated that WAAM can perform localised repairs to significantly reduce costs differing from replacing with a new part[5]. Furthermore, the WAAM process attracts significant interests from the various industries due to its high potential for improving material usage and short production lead time. Owing to such advantages, WAAM is considered as an effective way to fabricating large-size block structure parts.

The Gas Metal Arc Welding (GMAW) process typically uses Cold Metal Transfer (CMT) or Surface Tension Transfer (STT) to ensure dimensional accuracy[6]. Due to the urgent industrial requirement for high deposition rate, the existing single-wire process cannot satisfy the practical demands. Therefore, the twin-wire GMAW process

is widely proposed to increase the deposition rate by 28.3% to 80%, compared with the traditional WAAM[7]. Furthermore, a tandem GMAW process which contains two distinct power sources has been developed to achieve better control flexibility than the twin-wire GMAW[8]. Scalet Rossini et al. [9]proposed that these two electrical arcs make the tandem GMAW process possible to double the deposition rate of WAAM. Although both multi-wire GMAW methods dramatically increase the deposition rate, the accuracy of the workpiece is sacrificed. This is because the molten pool geometry is difficult to control with a high heat input[10]. The higher dimensional error accumulates layer by layer, which leads to an unflatten surface and the varying stick out induces an unstable welding process.

A precise dimension of components can save a lot of machining costs[11]. Effective monitoring and robust control methods are necessary for fabricating accurate components. For instance, Wang et al. [12]developed an online height measurement model based on arc length, which is considered as the feedback signal in a closed-loop height control system. This system is determined to ensure a uniform layer height even in a complex workpiece. The drawback is the unacceptable cost on the control unit for efficient production. Besides, Zhang et al. [13]established a hybrid technology combining WAAM with milling, concluding that the height accuracy is improved from ± 0.5 mm to ± 0.01 mm. However, the efficiency of the deposition process decreases with the extra milling procedure.

The improvement of manufacturing efficiency while maintaining the product quality is a challenge for extensive industrial use of GMAW-based additive manufacturing. One common way to balance the manufacturing efficiency and geometrical accuracy is to introduce an active cooling strategy between layers. Hackenhaar et al. [14]applied an air jet impingement to ensure a consistent interlayer temperature. The active cooling

helps to reduce the system downtime to improve manufacturing efficiency. It does not address the improvement of molten pool stability with high heat input. Zhao et al. [15] proposed a process planning strategy based on thermal behaviour for the workpiece, which aims to predict welding parameters for sequence layers to ensure a uniform layer geometry. They found that varying process parameters can help mitigate heat accumulation and then improve the manufacturing efficiency for fabricating parts with thin-walled structure. It is still necessary to further investigate if the proposed method can be applied to the fabrication of parts with more complicated geometries.

This paper aims to develop a novel WAAM strategy for improving production efficiency and quality simultaneously. In Section 2, the challenges are investigated and described in detail. Section 3 presents the concept and methodology of the proposed strategy. Section 4 provided the experiment details and followed by the result and discussion in Section 5. Finally, Section 6 concludes the research and states future works.

1.2 Aims and objectives

This thesis presents a novel heat input control strategy to achieve a continuous welding process and high product quality at the same time using robotic WAAM process. The objectives of the thesis are listed as follows:

- Preliminary study on the fabrication of solid structure component
 - (a) Compared with the thin-wall structure, the solid structure contains multi-beads in a layer. The existing strategies for thin-wall structure cannot directly be applied to the solid structure.

(b) The heat accumulation has more influence on the geometry shape of the substantial component. Without the head input control, it is difficult to achieve a defects-free component.

- Programming of the heat input control strategy

(a) Bead modelling to obtain the geometry shape of beads such as width and height under different welding parameters and to establish a mathematic model to predict other beads' geometries.

(b) Propose an overlapping strategy to calculate the overlapping distance to form a flat surface.

(c) Applying slicing algorithm to get each sliced layer's profile.

(d) Setup path to plan the movement of the robot.

(e) Validation experiment.

- Further the development of the heat input control strategy

(a) Adaption for other material such as aluminium, mild steel.

(b) The mechanical properties will be further investigated.

1.3 Chapter summary

The summary of the remaining chapter's is given below:

Chapter one provides a brief overview of the wire arc additive manufacturing process.

The introduction provides a review of recent research work and analyses the gap from these research works. According to the gap found in the literature, the aim and objects are proposed. After that, the problem statement is used to show the current problem.

Chapter two provides a literature review of the current wire arc additive manufacturing.

The review contains the AM technology, welding process, metal transfer mode, bead modelling, overlapping model, slicing and path planning.

Chapter three is the research methodology of the thesis. The methodology proposes a heat input control strategy to maintain the welding efficiency and geometric accuracy for the deposited component at the same time.

Chapter four illustrates the experiment setup, including the hardware and software setup.

Chapter five presents a discussion.

Chapter six provides a conclusion and future work.

Chapter 2 Literature review

2.1 Additive manufacturing

The significant features of AM technology are usually proposed in the context of comparison with all kinds of traditional manufacturing processes, which is shown in Fig. 1. The ASTM F42 committee ultimately chose the term "additive manufacturing" because it clearly distinguishes subtractive manufacturing techniques, for example, cutting and milling to remove material from the workpiece[16]. The advantages of AM technology can be discussed from different aspects:

Flexible design technique: The outstanding feature of the AM process is that it applies the layer by layer manufacturing method, which can create almost any complex geometry[17]. The layer by layer deposition strategy is in contrast to subtraction due to its limitation in design flexibility such as the need for fixtures, different tooling, possible collisions in the manufacture of complex geometry, and the difficulty of tool access to more profound and invisible areas [24]. Considering other conventional manufacturing processes, including forming technologies, for example, casting and forging. In casting and forging, there are other additional design constraints inherited by conventional techniques used to manufacture the required tools and dies. AM technology only imposes some restrictions, so that designers can selectively place (a variety of) materials precisely where they need to be in order to achieve the function of the design[18]. Therefore, AM technology is coupled with digital production lines, enables topology optimised structures or, on the other hand, mesoscopic cell structures to reduce material use and quality.

The cost of geometric complexity: Nowadays, the AM technology provides researches with a high degree of freedom to design and build complex geometry components.

When applying other fabrication methods to manufacturing components, such as forging, this complexity design occurs in the shape model, which requires an additional cost. On the other hand, there is no additional cost in the AM, due to the AM technology is free of additional tools, repositioning and manufacturing time[19].

Dimensional accuracy: Compared with the original digital model, the dimensional accuracy determines the derivation of the finished product model. In the conventional production lines, the dimensional tolerances and machining allowance, which are based on ISO and US standards are necessary conditions for quality assurance[20]. Most of the AM machines are used to make parts a few centimetres or larger in diameter and have more tolerance capabilities. In the early AM development, which was widely used for prototyping, the difference between precision and resolution was not significant.

Assembly is required: The AM technology can be applied to fabricate "single component assembly" products with the integrated mechanism. Parts and joints are deposited in place and suspended by supporting material, which must be removed during post-treatment (which may cause some geometric errors).

Time and cost efficiency of production operation: Several traditional manufacturing processes, for example, the injection moulding is time-consuming and expensive for large-scale production, as well as the expensive setup. Although the AM technology is not much efficient than injection moulding for manufacturing components, they are more suitable for the small number of parts because there is no need for start-up tools in the production process[21]. Also, on-demand production and on-site production can reduce inventory costs and may reduce supply chain and delivery-related costs.

Very little material is wasted in manufacturing components through AM: Although the support structure and power recovery in powder bed fusion technology can produce some material waste. The combination of improved design and reduced

supply chain and delivery management costs can prove to be an economic AM technology in various applications.

Fig. 1 The application of the additive manufacturing[20, 22]

Fig. 2 shows the timeline for significant development and final products of four different sets of AM solutions: industrial, amateur, supporting community, and 3D design or modelling software[20, 23]. The timelines of these four sets are similar, which is from the printing capabilities of open source and various materials to various applications, such as art piece, electronic devices, engineering prototypes and customization. Most of them go through various acquisitions and cooperation with other organizations. In the third column, the global business communities and markets are listed which they aim to support 3D printing, including shapewear.

The existing computing support tools can be divided into two categories: the application of computer-aided design (CAD) software to create virtual models, and the application of 3D scanners to capture physical objects[20, 24]. The first step is to generate a

geometric modelling method that uses manufacturing parameters, geometry dimensions, parts' features and relationships to capture the expected geometric features of 3D object design. The organizations have gained the highest market share, including the Autodesk 3D scanning method, which was initially expensive and only suitable for industrial applications. Now the economical methods include the following two points:

- (1) Using RGB Camera and a depth sensor
- (2) Using an image-based mesh generator[25].

Fig. 2 The timelines for the development of the AM[20]

2.2 Classification of additive manufacturing

In 2003s, kruth[26] classified the additive manufacturing processes based on three aspects: liquid-based, powder-based (powder) and solid-based (metal) systems based on different material. German production process two standards DIN8580 and DIN8581to proposed the classification of AM processes, including research and

business methods[20]. Williams[27] also proposed the function classification mode of the AM system. Recently, the ASTM international divides am technology into seven categories, which are listed as follows:

- (1) Material extrusion
- (2) Powder bed melting
- (3) Reductive photopolymerization
- (4) Material spray
- (5) Adhesive spray
- (6) Sheet lamination
- (7) Directional energy deposition.

All of these technologies are presented through an overview of the technical development and research review of commercial AM systems over the past 20 years, which is shown in Fig. 3. In this thesis, it is mainly focused on metal additive manufacturing, which will be reviewed in the next section.

CATEGORIES	TECHNOLOGIES	PRINTED “INK”	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	<ul style="list-style-type: none">• Inexpensive extrusion machine• Multi-material printing• Limited part resolution• Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	<ul style="list-style-type: none">• High Accuracy and Details• Fully dense parts• High specific strength & stiffness• Powder handling & recycling• Support and anchor structure• Fully dense parts• High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder	Electron Beam	
	Electron Beam Melting (EBM)			
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	<ul style="list-style-type: none">• High building speed• Good part resolution• Overcuring, scanned line shape• High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	<ul style="list-style-type: none">• Multi-material printing• High surface finish• Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	<ul style="list-style-type: none">• Full-color objects printing• Require infiltration during post-processing• Wide material selection• High porosites on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	<ul style="list-style-type: none">• High surface finish• Low material, machine, process cost• Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	<ul style="list-style-type: none">• Repair of damaged / worn parts• Functionally graded material printing• Require post-processing machine

Fig. 3 The classification of the additive manufacturing[20]

Fig. 4 shows the different types of AM system based on different types of power source and feedstock. The feedstock can either be the powder or wires[28]. The instructions of the types of the AM system are summarized as follows:

(1) Fig.4 (a) is the schematic view of a typical Directed Energy Deposition-Laser (DED-L) system. The advantages of the DED-L are that there is almost no restrict of the shape of the component.

(2) Fig.4(b) shows the Directed Energy Deposition – Electron Beam (DED-EB) system. The DED-EB system uses an electron beam as a heat source and wire as feedstock to deposit material layer-by-layer. (3) Fig. 4(c) is the Wire Arc Additive Manufacturing (WAAM), which is commonly used in metal additive manufacturing due to its high deposition rate[29].

(4) Fig. 4 (d) is the Powder Bed Fusion – Laser (PBF-L) system. Similar to other method, it starts with a designed CAD model, orienting it in the build volume to include supporting structures, slicing into several layers, configuring scan paths, and construction files based on a pre-specified set of material parameters and machine configurations.

Fig. 4 Four types of Additive Manufacturing. (a) Directed Energy Deposition-Laser (DED-L) (b) Directed Energy Deposition – Electron Beam (DED-EB) (c) Wire Arc Additive Manufacturing (WAAM) (d) Powder Bed Fusion – Laser (PBF-L)[28]

2.3 Metal additive manufacturing

Additive manufacturing is developed from rapid prototyping. Rapid prototyping manufacturing was developed for more than three decades. It is mainly used for the fabrication of complex structural components. The relatively new field of metal AM can fabricate components with complex structures and shapes that are difficult to manufacture. Complex parts are challenging to be manufactured by traditional methods as direct substitutes for traditional manufacturing parts. The metal AM is now widely used in shipbuilding industries, aerospace industries etc. However, there are different aspects between the conventional manufacturing process and the AM process, such as mechanical anisotropy, residual stresses, and defects specific to the AM process. The problem related to the AM process must be addressed in critical aerospace applications, especially those that require exposure to high-temperature fatigue[30]. Applications such as fuel injectors and other highly complex components are now being certified. On the other hand, some high-performance components, such as turbine blades, are in the early stages of development. The alloy used in the AM originates from metal powder technology, high energy beam welding, cladding and prototype manufacturing. The existing research methodology in the traditional AM process is helpful, but it cannot be adapted into metal additive manufacturing directly.

Table 1 Classification of metal additive manufacturing[28]

Process	DED			PBF
Feedstock	Powder		Wire	Powder
Heat source	Laser	E-beam	Electric arc	Laser E-beam
Nomenclature	DED-L	DED-EB	DED-PA/DED-GMA	PBF-L PBF-EB
Power (W)	100-3000	500-2000	1000-3000	50-1000
Speed (mm/s)	5-20	1-10	5-15	10-1000
Max. feed rate (g/s)	0.1-1.0	0.1-2.0	0.2-2.8	-
Production time	High	Medium	Low	High
Dimensional accuracy (mm)	0.5-1.0	1.0-1.5	Intricate features are not possible	0.04-0.2
Surface roughness (lm)	4-10	8-15	Needs machining	7-20
ref	[31-34]	[35-37]	[38-40]	[41, 42]

2.3.1 Powder Bed Systems

Powder bed fusion technology uses an energy beam, for example, laser or electron beam to melt the powder bed selectively. After scanning one layer, the next layer of powder diffuses through the rolling mechanism. Scan the next layer and fuse with the previous layer. The polymer powder bed melting process was initially developed by Bartels[43] and is usually used to process polyamide and polymer composites. The process can also be used for indirect manufacturing of fused polymer mixtures of ceramic and metal. The powder bed cladding technologies can be regarded as Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM) and Selective Laser Melting (SLM)[28]. Fig. 5 is a schematic diagram of a typical EBM system which requires a vacuum. The energy can be either e-beam or laser beam to melt bed or sinter the powder into the desired shape.

Fig. 5 Overview of the powder bed system[28]

2.3.2 Powder feed system

The general diagram of AM powder feeding system is shown in Fig. 6. The construction volume of these systems is usually large (e.g. $> 1.2 \text{ m}^3$ for the optomec lens 850-r unit[30]). Besides, compared with the powder bed device, the powder feeding system is more natural to expand the volume. In these systems, the powder is transported to the building surface through nozzles. Lasers are used to melt single or multiple layers of powder into desired shapes. Repeat this process to create a substantial 3D component. There are two main types of systems on the market. The workpiece remains stable, and the deposition head moves. Conversely, the deposition head remains unchanged, and the workpiece moves. The advantages of this system are that it includes larger construction volume and the ability to repair damaged parts rather than building a new one.

Fig. 6 Overview of the powder feed system[28]

2.3.3 Wire feed system

The schematic diagram of the CMT based wire feeding unit is shown in Fig. 7. The feedstock is the metal wire, and the energy sources can be regarded as electron beams, laser beams and plasma arcs. Beads are deposited and constructed layer by layer to form a three-dimensional structure. Generally speaking, the wire feed system is very suitable for high deposition rate processing and has a sizeable forming volume; however, processing products usually require more extensive processing instead of a powder bed or powder supply system. The wire feed system is always combined with the industrial robots or the CNC machine. With the help of industrial robots, the deposition process is more efficient and stable. On the other hand, industrial robots are commonly six degrees of freedom, which is suitable to move the welding torch in any position. The main advantages of the movement flexibility are that the wire feed system can fabricate any shape component, extraordinarily complex structural components such as a polygon.

Fig. 7 Schematic view of the CMT based wire feed system[44]

2.4 Metal transfer in GMAW

The way of material to transfer from the wire tip to the molten is regarded as the metal transfer. Generally, there are three kinds of metal transfer, regarded as short circuit transfer, globular transfer and spray transfer. The globular transfer and spray transfer can be summarised as the free-flight transfer. In this section, two welding process, Cold Metal Transfer(CMT) mode, which is one of the short circuit transfer and Pulse mode, which is one of the spray transfer are reviewed.

2.4.1 Cold Metal Transfer (CMT)

CMT is firstly developed by Fronius company which is aim to achieve a lower heat input and less spatters. The CMT welding electrical cycle is shown in Fig. 8. Three phases need to be further discussed, (i) The peak current phase, (ii) The background phase and (iii) The short-circuiting phase.

First of all, in the peak current phase, the current is reached at a high level to ignite the arc so that the wire tip is burned and heats the base metal to form the molten pool. Secondly, in the background phase, the current decreases to a low level. A liquid droplet is formed at the wire tip, to inhibit the globular transfer, the current needs to decrease. The low current keeps constant until the third phase. At the same time, the wire feed system continuous feeding the wire. When the wire tip contacts the base metal, the third phase, the short-circuiting phase occurs. During the short-circuiting phase, the droplet attaches the base metal to form short-circuiting so that the current becomes zero at this phase. In the meantime, there is an additional force, back-drawing force to pull back the wire. With the help of the back-drawing force, the droplet is urged to transfer to the molten pool. In the end, the arc ignition again to perform another cycle.

Fig. 8 The current and voltage waveform of the single cycle of the CMT process[45]

Fig. 9 The metal transfer process in the CMT process[45] shows the short circuit transfer in a single waveform with the help of a high-speed camera. The first three pictures are the arc peak time and the metal droplet forms at the end of the tip. After that, the current remains at a low level during the background time. When the wire tip contacts the substrate, as shown in the picture(12) to picture(15), the short-circuit happens. With the help of drawback force, the metal transfers into the molten pool and the arc ignites again.

Fig. 9 The metal transfer process in the CMT process[45]

2.4.2 Pulsed GMAW

Generally, the pulsed GMAW is regarded as a spray transfer. In the spray transfer, the arc is always ignited when the welding starts. Commonly, the current applied in the spray transfer is much higher, over 250A as a higher current applied on the wire tip, droplets forms at the end of the wire tip. Then, transferring into the molten pool as a droplet, as shown in Fig. 10. In the pulsed GMAW, additional current is added to push the droplets into the molten pool. Compared with the normal GMAW process, which the current can be presented as a straight line, the pulsed GMAW lower the current when the extra power is not used. Because of this, the pulsed GMAW can achieve a lower heat input than the conventional GMAW.

Fig. 10 The droplet transfer[46]

The general waveform of a single cycle of the pulsed GMAW is shown in Fig. 11. I_p is the pulsed current, I_b is the background current, T_p is the duration of pulsed current and T_b is the duration of the background current.

(i) Pulsed current: The pulsed current is the peak current in one cycle of the pulsed GMAW process. It is applied to ignite arc and keep the arc. In this current, the spray transfer can be achieved.

(ii) Background current: In this phase, the current drop down to maintain the arc. It is not enough for the metal to transfer.

(iii) Duration of pulsed current: It is defined as the time between the arc on and arcs off.

(iv) Duration of the background current: It is defined as the time for background current to maintain the arc.

Fig. 11 The pulse GMAW process[47]

2.4.3 CMT-P

The CMT-P process is developed by the Fronius company, which is an innovation from the CMT mode. The CMT-P process contains several CMT welding cycles in the tradition Pulse welding cycles. The traditional CMT process provides a lower heat input during welding, which guarantees the stability of welding. The Pulse cycles provide a higher heat input, which is suitable for welding the thicker structures. A typical waveform of one CMT-P cycle is shown in Fig. 12[48].

Fig. 12 The waveform of one CMT-P cycle[48]

The CMT-P cycle can be described as follows:

- (1) During the Pulse peak time, the current and voltage remain at a high level which forms small molten droplets.
- (2) In the Pulse base time, the current and voltage decrease. The droplets transfer into the molten pool by the sustained heat input.

The CMT cycle has been fully described in Section 2.4.1.

2.5 Bead modelling

Bead modelling is a significant process during WAAM. The more accurate model, the more precise prediction of WAAM process[49]. Bead modelling means that using a mathematic model to describe the formation of welding bead under different welding parameters, such as welding current, welding voltage, travel speed, wire feed speed[50]. For continuous welding, research has focused on the cross-section profile of the bead, which means the width, height and penetration of the bead, as shown in Fig.13. Various mathematic models such as sin function, parabola function, arc model are used to predict the bead profile[51].

Fig.13 Geometry shape of a single bead[52]

In the literature, there are three kinds of mathematic model to describe the shape of the bead, which is listed in the following table.

Table 2 Three different bead models[49]

Models	Model function	Bead width(mm)	Bead height(mm)	Bead area(mm ²)
Parabola model	$y = ax^2 + c$	$2\sqrt{\frac{-c}{a}}$	c	$\frac{4c}{3}\sqrt{\frac{-c}{a}}$
Cosine model	$y = a \cos(bx)$	$\frac{\pi}{b}$	a	$\frac{2a}{b}$
Arc model	$y = b + \sqrt{a^2 - x^2}$	$2\sqrt{a^2 - b^2}$	a-b	$arcos\left(-\frac{b}{a}\right) - b\sqrt{a^2 - b^2}$

On the other hand, Suryakumar et al. [16] proposed to make a mathematic model which combines the torch speed, wire diameter and wire feed speed, which is shown in Fig. 14.

Fig. 14 The cross-section profile of the bead[16]

Moreover, the experiment based model setup is very time consuming and difficult. In order to tackle this problem, many types of research trying to use Artificial Intelligence to predict the bead shape, for example, Artificial Neural Network (ANN)[49], Support Vector Machine (SVM)[35]. The typical used model is regarded as ANN, which is shown in Fig. 15[53]. Through the ANN, the bead shape of other welding parameters can be predicted.

Fig. 15 ANN for the bead modelling[53]

2.5.1 Multi bead overlapping model

After obtaining an accurate bead model, the next step is to determine a flat surface strategy. Otherwise, the uneven surface will accumulate error and lead to the low geometry accuracy of the final product[54]. One of the standard ways to achieve the flat surface is to use the overlapping model, as shown in Fig. 16[54] which means that two adjacent beads may overlap a part of each other so that the valley can be fulfilled. The model aims to find a sufficient step over distance to achieve a flat surface, as shown in Fig. 16 (c). The other choices will make the surface either higher or lower, as shown in Fig. 16 (b) and Fig. 16 (d). Literature shows that the optimised step over distance is $d = 0.667w$, where w is the width of a single bead[54]. Furthermore, Li et al. [35] proposed an enhanced overlapping model to tackle the material shortage at the boundary bead. According to this research, the overlapping model is well determined. All the experiment results show that a flat surface is achieved.

Fig. 16 The schematic view of the overlapping model (a) no overlapping (b), not enough overlapping (c) optimised overlapping (d) too much overlapping.[6]

Ding et al.[54] firstly introduced the overlapping tangent model, which is shown in Fig. 17. The difference between the traditional overlapping model is that the overlapping tangent model has a ‘critical valley’ area, which has a better approximation than the overlapping area. The experiment results show that the TOM has better surface finishing.

Fig. 17 The TOM overlapping model[54]

Furthermore, Li et al. [35] improved the TOM model and developed the enhanced bead modelling method. They found that the existing overlapping model has bad surface finishing at the boundary layer because of the material shortage. Based on the

calculation, the enhanced bead modelling successfully solved that problem. The schematic view of the enhanced bead modelling is shown in Fig. 18.

Fig. 18 The enhanced bead modelling[35]

2.5.2 Summary of bead modelling

When fabricating significant block structure components, the bead modelling and overlapping model can provide a precise prediction. After getting the bead modelling data, the area of the cross-section profile can be calculated. This information is used in the manufacturing process.

2.6 Slicing

After the bead model has been established, the WAAM technology requires more information about each layer. In order to get each layer's information, the slicing method is first introduced. The typical slicing process is shown in Fig.19, which is based on the STL file(Slice file format: stereolithography)[55]. The slicing mainly includes the following steps:

- (1) Load the model and pre-process the model.
- (2) Slice to obtain the boundary.
- (3) Divide the slice into various components.

Fig.19 (a) The STL file (b) The slicing result[56]

2.6.1 Overview of the slicing methods of computer-aided design models

Usually, CAD models are created based on direct modelling and using software, such as AUTOCAD[57]. As described by Mohan Pandey et al.[11], CAD models have many direct slicing methods, such as adaptive slicing of solid models based on the area deviation method with proper slicing procedures and surface quality. Directly slicing CAD models has a smaller file size than another slicing method such as multi-directional slicing. The directly slicing method improves geometric accuracy, reduced post-processing time, and eliminating the need to repair software. Multi-directional slicing methods are developed to achieve free-form manufacturing, such as using non-uniform rational B-spline (NURBS) surfaces, Bézier surfaces or T-spline surfaces[58]. Besides, the adaptive slicing technique, combined with the original model, has also been studied to avoid approximation errors and improve slicing efficiency[59, 60]. The following flowchart shows a typical slicing process, as shown in Fig. 20.

Fig. 20 A typical slicing process [61]

2.6.2 Unidirectional and multi-directional slices

For parts with simple structures and geometric shapes, the bottom-up slicing method can be used for continuous manufacturing in one direction[62]. The uni-directional slicing method is widely used in commercial AM equipment due to its robustness and simplicity. As shown in Fig. 21, a set of parallel plane shapes are obtained through the surface-plane intersection algorithm. For parts with complex structures and geometric

shapes, a method of selecting the best direction through adaptive slicing to minimise the volume deviation is studied.

Fig. 21 Effects of different slicing layers (a) thick layer (b) thin layer (c) variable layer[63]

However, choosing the best direction does not cover all parts. If there are overhangs and support structures, it is not always reasonable to slice in one direction. Because the manufacturing and disassembly of the support structure consume more construction time, it is impossible to eliminate the step error and the anisotropy caused by layered manufacturing. To manufacture metal parts with the required performance, Ding et al. proposed uni-directional and multi-directional slicing methods[64]. As shown in Fig. 22[65], multi-directional slicing reduces the use of supports. It avoids collisions between the printed part and the nozzle tip during the printing process, but the major drawback is the higher cost of complex algorithms.

Fig. 22 Schematic views of multi-directional slicing (a) target component (b) with support structure (c)

multi-directional slicing [11]

At the same time, a large number of complex structures are required in the industries such as the aerospace industry, shipbuilding industry. Compared to traditional slicing, multi-directional slicing is a breakthrough because it reduces staircase errors and reduces support.

2.6.3 Contour edge slicing

On the other hand, contour edge projection is also a multi-directional slicing method for identifying non-buildable surface features of a model along a user-defined build direction. Then, by using the Gaussian and Visibility Map to repeat the appropriate construction direction determination, the part is decomposed into a buildable volume. However, for complex parts with internal cavities, the implementation is complicated and computationally expensive.

2.6.4 Transition wall slicing

The transition wall[66] is proposed as another multi-directional slicing method applied to overhanging layers. It is identified by calculating the difference between adjacent layers to minimise support and improve the efficiency and surface quality of the moulded parts. Fig. 23 shows a schematic diagram of a transition wall constructed by rotating 90 degrees. However, the major drawback is that this method is straightforward for a subset of part geometry, which limits its application.

Fig. 23 (a) overhang structure (b) vertical deposition (c) horizontal deposition[67]

2.6.5 Centroid axis extraction

The central axis, also known as bone, has long been used to study biological morphology[68]. The central axis represents a three-dimensional shape of a series of curves/points, such as a human skeleton. This concept has been widely used in pattern recognition, shape analysis and mesh generation. Various methods have been studied to find the three-dimensional axis. Fig. 24 shows an example of the central axis, which provides a simple tool to understand the geometry of complex shapes.

Fig. 24 An example of the centroid axis extraction[69]

Fig. 25 shows the flowchart of the typical centroid axis extraction slicing method. Based on centroid axis extraction, a complete multi-axis algorithm is developed[69]. The position and direction of slices were determined by trial and error method to meet the requirement of volume difference. The final result is a slice sequence, defined as a slice contour queue. Given part A, the maximum layer thickness ΔL_{max} , the minimum layer thickness ΔL_{min} , and the allowable volume difference V . The advantage of the central axis are that it provides global and local topological information of 3D shape with simple structure. Since the centre axis provides sufficient information (topological and geometric information), it can be used in process planning in order to find the best

results. However, finding the centre axis is a costly calculation. In order to realize the intelligent multi-axis slicing method, a more effective geometric information extraction method is urgently needed.

Fig. 25 The flowchart of the centroid axis extraction slicing method[69]

2.7 Path planning method

Path planning is another critical step in additive manufacturing. It affects the surface roughness, dimensional accuracy, and part strength of printed parts. The path can be separated as either the outer layer, the inner layer or the filling path and the supporting path. This section focuses on the generation of filling paths to fill the area without interruption during printing. The choice of fill pattern depends on the slicing method, 2D or 3D, and design and manufacturing requirements. In the following sections, various methods are discussed. The available path planning in AM is mainly focused on 2D and less on 3D.

As reported in the literature, Ding reviewed the 2D filling strategy and compared the advantages and disadvantages of each other, especially in terms of filling efficiency and printing speed[70]. According to the filling mode and research results in typical slicing software, as shown in Fig. 26, typical 2D filling modes mainly include raster, zigzag, contour, concentric, spiral, mixed, mesh, triangle, star, cubic, and adaptive MAT path[71]. Due to simplicity and robustness, The most commonly used fill patterns in AM are contours and rasters. All available 2D fill patterns have been divided into four main groups: grid path patterns, continuous path patterns, mixed paths and continuous path patterns, and path planning and geometric shapes.

Fig. 26 Path planning pattern: (a) Raster path[72], (b) Zigzag path[73], (c) multi-direction raster[74], (d) Grid[75], (e) Contour path[75], (f) Spiral path[76], and (g) Hybrid path (a combination of Contour and Zigzag)[70]

Unlike the single path mode, Chao[77] proposed a new continuous filling algorithm based on the raster method to fill the Hilbert curve (Peano), as shown in Fig. 27. The hybrid path planning method leads to improving surface quality, less arc start and stop time. It can also reduce residual thermal stress of the part and reduce warpage of the part[78]. However, a large number of path turning movements means more construction time. As shown in Fig. 27 (b)[79], a construction style like a fractal can generate a fill pattern, allowing continuous placement of a single beat to fill an area of arbitrary shape. For larger areas, this method is time-consuming. It may cause heat to accumulate in certain areas for highly convoluted paths, resulting in excessive deformation of the part. It is not recommended to change the direction of tool path travel frequently in AM[80]. At the same time, sharp corners will bring a lot of bottom fill area and top fill area.

Fig. 27 Hybrid path planning methods (a) Hilbert curve[77] (b) Fractal-like build style [80] (c) Hybrid path (zigzag and contour)[76] (d) Hybrid path (zigzag, raster, contour)[81]

On the other hand, in order to tackle the problem of the void, the existing path planning is not feasible, so that many kinds of literature have developed novel path planning methods. Michel et al. [81] developed a modular path planning method, which aims to separate the part into several blocks. To each block, the segmentation and zoning strategy is applied to generate the path, which is shown in Fig. 28. The idea is from the design of a CAD model. If a complex 3D drawing is designed, it is necessary to split the part into several sections, which is aim to simplify a difficult problem into several easy problems. In the future, with the development of the AM technology, a lot of complex shapes need to be designed and deposited, such as turbine blades. The complex parts contain different structure in different layers so that it's impractical if using the same path planning method for all layers.

Fig. 28 The description of the modular path planning[81]

Nguyen et al.[82] developed the continuous eulerian tool path planning method to solve the problem of the void. The central concept of that path planning is to go a little further at the connection so that the overlapping area is enough to prevent the formation of voids. The strategy is shown in Fig. 29. Another essential contribution is that this path planning method is a continuous tool path. The aim is to prevent the multiple arc start and arc off times so that the unstable arc makes the deposition more difficult.

Fig. 29 (a) Traditional path planning method (b) Continuous eulerian path planning method[82]

Chapter 3 Problem statement and research methodology

3.1 Problem statement

A suitable deposition process is depended on the welding parameters. Defects such as voids and collapse will happen during the WAAM process because of the unstable welding process. In this section, voids and collapse defects are introduced.

3.1.1 Side collapse caused by excessive heat input

Collapse is a common defect which occurs at the boundary layer of a part, which is shown in Fig. 30 [83]. The reason this defect happens is that the heat accumulates too much during the deposition. There is no cooling strategy so that significant heat accumulation resulting in the collapse. The collapse makes the formation of the curved top surface. Moreover, the curved surface will accumulate through the deposition, so that the geometry accuracy of the parts cannot be guaranteed. Also, the large heat accumulation causes significant distortion of the substrate, which is shown in Fig. 31[29].

Fig. 30 The collapse phenomenon during the WAAM process[83]

Fig. 31 Distortion of the substrate[29]

The experiment is carried out to present the collapse phenomenon by applying the spray mode for the deposition. A total of five layers are deposited. As shown in Fig.33 (a), each layer's path contains two contours and a straight line, which corresponds to five beads. Beads are deposited from outside to inside. From the cross-section profiles which are shown in Fig.33 (b) and (c), there are no macro voids inside the part. However, the collapse phenomenon can be observed from Fig.33 (b). The vertical dash lines indicate the target layer height and the horizontal dash lines indicate the path offset distance. It can be seen that the layer height varies from the higher centroid to lower sides. Due to the deposited material remains the same, the layer width increases in consequence of the decrease of the layer height. The uneven surface makes the next layer deposition impractical. In addition, voids are formed at the corner due to the collapse, as shown in Fig. 33. The results demonstrate that it is difficult to fabricate a high geometric accuracy of NAB component with the spray mode.

Fig. 32 Overall view of the deposited shape by Pulse process (a) Layer 1 (b) Layer 2

Fig. 33 an overall view of the deposited part (a) Layer 1 and (b) Layer 5

3.1.2 Voids caused by insufficient heat input

Voids are generated because of the insufficient heat input between two beads, which is shown in Fig. 34[84]. When beads are overlapped together to form a flat surface, the insufficient heat input is not able to melt the deposited bead on the side. As a result,

there is a gap formed between the beads. The main reason for the generation of voids is because of unsuitable path planning and incorrect selection of the welding parameters.

Fig. 34 Voids generated inside the component[84]

Currently, WAAM technology is used to produce parts with different geometric features, including solid structure, thin-walled structure, and newly developed wire structure. For fabricating solid structure, weld bead is deposited side by side, which may lead to the formation of voids inside the parts. Researchers attempted to suppress the void inside part by increasing fusion with high system heat input. Due to the excessive heat input, the molten pool geometry of weld bead at the boundary is difficult to control. Thus, the geometrical quality is significantly affected due to the collapse of the layer outline. On the other hand, reducing the heat input is helpful to control the weld bead geometries as the high surface tension force weakens the fluidity of the molten pool at a relatively low temperature. However, the lack of fusion may lead to voids generation inside the parts again. Practically, it is difficult to balance the heat input for fabricating parts with good geometrical quality.

Generally, the CMT mode is regarded as a variant of dip transfer[85]. In the dip transfer, the droplet forms on the wire tip during the peak current phase. Then, the metal transfers when the wire tip contacts the molten pool and the voltage changes

into zero. The mean current remains at a low level. Due to the back-drawing force, the droplet transfers accurately on the target position with less heat input. For this reason, the CMT mode provides an accurate geometric shape and a low heat input[86]. The experiment is performed by applying the CMT mode, as shown in Fig. 35(a), the deposition path remains the same as mentioned above. The deposited part achieves a good surface finish. From the cross-section profile, as shown in Fig. 35(b), the layer height of the deposit is stable. However, voids are generated due to insufficient heat input. Moreover, voids decrease the mechanical strength, owing to the tensile stress concentration at the void area and then leading to the material fracture.

Fig. 35(a) An overall view of the deposited part by CMT process, (b) and (c) The cross-section profile

To conclude, the pulse process with higher heat input can provide a defects-free component, and extreme heat input is accompanied by collapse. da Besides, these two defects occur at different positions so that it is impracticable to fabricate defect-free parts with these two process modes identically.

3.1.3 Summary of the problem statement

In response to these problems, this paper presents a hybrid process strategy which combines the advantages of various heat input conditions for fabricating large block structure components. The basic idea is to separate depositing paths and apply different heat inputs at these paths. In contrast to the traditional depositing methods, the proposed technique can achieve a defects-free component as well as increase production efficiency.

The detailed diagram of the hybrid process system was shown in Fig. 36. First of all, the deposition paths were separated into a boundary path and multiple inner paths. Then, the boundary path is deposited twice with lower heat input such as CMT process to form a higher boundary layer. The CMT process provided narrow and tall beads such that the overall frame was produced, and the geometry accuracy was guaranteed. Finally, filling the inner paths continuously with higher heat input such as Pulse process to ensure the welding efficiency and void-free. Because the boundary layer was higher than the inner layer, the filling material will not overflow so that the collapse defect can be prevented. At the same time, the number of required beads decreases due to the geometry shape of beads become 'wide and short'. Compared to the conventional WAAM using the same geometry shape of beads, the hybrid process improves the welding efficiency. Next, we will detail the whole WAAM processes.

Fig. 36 Schematic view of the MHI process strategy

Fig. 37 is the flowchart of the WAAM system with the close-loop slicing method. Firstly, the CAD model was imported to the slicing programme. Based on the bead modelling, the initial slicing height was set to h . Second, the MHI process was employed to deposit the sliced layer. After deposition, the height measurement was carried out by a laser scanner. Finally, the next slicing height was corrected by h' , and the process parameters were selected to compensate for the height deviation. The conventional slicing programme adopted a fixed layer height. However, the layer height deviation can reach several millimetres, and the deposited shape was not accurately matched with the CAD model. It was demonstrated that the conventional slicing method was only used in simple geometry parts[7]. Therefore, under the feedback control, the close-loop slicing method maintained the real height consistent with the target height

to improve the deposition accuracy. Moreover, the variant layer height was flexible to fabricate incline workpieces.

Fig. 37 The flowchart of the close-loop WAAM process

3.2 Modelling of the thin-wall structure

The primary object of the boundary layer is to ensure that the boundary path was always higher than the inner paths so that the filling material will not overflow, as shown in Fig. 36. The boundary layer contains two beads with the same lower heat input was firstly deposited on the substrate. As shown in Table 3, 27 groups of parameters with different process modes are chosen to define the range of lower heat input, where the heat input can be calculated as:

$$\text{Heat Input} = \frac{\text{Welding Current} \times \text{Welding Voltage}}{\text{Travel Speed}} \quad (1)$$

The results show that the lower heat input, responding to 'narrow and tall' bead can be regarded as the range from 150 J/mm to 200 J/mm with CMT process when depositing NAB.

Table 3 Welding parameters and corresponding heat input

Welding process	WFS(mm/min)	Travel Speed(mm/min)	Welding Current(A)	Welding Voltage(V)	Heat Input(J/mm)	Height(mm)	Width(mm)
CMT	3.5	300	93	10.9	202.7	3.2	4.6
CMT	3.5	350	93	10.9	173.9	3.4	3.5
CMT	3.5	400	93	10.9	152	3	3.2
CMT	4	300	108	11.2	241.9	4	5
CMT	4	350	108	11.2	207.5	3	4.4
CMT	4	400	108	11.2	181.4	3.3	4.2
CMT	4	450	108	11.2	161.3	3	3.9
CMT	4.5	300	123	11.4	280.4	4	5.4
CMT	4.5	350	123	11.4	240.5	3.7	4.7
CMT	4.5	400	123	11.4	210.3	3.2	4.4
CMT	4.5	450	123	11.4	186.9	3	4.3
CMT	5	300	137	11.6	317.8	4	5.8
CMT	5	350	137	11.6	272.6	3.5	5.5
CMT	5	400	137	11.6	238.3	3.3	5
CMT	5	450	137	11.6	211.9	3.2	4.4
Pulse	5	300	163	20.2	658.5	3	6.5
Pulse	5	350	163	20.2	564.8	2.9	6.2
Pulse	5	400	163	20.2	493.9	2.8	6
Pulse	5	450	163	20.2	439.1	2.6	5.9
Pulse	6	300	193	21.2	818.3	3.5	8.5
Pulse	6	350	193	21.2	701.8	3.3	7.7

Pulse	6	400	193	21.2	613.7	3.2	7.2
Pulse	6	450	193	21.2	545.5	3	6.8
Pulse	7	300	219	22.4	981.1	3.5	9
Pulse	7	350	219	22.4	841.4	3.1	8.3
Pulse	7	400	219	22.4	735.8	3	7.9
Pulse	7	450	219	22.4	654.1	2.5	7.4

The bead modelling results are shown in Fig. 38 and Fig. 39. With the higher heat input, the bead becomes wider and shorter. Conversely, the lower heat input makes the bead taller and thinner. With insufficient heat input, the bead becomes twist. On the other hand, sufficient heat input makes the bead straight.

Fig. 38 Bead modelling results for the CMT mode

Fig. 39 Bead modelling results for the Spray mode

The relationship between the heat input Q applying the CMT mode and bead's height is shown in Table 3 and Fig. 40. With insufficient heat input, which $Q < 180\text{J}$, a twisted bead is observed. This is because the molten pool is not able to fuse into the substrate. Based on the bead-on-plate experiment, the heat input range applied at the boundary layer should be greater than 180J .

Fig. 40 Relationship between heat input and bead height

3.3 Filling process

In contrast, to deposit the boundary layer, the heat input applied in the filling process was much higher to increase the flow performance of material so that voids can be eliminated. The flowchart of the filling process was shown in Fig. 41. Firstly, due to the complicate welding process, it was difficult to describe the mathematic model for the boundary layer directly. After the build of boundary layers, a laser scanner was used to capture the profile of the boundary layer. The curve fitting results show that a parabola function can represent the boundary layer. Second, the position and welding parameters of the bead next to the boundary layer were specified. Then, the most suitable number of bead amount n was calculated. Finally, beads were deposited symmetrically from outside to inside to fulfil the volume, and the schematic view was shown in Fig. 42. The total width of the component W can be expressed as a function:

$$W(n) = w_1 + 2 * d^* + (n - 1) * w_2 * d \quad (n \in N^*) \quad (2)$$

Where w_1 is the width of the boundary layer, w_2 is the width of a single bead, d^* is the overlapping distance between the $B_{1,2}$ and the boundary layer, d is the critical overlapping distance.

It should be noticed that the total width is depended on both d^* and d because of the difference between the geometries of weld beads in the outer and inner path. The filling process was divided into two steps:

- Step 1: Finding the optimised centre distance d^* and its corresponding Wire Feed Speed (WFS) when beads are deposited next to the boundary layer. As shown in Fig. 43, the boundary layer was higher than the inner layer. The mathematic model for the leftmost wall can be obtained by the scanner, expressed as $g(x)$. The model for deposited bead can be obtained from bead modelling, expressed as $f(x)$. Line AD is tangent to $g(x)$ with the gradient k . If the coordinate of points A, D, E, F can be expressed as $A(x_1, y_1), E(x_1, 0), D\left(\frac{1}{2}w_1 + d^*, h\right), F\left(\frac{1}{2}w_1 + d^*, 0\right)$, where h is the height of a single bead, then S_{AEC} and S_{BDF} can be expressed using the following equation:

$$S_{AEC} = \int_{x_1}^{w_1} g(x) dx \quad (3)$$

$$S_{BDF} = \int_{\frac{1}{2}w_1 + d^* - w_2}^{\frac{1}{2}w_1 + d^*} f(x) dx \quad (4)$$

The aim is to find a set $Q = \{d^*, h\}$ that makes the overlapping area S_{BOC} equal or approximate to the area of the valley S_{AOD} , which can be presented using the following function:

$$S_{BOC} - S_{AOD} = S_{AEFD} - S_{AEC} - S_{BDF} \quad (5)$$

The difference between S_{BOC} and S_{AOD} can be defined as a function $S(d^*, h)$ such that :

$$S(d^*, h) = \frac{1}{2} \left(\frac{1}{2}w_1 + d^* - x_1 \right) (y_1 + h) - S_{AEC} - S_{BDF} \quad (6)$$

From Eqs. (5) there existed a numerical solution that $\forall d^*, \exists h$ such that $S(d^*, h) = 0$ i.e. $S_{BOC} = S_{AOD}$. The range of centre distance d^* and height h can be determined by :

$$\frac{w_1}{2} < d^* < \frac{w_1 + w_2}{2} \text{ and } \frac{1}{2}H_{wall} < h < H_{wall}$$

where: H_{wall} is the height of the boundary layer.

From the bead modelling, each h corresponds to a WFS, annotated as B_{WFS} . Similarly, the bead next to the rightmost wall is deposited at $-d^*$ and with the same WFS as B_{WFS} .

Fig. 43 Schematic view of the overlapping with the boundary layer

• Step 2: According to the bead modelling and overlapping model to predict the number of required beads n . As suggested in the literature, Ding et al. [54] found the overlapping distance among two same beads was $0.667w$, where w is the width of the single bead. Based on the Eqs. (1), the relationship between the bead amount and the total width was shown in Fig. 44. The WFS, 5m/min and 7/min with the constant 400mm/min travel speed were selected to determine the range of total width. It should be noted that the minimum value of the total width depended on both w_1 and the calculation results from step 1, expressed as $W_{min} = w_1 + 2 * d^*$. The shadow area determined the total width with the WFS between 5m/min and 7m/min based on the algorithm implemented in our previous work[49]. The ΔW and Δh presented the width's variation between different WFS and number of beads, respectively. When $\Delta W > \Delta h$ for any bead amount, it should be demonstrated that $\forall W \in \{C | C > W_{min}\}, \exists n \in N^*$, where W is the target width, and C is a constant.

Geometrically, the target width was presented by a horizontal line. The intersections with the shadow area were considered as the solutions of n , named as $P_1 \cdots P_n$. This means that the most suitable n should be selected from the alternatives. In such a way, a flat inner surface can be achieved.

Fig. 44 The relationship between the bead amount and the total width

As an intermediate conclusion, section 3.2 and 3.3 specified the fundamental principles of the hybrid manufacturing strategy. Eqs. (1)-(5) provided a generation process for welding parameters. For a given sliced layer for which W was known and w_1 was obtained from the scanning result. Eqs. (5) was applied to calculate the deposition position and parameters of the first and the last bead in the layer. Then, based on Eqs. (1), the graph of the function $W(n)$ was plotted (e.g. Fig.42). From the plot, the number of bead n in the layer was obtained. After the concerned layer was deposited, the current height was measured by the laser scanner. The next slicing took place at the modified height. In such a way, the deposition of multi-layers can be realised. The feasibility of this strategy will be validated through a case study presented in the next section. Finally, a large real-life component with $565 \times 265 \times 150\text{mm}$ applied at the bridge is fabricated.

Chapter 4 Experiment

4.1 Hardware setup

4.1.1 Industrial Robot

In this experiment, the robot used is the ABB IRB 2600 robot, as shown in Fig. 45. The IRB 2600 robot is a 6-axis robot, which has a six degree of freedom. The advantages of this robot are summarised as follows:

- (i) It has sharp accuracy. With the control of mechanism, the accuracy of the robot can reach up to 0.1mm, which is to demonstrate a suitable robot to do arc welding[87].
- (ii) It has a high working load which is up to 20kg.
- (iii) It has a large working envelope, which is shown in Fig. 46.

Fig. 45 ABB IRB 2600 robot [88]

Fig. 46 The working envelope of the IRB 2600 robot[88]

4.1.2 Welding system

Fronius firstly introduce the welding system for this experiment. It is composed of a CMT advanced 4000 welding machine, a VR 7000 CMT wire feeder and an RCU 5000i remote control, as shown in Fig. 47. The CMT advanced 4000 machine provides a lot of synergic programs such as mild steel, stainless steel, aluminium. When the material, wire diameters and shielding gas are selected, the synergic program will automatically calculate the welding parameters based on the welding power. The welding power in this situation can be regarded as the wire feed rate. In the Fronius CMT welding, the arc length is detected through welding. There is a feedback control inside the welding machine to maintain the arc length by adjusting the welding power. On the other hand, the VR 7000 wire feeder plays a vital role in the welding process. It is used to push and pull back the wire to form a unique welding process, which is mentioned in Section

2.2.1. The control of the welding machine can be either internal or external. In the private mode, the adjustment of welding parameters can be made on the teach pendant. On the other side, when the external mode is chosen, all the welding settings can be set from the RobotStudio.

Fig. 47 CMT advanced 4000 welding machine, VR 7000 wire feeder and RCU 5000i remote control.

The schematic view of the combination of the CMT welding machine with the industrial robot is shown in Fig. 48[89]. The wire buffer is the innovation of the CMT machine, which is used to draw back the wire. With the help of Digital Signal Processor (DSP), the frequency of the draw back process can reach to 70Hz to form a stable droplet transfer.

Fig. 48 The schematic view of the assembling of the CMT machine with a robot[89]

4.1.3 Multi-sensor system

In order to achieve perfect welding, feedback control is necessary. From the multi-sensor system, a lot of raw data such as voltage signal, a current signal, the temperature can be obtained. With the help of the developed algorithm, these raw signals are processed and analysed. In this section, three types of sensors, CCD camera, 2D laser scanner and thermal camera are introduced as follows.

(i) **CCD camera:** A charge-couple device (CCD) contains an array of capacitors which are used to transfer electric charge to a neighbouring [90]. In the experiment, the CCD camera is used to capture the picture after deposition. The type of used CCD camera is MER-502-79U3M, as shown in Fig. 49. It has a resolution of 2448×2048 with a frame rate of 79fps.

Fig. 49 MER-502-79U3M CCD camera[91]

(ii) **Thermal camera:** The thermal camera or also called the infrared camera is a kind of camera using infrared radiation to create pictures[92]. To measure the temperature, two types of measurement are used, contact and non-contact measurement. The contact measurement is regarded as using the thermocouple, which is welded at the base plate or inside the wall. The non-contact measurement applied in this experiment is the thermal camera. The advantages of using the thermal camera are that in the experiment, there is no need to know the in-process temperature. Because of this, the application of thermocouple is more complicate than the thermal camera. Moreover, the thermal camera provides an SDK, so that it is convenient to integrate the temperature measurement into a Labview program to establish a feedback control. However, the drawback is that the settings and calibration of the thermal camera are not easy. In the settings, the material immensity is firstly needed to be set so that the camera can get an accurate temperature. In the meantime, the measurement process is also affected by the reflective. In this experiment, the interlayer temperature is set as a constant, so that accurate measurement is not necessary. Based on the above analysis, the Optrix PI 400i thermal camera is used to obtain the interlayer temperature, which is shown in Fig. 50.

The thermal range is up to 80Hz, and it has very high thermal sensitivity, which is up to 40mK[93].

Fig. 50 The thermal camera

(iii) **Laser scanner:** The laser scanner uses a moveable mirror to steer the laser beam to capture the 2D profile of the parts[94]. In this experiment, the laser scanner used is the ScanControl 2600-100, which is attached at the torch, which is shown in Fig. 51. The measurement speed is up to 300Hz, and the reference resolution is up to 12 μ m[95]. The working envelope of the laser scanner is shown in Fig. 52.

After the welding, the robot will move to another orientation to make laser scanner face to the work table. Then, the laser scanner will obtain the part profile, which is the width and height of the part. With the increase of the deposition height, the laser scanner position will also increase to maintain the same scanning distance.

Fig. 51 The laser scanner attached at the torch

Fig. 52 Working range of the laser scanner

4.2 Software setup

In this section, the software of the WAAM system is introduced. The software is mainly composed of the (i) RobotStudio, which is used to program the robot motion and simulate the result.

(ii) Labview, which is the platform to integrate the multi-sensor system.

(iii) Python-based slicing and path planning algorithm.

Fig. 53 shows the WAAM system established in the University of Wollongong[6].

Based on the whole system, thin-wall structure and solid structure parts can be deposited efficiently[96]. In the following section, three main software setup will be fully introduced.

Fig. 53 Robotic based WAAM system in the University of Wollongong[6]

4.2.1 RobotStudio

The RobotStudio is the offline programming developed by ABB company[97]. In the experiment, it is used to program the robot motion and simulate the robot path. In the meantime, the RobotStudio integrate a varies of welding machines, such as Fronius. The communication between the robot and welding machine is done in the I/O settings in the RobotStudio. By using the Rapid Program, it is convenient to control the robot as well as the welding machine.

Fig. 54 The simulation interface in Robotstudio

As shown in Fig. 54, the robot used is the IRB-2600 industrial robot. The coordinates shown in the plant are the tool data and the work object data.

4.2.2 Labview based signal acquisition

In the welding process, there are varieties of signals that need to be collected and analysed. In-progress signals such as welding current, welding voltage, temperature are captured using National Instrument cards. Post-progress information such as bead height, bead width, part's pictures, scanning data is captured by varieties of sensors as mentioned in Section 4.1.3. It is difficult to process these signals partly because they are captured by different hardware. The merge of these signals can be done through

Labview, which is shown in Fig. 55. The Labview program combines all these raw signals at one GUI interface. The Labview program can record the welding current and welding voltage during the welding process. After the deposition, user can choose different options such as scan, photo and temperature measurement. The corresponding result is shown as follows.

Fig. 55 shows the LabVIEW interface for the current and voltage collection. In this interface, the welding current and welding voltage is collected through the NI capture card. Then, the Fourier transform is used to transfer the time domine to the frequency domine. The Fourier transform equation is shown in Equation (6).

$$\hat{f}(\xi) = \int_{-\infty}^{\infty} f(x)e^{-2\pi i x \xi} dx \quad (7)$$

By using Equation (6), the welding current and welding voltage is transformed from the time domine to the frequency domine. The standard frequency of the welding current is around 70Hz, which corresponds to the CMT welding phase. If the frequency is higher or lower to 70Hz, some defects happened during the welding process. To conclude, the welding current and welding voltage are essential data for monitoring welding process.

Fig. 55 The LabVIEW interface for collecting welding current and voltage

Fig. 56 shows the scanning result of the deposited part. The scanner used is mentioned in Section 4.1.3. In the interface, the robot will move to the desired position if the start scan is triggered. Then the laser scanner collects the profile of the deposited part and saves as an excel file. The collected data is used to analysis the flatness of the surface, the peak value of the part and the geometry of the part. In future research, the scanning data is a vital feedback signal which is used to control the bead shape. The idea is described as follows:

- (1) Start deposition with the limited model (bead modelling, overlapping model).
- (2) Scan the whole piece and obtain the height, width, geometry of the part.
- (3) Compared with the sliced CAD model to get the error between the desired and the actual.
- (4) PID controller is used to adjusting the welding parameters to make the next layer deposition more accurate.

These ideas are used under limited information about the model. In the future, there are varieties of parts, materials. To establish the model for each part is impractical. By applying the feedback control, the design procedure is simplified, which increase the manufacturing efficiency.

Fig. 56 The scanning results of the deposited part

Fig. 57 shows the image result from the CCD camera. After the deposition, the pictures are captured to do a further defect analysis. Macro-defects such as undercut, gaps can be observed from the pictures. At the same time, pictures can be regarded as another demonstration when the multi-sensor system is used. When defects happen during the welding process, the welding current and voltage will change. The deviation of the welding current and voltage can be regarded as a reason. The change of welding current and voltage can also be found through the macro-structure, or in other words, the pictures captured from the CCD camera. Since only one sensor cannot predict or demonstrate the defects. The mutual corroboration can improve the accuracy of the

multi-sensor system. Moreover, the multi-sensor system is more reliable than the single-sensor system.

Fig. 57 CCD camera used to capture the macro-profile

4.2.3 Python-based slicing and path planning

The slicing method used in this experiment is the uni-directional slicing method, as mentioned in Section 2.4.2. Due to the parts do not belong to much complicated such as overhang structures, the existing uni-directional slicing method is suitable. After deposition, the layer height is measured by the laser scanner, and the current height is set as the next layer sliced height. Initially, the sliced height is set as 3mm, as shown in Fig. 58. A total of 10 layers have been sliced.

Fig. 58 The python-based slicing program

After that, the algorithm will automatically generate the path based on choices such as contour, raster. In the path planning settings, there are two variable that can be adjusted, the overlapping distance and number of contour. The overlapping distance is based on the previous model, as mentioned in Section 3.1. The path planning interface is shown in Fig. 59. The programmed path will automatically be saved as two files. The first one is the points file which contains all the robot target data. The second file is the rapid code, which can be called by the controller.

Fig. 59 The python-based path planning program

4.3 Overview of the WAAM system

A schematic diagram of the WAAM system is shown in Fig. 60. It is mainly composed of a Cold Metal Transfer (CMT) TPS 5000 power source, an ABB IRB-2600 robot, a rotary table, a scanCONTROL 2600-100 scanner, a CCD camera, an Optris PIX thermal camera and a cooling air gun. The 3D laser scanner with 300 Hz measurement speed was attached with the welding torch to obtain the profile of component after deposition. The thermal camera fixed on the wall was calibrated by the K type thermocouple to measure the average temperature of the workpiece. In the validation study, the deposition material used was Φ 1.2mm wire of S216 NAB alloy. In the real-life application, the manufacturing was conducted by Φ 1.2mm wire of ER4043 aluminium alloy. The forming substrate was an aluminium plate with a dimension of $670 \times 465 \times 25$ mm. The composition of the wires and substrate are listed in Table 4. The melting point, mechanical properties of both wires are listed in Table 5. The shielding gas for the welding torch was Ar (99.99%) gas with the flow rate of 25L/min. The stick-out was the distance from the contact tip to the unmelted electrode end, which

was kept constant (15mm). Through the offline programming software RobotStudio®, the rapid code can be simulated before starting the deposition.

Fig. 60 Multi-sensor based WAAM system

Table 4 Composition of S216, ER4043 wire and 5A06 plate

Element	Si	Fe	Mn	Mg	Zn	Ni	Cu	Al
S216	0	0.5-2.5	0.5-2.5	0	0	0.5-3.0	Rem	7.0-9.5
ER4043	4.5-6.0	0.8	0.05	0.05	0.1	0	0.3	Rem
5A06	0.4	0.4	0.5-0.8	5.5-6.8	0.2	0	0.1	Rem

Table 5 Melting point and mechanical properties of S216 and ER4043 wire

Element	Melting point	Ultimate tensile strength	Hardness
S216	1015-1045°C	450-560 N/mm ²	150-170HB
ER4043	574-632°C	145-228 N/mm ²	77HB

4.4 Implement

The L-shaped connector which links both horizontal and vertical parts is used as the typical model to validate the hybrid manufacturing strategy. As shown in Fig. 61 (a),

the dimension graphic of the specimen was depicted, and the simplified component is shown in Fig. 61 (b). For comparison, the test model was also deposited by other WAAM process available in the literature, which was mentioned in Section 2. The range of welding parameters was shown in Table 3.

Fig. 61 Test piece designed to validate the MHI process. All dimensions in mm (a) L shaped connector, (b) Deposited component

In the beginning, The slicing plane sliced the CAD model at the $H = 4\text{mm}$. Based on the sliced layer, the boundary layer was subtracted. The 3.5 m/min WFS was selected to deposit the boundary layer due to its lower heat input. After that, the geometry of the boundary layer was individually measured by the laser scanner. The scanner moves along the deposition direction, and the average measured value was determined as the detected value. Fig. 62 (a) and (b) shows the scanning and fitting results of the boundary layer, respectively. Based on the scanning results, the total width of the boundary layer w_1 was 6.48mm , and the height was 4.96mm . The curve fitting result shows that the parabola model produces an accurate approximation with the highest value of R^2 i.e. 0.996 . After these measurements, the position and geometries of beads next to the boundary layer were specified. In this validation study, the range of height h was specified as $2.62\text{mm} < h < 4.96\text{mm}$

Fig. 62 (a) The scan result of the boundary layer (b) The curve fitting result of the boundary layer

From Eqs. (2), the upper and lower limits of the function $W(n)$ was first determined. w_2 and h of the upper limits was set to 7.86 mm and 4.2mm, respectively, which corresponded to 7m/min WFS. Therefore, as mentioned in Sect.3.2, the Eqs. (5) was applied to calculate d^* , for which $3.24\text{mm} < d^* < 7.17\text{mm}$. From the calculation result, $d^* = 6.48\text{mm}$ was obtained to make the overlapping area equal to the valley. Similarly, the set $Q = \{4.02, 3.3\}$ was specified as the lower limit of $W(n)$. After that, the graph of the function $W(n)$ was plotted, as shown in Fig. 63. The minimum value W_{min} was calculated as 14.52mm, and values of the width difference ΔW and Δh were listed in Table 6. It can be seen that, for any bead amount n , there existed $\Delta W > \Delta h$ such that for any width, there existed at least an integer n to achieve the target width. In this case, the total width of the component was indicated as $y = 30$. The x coordinate of the intersection point was the required bead number (e.g. $n = 3, 4, 5$), as shown in Fig. 63. In practical, a solution should be chosen and applied to the deposition. The

principle for the selection was that the number n should be as small as possible to increase the welding efficiency. According to this, the set $Q = \{6.48, 4.2\}$ corresponding to 7 m/min WFS was selected such that the filling process can be accomplished by three identical beads. After the generation of manufacturing parameters, the deposition process was detailed as follows.

Table 6 The difference between ΔW Δh and bead amount

Number of beads	$\Delta W(\text{mm})$	$\Delta h(\text{mm})$
1	4.92	
2	6.42742	
3	7.93484	
4	9.44226	3.7352
5	10.94968	
6	12.4571	
7	13.96452

Fig. 63 The generation of the welding parameters for the sliced layer

Weld beads were deposited in several parallel contour paths and a single path. The contour path was a close loop which the arc striking overlapped the arc extinguishing to maintain the same height through the deposition. With the same reason, the opposite direction of the single path was adopted. For every contour, the start and end position were randomly distributed along the welding path to prevent the excavation effect of the arc. In practical, the end position of every bead was extended for 1mm along the deposition direction to compensate the arc extinguishing time. After a layer was deposited, the system waited until the temperature obtained from the IR camera was lower than 150°C to prevent the heat accumulation. During the waiting time, the 2D scans were applied to collect the surface details and measure the current height $H' = 4.24mm$. The modified height was set as the new sliced height. The mean square value of the surface details indicated the workpiece surface flatness. Subsequently, this processing cycle was repeated until the part was fabricated.

Chapter 5 Discussion

5.1 Macrostructure

Under the carefully planned process, every two layer's results are shown in Fig. 64. A total of 40 mm height is achieved. From the appearance of Fig. 64 (a) to (d), the boundary layer is higher than the inner layers. When depositing the last layer, the adjustment of slicing height achieves the target height. The fabricated component with uniform dimensions is shown in Fig. 64(e). It can be observed from each layer that there are no peaks at the corner. Moreover, all beads are well overlapped each other at the corner. The arc extinguishing overlaps the arc ignition such that there is no material shortage at the end position.

Fig. 64 The experiments result for each layer

To check the potential internal defects, two positions of the cross-section profile indicated in Fig.63(a) was shown in Fig. 65 (b) and (c). It can be observed that there are no macroscopic voids. The height variance between the layer's edge and layer's body is small such that there is no material shortage at the boundary[35]. Compared with the conventional WAAM described in Sect.2, the MHI process successfully tackle two major problems, i.e. collapse and voids.

Fig. 65 (a) An overall view of the deposited part by MHI process, (b) and (c) The cross-section profile. The surface flatness was calculated based on the scanning data of the deposited part. A total of 60 sets of data are obtained without the start and end sections of arc, and each set has 637 points. Taking the average of 60 sets, the results are shown in Fig. 66. The scanning results of the finished parts with the partial enlarged drawing. In the middle, 207 points are used to calculate the average height $H_{avg} = 39.15\text{mm}$. Then the standard deviation of the layer height μ_h can be calculated as:

$$\mu_h = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (H_i - H_{avg})^2} \quad (8)$$

Based on Eqs. (8), $\mu_h = 0.341$ indicates that there is a lower deviation within the points such that a flat layer surface is achieved. In the meantime, the appearance of scanning results reveals no voids or gaps.

Another interesting finding from the scanning result is that there is a concave shape near the boundary layer, and the details are shown in Fig. 66. The shape of the bead, which is adjacent to the boundary layer, is shown in Fig. 67. The observed phenomenon can be explained from the following points of view: the weld bead remains in the weld

pool for a short time before solidification. There exists an additional force caused by Laplace pressure P_s at the border of the weld pool surface, which influences the shape of the weld pool. The P_s can be expressed as the Young-Laplace equation:

$$P_s = \frac{2\sigma}{r} \quad (9)$$

Where σ is the surface tension of the molten material, r is the radius of curvature. The direction of P_s points from the weld pool surface to the centre of curvature. Due to the additional pressure, the weld pool surface tends to shrink into the minimum area possible. However, P_s is inversely proportional to r . When larger WFS is applied, the increased size of the weld pool increases the radius of curvature. As a result, the P_s decreases such that the force applied at the border is reduced. Therefore, it is easier for the weld pool driven by the arc force to spread on the solidified wall at point A. At the same time, the weld pool at point B suffered its gravity so that it spreads on the last layer. Accordingly, this is the reason why a concave shape is formed next to the boundary layer.

Fig. 66 The scanning results of the finished parts with the partial enlarged drawing

Fig. 67 Schematic diagram of the additional pressure acting on the weld pool

5.2 Microstructure

Optical micrographs with low and high magnifications at top and majority regions of WAAM S216 samples deposited with different processes are shown in Fig. 68. As can be seen, samples processed with aforementioned conditions all consisted of coarse α columnar grains with some dark-etched β interdendritic phase. κ -type intermetallic phases (κ_{II} , κ_{III} and κ_{IV}) were revealed to be precipitated in α and β phase: κ_{II} -Fe₃Al phase was found to precipitate mainly in β interdendritic phase, κ_{III} -NiAl precipitates were nucleated at the α/β interface, and the κ_{IV} -phase (Fe-rich Fe-Al-Ni) was homogeneously distributed in α matrix [98]. It's worth noting that the β interdendritic phase appears to be coarser in the top region than that in the majority region for all conditions. This is because the majority region undergoes reheating and remelting processes, leading to the further growth of α phase in the previously deposited layers and partial transformation of β -phase according to the reaction of $\beta \rightarrow \beta + \kappa_{II} \rightarrow \alpha + \kappa_{III}$ [99]. Although β interdendritic phases in the top region of samples manufactured with different processes vary in size, the area fraction of interdendritic structure is similar, turned out to be 13.1%, 13.0% and 14.2% for CMT, spray, and mixed heat input, respectively, measured by Image Pro-plus. Furthermore, the area fraction of interdendritic structure in the majority region of CMT, spray, and mixed heat input samples was calculated to be much closer, coming out to be 12.6%, 12.5%, 12.3%, respectively.

Fig. 68 Optical micrographs with low and high magnifications at different regions of WAAM S216 samples deposited with different processes: (a1), (a2) top region of sample processed with CMT; (b1), (b2) majority region of sample processed with CMT; (c1), (c2) top region of sample processed with Spray; (d1), (d2) majority region of sample processed with Spray; (e1), (e2) top region of sample processed with Mixed heat input; (f1), (f2) majority region of sample processed with Mixed heat input.

The microhardness variation along the central line from top surface to the majority region of the WAAM S216 components experiencing CMT Spray, Mixed heat input

modes is shown in Fig. 69 (a). Correspondingly, Fig. 69 (b) compares the microhardness values of each as-built component. All the specimens have relatively smooth microhardness distribution trend with small fluctuations on the basis of process mode. The mean microhardness value is basically unchanged, with a quite slight increase from 122 to 129 HV0.2 as a result of deposition mode changing from CMT to Mix Heat Input. As reported, the κ -phase density exerts a significant role on hardness of the nickel-aluminum bronze alloy [100]. Lower κ -phase density (κ_{II}) found in β interdendritic phase brings about a reduction of hardness in β phase when compared with α phase, which is identified by higher κ -phase density (κ_{III} and κ_{IV}) with uniform distribution. Thus, the less volume fraction of β interdendritic phase contributes to the improvement in hardness, which could be an explanation on the similar microhardness values of samples processed with the above-mentioned modes.

Fig. 69 (a) Microhardness variation from top surface to the majority region along the central line and the (b) average microhardness values of the WAAM S216 components experiencing different modes (CMT, Spray, Mixed heat input). One standard deviation was represented by the error bar.

5.3 Improvement of welding efficiency and geometry accuracy

The comparison of layer width using the proposed method and the either CMT mode or pulse mode is shown in Fig. 70. It can be regarded that the proposed technique has a precise dimension than the others. The measurement results show that the variance of the optimised layer width is 0.5mm, while the others are 5mm and 0.6mm, respectively. It should be noted that the collapse defect occurred in Pulse process make the higher layer deposition impractical. Although the CMT process provides an accurate dimension, the defects are of no practical use. More seriously, the more significant dimension difference leads to a time-consuming post-machining and low material utilisation. The buy-to-fly ratio can be calculated as the ratio of the total remaining material and the deposited material. Based on the measured results, the calculation shows that the proposed method achieves a 98% material usage, which is 14% higher than the Pulse process.

Fig. 70 Comparison of the layer width using different methods

In addition, Table 7 compares the production time with conventional WAAM. It should be noted that the hybrid method considers a layer as two beads at the boundary and multiple beads inside. Due to the increase of welding current and WFS for inner beads, the inside volume can be filled. The overall results achieve the same effect as that two complete layers in the conventional WAAM. Thus, the number of contours required in the hybrid method is half of the normal method, which increases 50% welding efficiency.

Table 7 The required beads to achieve the same height with different process

Process method	Target height(mm)	Number of layers	Number of beads
MHI	4	1	7
Conventional WAAM	4	2	14

5.4 Further application

The proposed MHI process has been shown high dimensional accuracy and manufacturing efficiency. It should be noticed that this hybrid process method is flexible to integrate slicing and various path planning solutions, such as adaptive path planning[49]. Thus, the formation of complex defects-free topologies is feasible. Taking the validation one step further, a traffic barrier used at the bridge was built, and the 2D drawing is shown in Fig. 74(a). The deposited material is ER4043. The structure of the component is similar to the L shape component. However, there are some challenges associated with the deposition process, which will be thoroughly discussed in the next section.

5.4.1 The analysis of the deposition strategy

Based on the analysis of the component, it is necessary to deposit on both sides of the plate. The reasons are as follows:

(1) First of all, it is a large component which the estimate depositing time for a layer is an hour without cooling. With such a long welding process, heat accumulation becomes a big problem. The excessive heat accumulation will result in the distortion of the substrate.

(2) Secondly, to deal with the distortion problem, it is necessary to deposit on both sides of the plate.

Due to the heat flow transfers from the deposited part to the substrate, the deposition on both sides of the plate can offset the heat accumulation on either side.

(3) Finally, the deposition on both sides of the substrate can save much material. Due to the massive distortion of the substrate, the initial few layers cannot be used. The machining is considered as a high cost. On the other hand, the deposition on both sides considers the substrate as a part of the final component, which saves the deposition cost and time.

In order to realize the proposed deposition strategy, Fig. 71 shows the rotation of the 2D rotary table. First of all, the table will rotate 90° according to the y-axis, which y-axis points inside, as shown in Fig. 71 (a) to Fig. 71 (b). Next, the table will rotate 180° according to the x-axis to realize the deposition on both sides of the substrate.

Fig. 71 (a) 2D rotary table (b) Rotation according to the x-axis and y-axis

After that, the flip of the substrate is a kind of mirror effect. In order to maintain the same shape as deposited at both sides, Fig. 72 illustrates the strategy to achieve the effect. First of all, a hole is dug through the middle of the substrate. Secondly, to define two work object frame where the origin is the hole for both sides of the substrate, named as Wobj_Pos and Wobj_Neg. After programmed the path for the positive side, the path for the negative side is to negate the x coordinate, and the rest remains the same.

Fig. 72 The strategy of depositing on both sides of the substrate

5.4.2 Selection of the welding process

Considering the material properties of the Aluminium 4043, the following three welding modes are selected to the test: CMT mode, CMT-P mode and Spray mode. As mentioned in the previous sections, the CMT mode, Spray mode and CMT-P mode are fully introduced. The advantages and disadvantages have been discussed. In this section, the analysis of the different results based on different modes will be presented.

Regardless of the problem of the void during the welding process, there exists the porosity problem, especially for the aluminium. Because the solidification rate of the

aluminium is very fast, the gas cannot escape from the molten pool before the solidification. Thus, the porosity forms inside the component which influences the mechanical properties of the deposited component. Typically, the porosity always forms in the CMT mode, as mentioned in the literature[101]. In the test, there are two selected welding mode regarded as the CMT-P mode and the Spray mode. The deposited shape is the same as shown in Fig. 61. The deposition results with the cross-section profile are shown in Fig. 73

Fig. 73 The cross-section profile with (a) Deposited with the Spray mode (b) Deposited with CMT-P mode

When using the spray mode, there are many porosities inside the component. There is a huge difference between the solubility of hydrogen in solid and liquid aluminum, which is 0.036 and 0.69 cm³/100 g at a melting point of 660°C, respectively. Such a huge difference results that the gas formed during the welding process cannot escape easily. On the other side, the CMT-P has less porosities observed from the cross-section profile due to the CMT-P process decreases the escape distance for hydrogen compared to the pulse process. Due to such advantages, the CMT-P process is chosen as the welding process.

5.4.3 Bead modelling and establishment of the overlapping model

As previously stated in the NAB deposition, the bead modelling and the overlapping model of the Aluminium material is established. The experiment result is shown in Table 8.

Table 8 The bead modelling and the overlapping model

No.	Parameter design			Overlapping	Bead
				Distance	Height
	Wire feed speed	Travel speed	Temperature	(mm)	(mm)
	(m/min)	(m/min)	(°C)		
1	5.0	300	30	4.1512	3.23
2	5.5	300	30	4.1316	3.13
3	5.0	400	30	3.6320	3.15
4	5.5	400	30	3.7362	3.20
5	6.0	400	30	4.3169	3.66
6	6.5	400	30	5.0848	3.68
7	7.0	400	30	5.5641	2.82
8	7.5	400	30	6.0753	2.63
9	8.0	400	30	6.4088	3.15
10	5.0	500	30	3.5041	3.03
11	5.5	500	30	3.6953	3.16
12	6.0	500	30	3.9896	2.38
13	6.5	500	30	4.9416	2.72
14	7.0	500	30	5.3635	2.63
15	7.5	500	30	5.8111	2.72
16	8.0	500	30	5.9522	2.72
17	5.0	600	30	3.1104	2.74
18	5.5	600	30	3.2773	2.50

19	6.0	600	30	3.9812	2.43
20	6.5	600	30	4.7465	2.44
21	7.0	600	30	4.9754	2.52
22	7.5	600	30	5.3378	2.46
23	8.0	600	30	5.6388	2.47
24	5.0	700	30	2.9694	2.11
25	5.5	700	30	3.1887	2.16
26	6.0	700	30	3.4793	2.19
27	6.5	700	30	4.3357	2.23
28	7.0	700	30	4.8550	2.20
29	7.5	700	30	5.0885	2.07
30	8.0	700	30	5.3094	2.04
31	5.0	800	30	3.0521	1.93
32	5.5	800	30	3.0064	2.23
33	6.0	800	30	3.3423	2.16
34	6.5	800	30	4.4328	2.05
35	7.0	800	30	4.7776	1.97
36	7.5	800	30	4.9196	1.92
37	8.0	800	30	5.0488	1.86
38	7.0	900	30	4.7052	1.82
39	7.5	900	30	4.8898	1.79
40	8.0	900	30	4.9625	1.69

5.4.4 Results

Based on the bead modelling results presented in Table 8 and the formula established in Section 3.3, the calculated process parameters are shown in Table 9, while the final product is shown in Fig. 74(b). The machined part shows no defect. It is recognised that the proposed method is capable of fabricating large block structure and has great potential for adapting different materials.

Fig. 74 A bridge traffic barrier fabricated with MHI strategy (a) 2D drawing of component (b)

Deposited component

Table 9 Process parameters for the bridge traffic barrier

Position	Welding process	TS(mm/min)	WFS(m/min)	Current(A)	Voltage(V)	Number of beads
Boundary layer	CMT-P	400	4	87	15.1	2
Inner layers	CMT-P	400	6	136	17.7	4

Chapter 6 Conclusion and future work

This work presents a novel hybrid heat input strategy for WAAM process when fabricating large block structure components. In WAAM, the deposition quality is mainly linked to the welding process and the selection of the welding parameters. The main results can be summarised as follows.

- Variable heat input conditions provide a different effect on the shape of beads. The lower heat input makes the bead 'narrow and tall', while as the higher heat input makes the bead 'wide and short'.
- The change of heat input can be regarded as the process mode (i.e. CMT, Pulse), the WFS associated with the welding current and voltage and the travel speed.
- To avoid defects (i.e. collapse and voids), the MHI strategy is proposed which aims at combining variable heat input conditions within a sliced layer. It was found that the dimension accuracy was guaranteed by applying lower heat input at the boundary layer, and the inner layers were fulfilled with higher heat input to increase deposition efficiency.
- The strategy has been validated through a test-piece, shape as an L, and demonstrate the ability of the MHI to provide a more uniform shape and void-free component than the conventional WAAM. Furthermore, the production of a traffic barrier shows that the MHI has great potential to be applied in other materials.
- The experiment results show that the buy-to-fly ratio can reach 98%, and the deposition rate is up to 1 kg/h without active cooling.

Future research proposals can be considered as the following aspects. Firstly, the application in fabricating complex shapes such as polygon, perforated contours will be developed. Secondly, the effect of integration with different slicing and tool path

planning methods will be studied. Thirdly, the microstructure and mechanical properties such as tensile test will be further focused. Finally, the utilisation in other materials such as carbon steel, aluminium needs further research investigations.

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