Pertanika J. Sci. & Technol. 32 (2): 917 - 942 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Bead Geometry Control in Wire Arc Additive Manufactured Profile — A Review

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ABSTRACT

Wire arc additive manufacturing (WAAM) is a well-established additive manufacturing method that produces 3D profiles. A better deposition efficiency can be achieved by understanding the parameters that may influence the geometry of the bead. This paper provides a review that focuses on the factors that may influence the formation of the 3D profile. The included factors are the flow pattern of the molten pool after deposition, the built structure and orientation, the heat input and cooling conditions, the welding parameters, and other uncertainties. This review aims to facilitate a better understanding of these factors and achieve the optimum geometry of the 3D parts produced. According to the literature, the behavior of molten pools is identified as one of the major factors that can impact the deposition efficiency of a bead and govern its geometry. The review indicated that the flow behavior of the molten pool and the geometry of the deposited bead are significantly affected by most welding parameters, such as torch angle, wire travel speed, filler feed rate, and cooling conditions. Furthermore, this paper incorporates the technology utilized for comprehending the behaviors of the molten pool, as it constitutes an integral component of the control strategy. It has been concluded that automated planning and strategy are necessary to ensure efficient deposition by controlling those factors. The integration of artificial intelligence could bring benefits in planning to address the variation and complexity of shapes.

Keywords: Bead geometry, deposition efficient, molten pool, wire arc additive manufacturing

ARTICLE INFO

Article history:
Received: 19 April 2023
Accepted: 12 September 2023
Published: 26 March 2024

DOI: https://doi.org/10.47836/pjst.32.2.23

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ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

Wire Arc Additive Manufacturing (WAAM) has been highlighted as a metal 3D printing method that holds immense promise for large-scale (Ermakova et al., 2020; Laghi et al., 2021) 3D printing applications across a wide range of sectors. WAAM employs arc welding methods that are also used in gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), or plasma arc welding (PAW). WAAM, on the other hand, stands out due to its far superior computer control. WAAM's key features are material and feedstock, software, power supply, and understanding of these aspects. WAAM, in particular, can work with a wide variety of metals as long as they are in the form of wire. Metals include stainless steel, nickel-based alloys, titanium alloys, and aluminum alloys. Furthermore, WAAM is compatible with any metal that can be welded and utilizes a heat source for melting the wire. The wire melts and is subsequently deposited onto the substrate in the form of a molten pool. Once cooled to room temperature, it undergoes solidification and forms into a bead. The process is repeated, layer by layer, until a 3D profile with a specific geometry is formed. The geometry of the bead depends on various process factors, including current, voltage, travel speed, wire feed rate, torch angle, and the distance between the torch and substrate.

WAAM offers various advantages, including a high deposition rate, which can provide significant benefits for production and throughput (Lin et al., 2021; Liu et al., 2020; Rodrigues et al., 2019). A wide range of materials can be used for WAAM in wire form (Rodrigues et al., 2019). The material properties in WAAM parts are improved through supplemental considerations, including heat input and the cooling process (Su et al., 2019). Producing metal 3D parts, which requires an established manufacturing process such as the welding process, is also beneficial in terms of reasonable cost (Li, Chen et al., 2018; Liu et al., 2020; Shen et al., 2020). Despite the benefits, WAAM has shortcomings, such as high residual stress and distortion, low part accuracy and surface roughness (Paskual et al., 2018), and near net shape, which requires an additional finishing process like machining (Wu et al., 2018b). Residual stress and distortion commonly occur due to excessive energy input, high deposition rate, and large temperature gradient in wire-fed additive manufacturing (AM) processes. The most difficult challenge in WAAM is heat management because the process requires metal in wire form to be melted. The geometry of the deposited material is determined by the behavior of molten material in a pool. This behavior is influenced by heat, mass transfer, and cooling.

Gas Metal Arc Welding (GMAW) is the most commonly used energy source in WAAM because GMAW-based additive manufacturing has several advantages, the most important of which is lower cost (Chernovol et al., 2020; Giarollo et al., 2022; Navarro et al., 2021; Van Thao, 2020). In addition, the technique offers a high deposition rate (Chaturvedi et al., 2021; Nagasai et al., 2021; Paskual et al., 2018; Shen et al., 2020; Van Thao, 2020) and high welding efficiency, that is, material and energy (Giarollo et al., 2022; Greebmalai

& Warinsiriruk, 2020; Henckell et al., 2020; Paskual et al., 2018; Reisgen et al., 2020). GMAW is more suitable for medium and large components (Feucht et al., 2021; Gierth et al., 2020; Pandey, 2019; Waldschmitt, 2019). Other important features of GMAW are multi-material (Hauser, Reisch, Seebauer et al., 2021; Karayel & Bozkurt, 2020; Leicher et al., 2020) and improved material properties like impact strength (Nagasai et al., 2021; Waqas et al., 2018) but less in terms of dimensional accuracy (Rosli et al., 2019; Wang et al., 2022).

The paper commences by providing a comprehensive explanation of fundamental WAAM knowledge, including the molten pool, bead geometry, and the behaviors of different WAAM welding and process parameters that result in efficient material deposition. The efficacy is measured based on the geometrical representation of the profile, which includes height, width, and volume. It is assumed that the integrity issue has been resolved. It is important to understand the behavior of the molten pool during deposition to achieve a good bead geometry for a thin wall structure. This understanding enables shorter building times or higher welding efficiency.

BEAD GEOMETRY

The geometry of beads is a crucial aspect of WAAM, as it impacts the quality of the parts, their structural integrity, and overall performance. In WAAM, a welding bead is a deposited layer of molten metal laid down by the welding process to construct a three-dimensional object. Like other welding processes, a welding bead is created in WAAM when the welding wire is melted and fused with the underlying base material. However, in the context of WAAM, these beads are deposited layer by layer to gradually construct a complex part or component. Figure 1 depicts a schematic diagram of the typical geometry of a bead. The welding bead cross-section can determine the bead height, width, radius, and degree of contact angle. The parameters set during the deposition process determine the size and geometry of the welding bead. Bead geometry includes shaping individual beads, ensuring bead consistency, managing the overlapping of multiple beads, controlling thin wall formation, and achieving accurate solid structures. Figure 2 depicts an example of geometry produced by the WAAM process.

Single bead shaping involves the control of the shape and dimensions of individual beads as they are deposited layer by layer. Properly shaping a single bead contributes to the accuracy of part dimensions and surface finish. Optimize process parameters (arc voltage, wire feed rate, and travel speed) for precise bead shaping. According

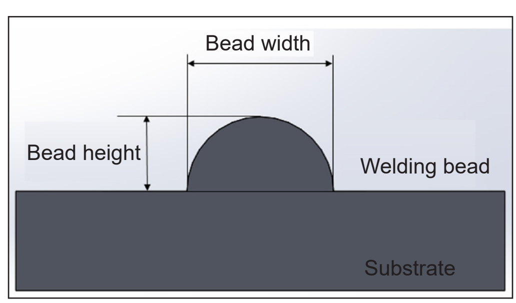


Figure 1. Schematic diagram of a weld bead

to Venkatarao's (2021) research, the depth of the weld bead is primarily determined by current and torch angles, while the breadth and height are influenced by wire feed speed and welding speed (Venkatarao, 2021). When different torch angles are used, the bead results are comparable. For instance, when a 90° torch angle is used, the influence of arc force at a 60° angle has a lesser effect on the molten pool and depth of metal deposition. In comparison to single-bead shaping, multi-bead shaping necessitates greater attention due to the importance of effectively managing the interaction between adjacent beads as they overlap to achieve a bond that is seamless and robust. Properly overlapping multiple beads prevents the occurrence of gaps or voids between the beads, thereby ensuring a continuous and robust build. To achieve proper multi-bead overlapping, selecting appropriate overlap strategies (full or partial) based on part specifications and optimizing the overlap amount and pattern for uniform fusion and minimum gaps is necessary. Maintain consistent spacing between overlapping beads, and by adjusting the travel speed and direction, produce a seamless transition between beads.

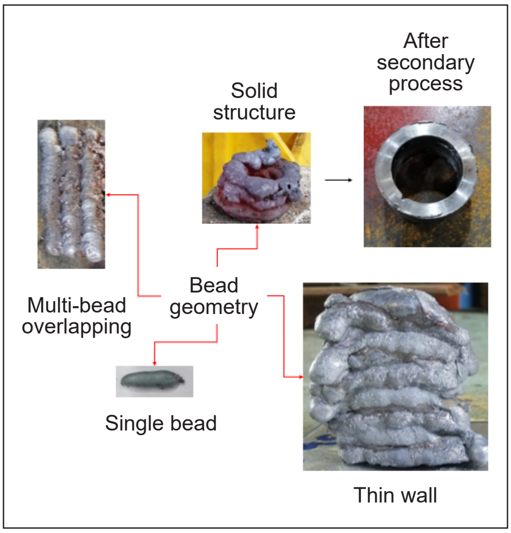


Figure 2. Example of bead geometry produced by WAAM

In modern times, the prediction of bead geometry size can be achieved through applications such as the artificial neural network (Karmuhilan & Sood, 2018). The diagram of this approach is shown in Figure 3. Panchagnula and Simhambhatla (2018) also introduced a mathematical model that predicts the geometry of subsequent layers based on the height

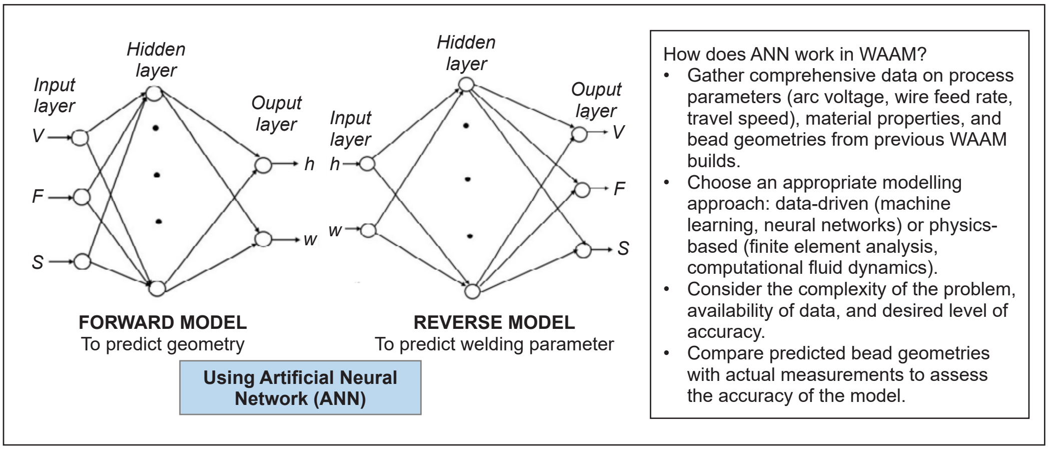


Figure 3. ANN model in predicting bead geometry (Karmuhilan & Sood, 2018)

and width of the first layer. The mathematical model can also demonstrate the relationship between the parameters and bead geometry (Panchagnula & Simhambhatla, 2018). Li, Ma et al. (2018) discovered that the stability of the formed bead is also important in the fabrication of large parts using weave beads. According to Dinovitzer et al. (2019), the geometry and microstructure of welding beads were determined to be the most affected by travel speed and current. In addition to single and multi-bead, printing a thin wall structure also necessitates meticulous control of deposition parameters to avoid distortion, warping, or collapse of said structure. It is recommended that the process parameters be fine-tuned to balance heat input and prevent warping to achieve a good bead geometry for a thin wall structure. By utilizing preheating or controlled environments, one can minimize thermal stresses.

One can achieve accurate deposition of thin walls by opting for smaller layer heights. It is essential to maintain bead consistency in thin walls for structural integrity. The user is interested in controlling the placement and dimensions of beads to accurately replicate the intended design of a solid structure. One is suggested to have an accurate bead deposition to ensure the final part meets design specifications and functional requirements. Employing precise CAD/CAM software makes it easier to produce an accurate part design and bead path planning, as shown in Figure 4. It is important to define a path for the depositing process because the backward fluid flow and swelling of metal in the molten pool can explain the uneven bead geometry and the length of the beginning region is positively related to the sloped shape at its end and the length of the molten pool (Jafari et al., 2021). Implementing iterative testing and optimization based on data from part inspection and using in-process monitoring (thermal imaging, sensors) to detect and correct deviations also aids in accuracy control. According to Jafari et al. (2021), shielding gas is also a significant factor affecting the weld bead's physical appearance. Improper shielding can lead to irregular bead profiles and diminished dimensional accuracy. Arc Striking (AS) and Arc Extinguishing (AE) are important considerations in Wire Arc Additive Manufacturing

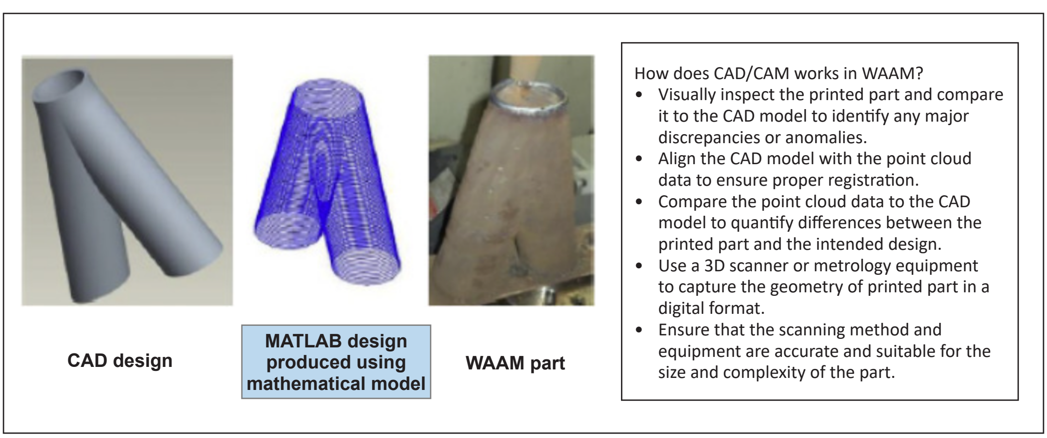


Figure 4. CAD/CAM verification shaping for geometry accuracy in WAAM (Jafari et al., 2021)

(WAAM). They are crucial in achieving precise bead geometry and maintaining process stability. These conditions can lead to variations in bead shape, dimensions, and overall part quality.

Tang et al. (2019) discovered that these two conditions result in limitations on the control of bead geometry in WAAM, and they also lead to low precision of the bead. The goal is to ensure uniformity in bead dimensions, shape, and material properties across multiple layers and throughout printing. The beads' consistency impacts the overall mechanical properties and the structural integrity of the printed part. The geometry of beads plays a crucial role in the surface finish, formation of defects, and mechanical properties of parts produced using WAAM processes. Figure 5 summarizes the influence of bead geometry on the surface finish and mechanical properties, with various effects listed. According to research conducted by Han et al. (2018), installing a controller that utilizes a rule-based engine eliminates height variation in multilayer depositing styles (Han et al., 2018). The surface polish improves accuracy and smoothness, which results in fewer or no defects being discovered inside the deposited bead and built wall. Excessive material deposition or insufficient fusion between adjacent beads can result in a rough surface finish due to too much overlap or improper spacing between beads. A smoother surface finish can be achieved by spreading out the molten material and minimizing irregularities through the controlled oscillation of the welding torch during deposition. The geometry of the bead indirectly affects the mechanical characteristics through the deposition of the produced bead. The welding parameters used during the depositing process affect the mechanical properties. Table 1 displays the impact of bead geometry on mechanical properties, surface finish, or defects based on the available research.

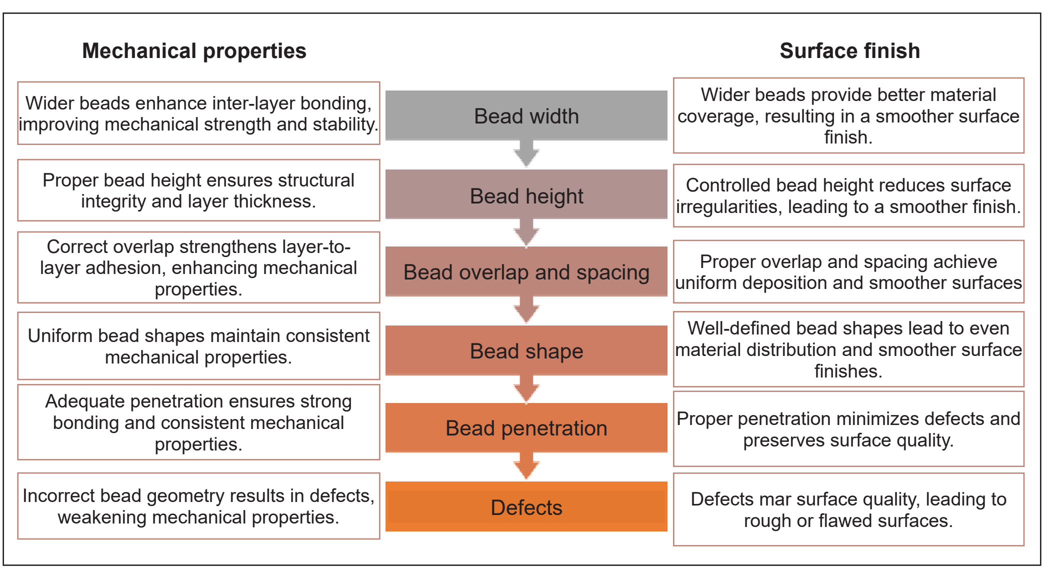


Figure 5. Summary of bead geometry effect on surface finish and mechanical properties

Table 1
Influence of bead geometry on mechanical properties, surface roughness or defects

Reference	Welding technique	Filler material (wire diameter)	Effect of the bead geometry on:		
			Mechanical properties	Surface finish	Defect
Xiong et al., 2018	GMAW	H08Mn2Si (1.2 mm)		/	
Liu et al., 2019	compulsively constricted WAAM (CC-WAAM)	ER70S-G (1.2 mm)	/	/	/
Dinovitzer et al., 2019	TIG	HASTELLOY X alloy (NA)		/	/
Su et al., 2019	CMT	ER5356 alloy (1.2 mm)	/		/
Aldalur et al., 2020	GMAW	ER70S-6 mild steel (1.2 mm)	/	/	
Yuan et al., 2020	CMT	ER70S-6 (0.9 mm)			/
Zeng et al., 2020	TIG	NiTi wire (0.7 mm)			/
Vora et al., 2023	GMAW	SS-309L (1.2 mm)	/		/
Ni et al., 2023	GMAW	ER70S-6 (1.2 mm)		/	/

BEAD GEOMETRY CONTROL

The control of bead geometry is a crucial aspect of WAAM. It entails the management of the shape, dimensions, and quality of each bead deposited during the additive manufacturing process. Precise control of bead geometry is essential to ensure the accuracy of the part, mechanical properties, and overall performance. Effective bead geometry control can be achieved by utilizing optimized parameter control, advanced CAD/CAM software, consistent layer height control, optimal overlap strategies, proper shielding gas, conducting material testing, and continuously analyzing data. Mu et al. (2021), who implemented an online layer-by-layer controller under various welding conditions to improve the deposition accuracy of the WAAM process, is just one example of the numerous approaches taken by previous researchers to improve the deposition accuracy of the WAAM process. The deposited profile is measured with a laser scanner and compared to the CAD model during the process. Errors are then compensated by generating a new set of welding parameters for the subsequent layer. In their measurement, Wang et al. (2020) utilized the same device and adopted the response surface optimization method to obtain accurate bead geometry. They considered the width, layer height, penetration, accumulated area, penetration area, aspect ratio, and dilution ratio.

In another case, the utilization of the dual pulsing combination of both high and low-frequency pulsing is employed to observe the effects on the weld bead geometry and heat-affected zone of Gas Tungsten Arc Welding (GTAW) (Benakis et al., 2020; Manokruang et al., 2021). Machine learning was employed to create a fully intelligent WAAM system, as demonstrated by Ding et al. (2021) and Tang et al. (2019). In their study, Ding et al. (2021) discovered that integrating three crucial modules, namely the data generation module, the model creation module, and the welding parameter generation module, led to notable enhancements in product quality and reductions in manufacturing costs. These cost reductions encompassed aspects such as raw material usage and manual labor. Tang et al. (2019) focused on determining abnormality by examining the arc-striking and arc-extinguishing areas of the bead. Using a burning-back method, they optimized the weld bead on both ends.

MOLTEN POOL FLOW BEHAVIOUR

A molten weld pool is a dime-sized weld volume where the filler metal has reached its melting point and is beginning to solidify. In their study, Tang et al. (2019) found that several physical properties influence a molten pool. These properties include droplet transfer, gravity, arc force, heat radiation, and conduction. The flow of liquid inside the weld-molten pool contributes to the dynamic nature of these properties. The flow direction of the molten pool varies at the arc strike, middle point, and arc extinguishing area due to different forming conditions, which results in a variation of weld geometry. Controlling these parameters may lead to the achievement of optimal bead geometry. Controlling heat accumulation in Gas Tungsten WAAM is difficult, which makes achieving good geometry and stable metal transfer challenging (Wu et al., 2018a). Figure 6 shows a schematic diagram of the molten pool from different perspectives. As the travel directional movement increases, the heat dissipation over the substrate becomes broader.

As mentioned earlier, droplets from the welding wire create the welding bead, which varies in size based on the heat dissipation determined by the setting parameter. Raising the arc force increases the droplet impact force on the molten pool even more. The heat dissipation modes from the beginning, during the built-in thin-wall part, and the overlapping welding bead are all detailed in Figure 7, which also shows the heat dissipation. As the material begins to solidify, primary and secondary penetration pushes to the back of the molten pool and creates the crown (Ou et al., 2018). In this context, the crown refers to the formed welding bead on top of the substrate.

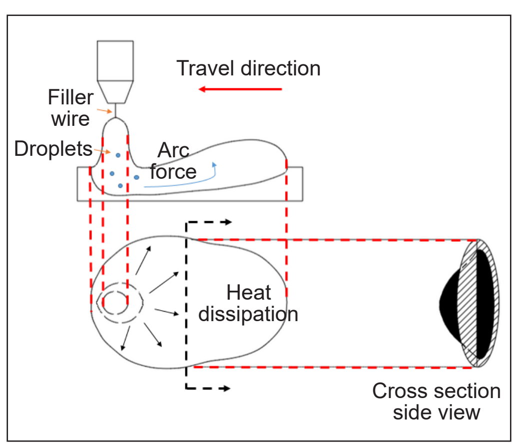


Figure 6. The schematic of weld molten pool in WAAM

The most frequent cause of a molten pool with poor uniformity and final appearance is a combination of high temperature and

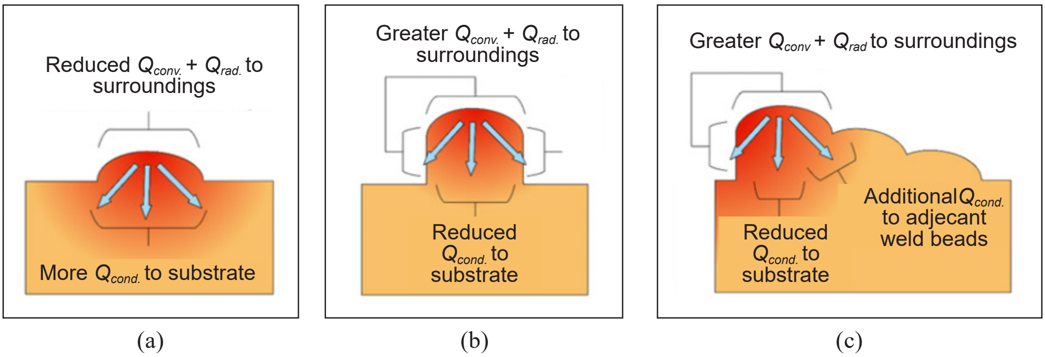


Figure 7. Schematic diagram of the heat dissipation modes: (a) at the beginning of WAAM; (b) during the build of a thin wall part; and (c) for a part with overlapping weld beads. (Cunningham et al., 2018)

deposition rate. The appearance of the welding bead is affected by heat accumulation during the movement of the welding torch, which causes the shape to vary as the molten pool cools (Cunningham et al., 2018). Multilayer deposited welding beads exhibit a semi-elliptical shape for each layer segregation (Bai et al., 2018; Dinovitzer et al., 2019; Jia et al., 2020). In order to achieve a near-net shape and good material utilization, it is necessary to regularly control the temperature during the WAAM process. In multilayer welding, it is necessary to appropriately maintain or define the distance between the welding torch and each successive layer. The molten pool on the first layer differs from that on the subsequent layer because the amplitude of the heat flow decreases as the number of deposited layers increases, resulting in heat accumulation. Several methods for reducing heat accumulation include an inter-pass idle period, active cooling, and in situ active cooling or in situ heating.

By utilizing indirect arc and force constriction, Compulsive Constricted WAAM also aids in the resolution of heat accumulation and low precision (Guo et al., 2020; Liu et al., 2019). Hejripour et al. (2018) expanded on the research by considering fluid flow and mass transfer. Heat conduction models are progressively replacing more realistic models that account for convective heat transfer. Errors in the setting of depositing parameters (such as current, voltage, welding speed, filler feed rate and torch angle) result in various issues within the molten pool. These errors cause defects like porosity, cracks, and small pores.

Monitoring Technology

Skills and techniques are required to carry out the precise setting and monitoring of the depositing process. Table 2 summarizes research on monitoring molten pool behavior, temperature gradient, flow control, and geometry determination using various types of technology. Adaptability to a high-temperature environment and the ability to closely monitor changes in temperature and the flow of a molten pool are among the most important technological criteria.

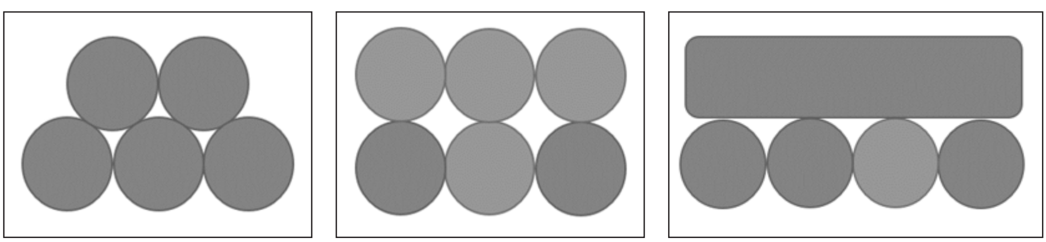
Table 2
Summary of methods used in the molten pool studies in recent research

Reference	Year	Technology used	Observation
Hu and Kovacevic, 2003	2003	A closed-loop control system based on the infrared image	Acquire infrared images of the molten pool real-time, control of the heat input and size of the molten pool
Zeinali and Khajepour, 2010	2010	Charge Couple Device (CCD) camera	Obtain the molten pool height and feedback control
Hofman et al., 2012	2012	Complementary Metal Oxide Semiconductor (CMOS) camera	Obtain the width of the melt pool during a laser AM process, and a Proportional Integral (PI) controller was then used to control the width of the pool during deposition
Clijsters et al., 2014	2014	High-speed near-infrared (NIR) thermal CMOS camera and a photodiode	Obtaining the geometry of the molten pool and the photodiode is used to get the molten pool size
Bai et al., 2018	2018	Process camera (Xiris XVC-1000e)	Obtain images for the characteristic dimensions of deposited bead and molten pool
Su and Chen, 2019	2019	High-speed camera (CR600X2)	Effect of torch angle on the dynamic behavior of the weld pool
Halisch et al., 2020	2020	A high-speed camera and high dynamic range two-colored pyrometric camera (Pyrocam)	Obtain melt pool size measurement in GMAW
Cadiou et al., 2020	2020	High-speed camera (Keyence VM-600 M)	Visualize the melt pool and its interaction with the filler wire
Xiong et al., 2020	2020	Novel virtual binocular vision sensing system including a single camera and a biprism	Monitoring the molten pool geometry
Liu et al., 2020	2021	Fluke TI400 thermographic infrared camera	Measuring the temperatures during the depositions
Mu et al., 2021	2021	Laser scanner	Improve the accuracy and flexibility of the deposited bead.

Built Strategy and Bead Orientation

Planning for an appropriate process Variables such as bead orientation, support structure, number of layers, tool path, and process parameters play a significant role in the production of parts (Ríos et al., 2018). During the profile design phase, the orientation and direction of each layer must be clearly defined (Qin et al., 2021). Bead orientation in welding refers to how a bead is arranged during welding. Vazquez et al. (2021) referred to it as build strategy. In the case of a single layer, the beads may be arranged either side by side or overlapping, as demonstrated by Vazquez et al. (2021). They tilted the torch 20o away from the vertical position to create a bead that had a 50% overlap with its adjacent bead. The bead can be arranged alternately, in line, or perpendicularly for multiple layers, as shown in Figure 8 (a), (b), and (c), respectively. In their study, Cunningham et al. (2018) found that the arrangement of beads can impact heat dissipation, ultimately leading to improved dimensional control.

The orientation may vary depending on the welder's experience in previous decades. The current practice is to automate the appropriate orientation for creating a part, determined by part production criteria. The output varies in physical appearance, width, and height because the molten pool behavior determines the bead orientation specification. For example, if the welding direction is reversed between each layer, the difference in deposition height is modest. However, if the orientation is not changed for the subsequent layering process, the height becomes irregular, with the starting point being higher than the ending point (Shen et al., 2020). Qin et al. (2021) recommend considering several factors related to building orientation to achieve optimal building orientation. These factors include part property, part accuracy, surface quality, support structure, built time, built cost, post-processing time, and post-processing cost. Bead orientation is a critical decision because it affects the formation of the developed profile.



(a) (b) (c)

Figure 8. Different bead formations with the same orientation: (a) alternate; (b) in-line; and (c) perpendicular

WELDING PARAMETERS

The properties and geometry of welds are significantly affected by numerous parameters. The parameters that are commonly referred to when producing a 3D part with WAAM can be divided into two categories: process parameters. These process parameters include welding current, filler feed rate, welding voltage, and welding travel speed. The other category is design parameters, which include cooling rate, material types, build strategy, and deposition path. Since these variables can be altered over a broad range, they are regarded as the most important adjustments in every welding process. The ideal welding bead should possess a consistent width, exhibiting uniform and well-worn ripples integrated into the substrate. In addition, it is important that the welding bead does not burn as a result of excessive heat. In order to determine the optimum bead parameter, it is necessary to conduct a comprehensive examination of each WAAM process. The process includes pre- and post-welding processes, such as designing, machine setup, welding, and cooling.

Parameter optimization and process improvement during the engineering phase can be accomplished by creating a process database for the described processes (Chaudhary et al., 2021).

The welding bead size in height and width is influenced by other factors such as welding torch position, torch angle, flux composition, gas control, and power supply. The parameters must be configured correctly before beginning the welding process because they are linked. In order to experiment, it is necessary to determine the parameters for the WAAM. It can be done by referring to welding preferences, existing research, expert experiences, or gathered data. Many researchers discuss the process parameters, as improper process parameters can lead to the formation of a welding bead of low quality (Halisch et al., 2020). Chaudhary et al. (2021) emphasized the impact of voltage, welding speed, and filler feed rate on penetration depth, bead width, and reinforcement height in their study. The width of the bead was observed to increase significantly with voltage and wire feed rate, but it decreases as the welding speed increases. Even though wire feed rate has a strong beneficial effect on reinforcement, the height of reinforcement decreases significantly with welding speed and marginally with voltage. In order to produce homogeneous material properties in WAAM, it is necessary to control the size of the melt pool (Halisch et al., 2020). The deposition experiments conducted by Ji et al. (2022) also revealed that ultrasonic devices can expand the size of the molten pool.

Temperature dissipation can be measured using various methods, such as pyrometers, thermocouples, and thermal cameras (Pan et al., 2018). The molten zone is where the pool flow occurs, and the direction of its flow during the WAAM process leads to the formation of the welding bead. A preliminary relationship was established between current and droplet diameters to forecast droplet size. According to Jia et al. (2020), the droplets were found to have a minor impact on the behaviors of the molten pool, which led to stable shapes of the molten pool. The X-ray method can observe droplet transfer in the WAAM process (Huang et al., 2022). Current and voltage are the most influential factors on molten pool flow and welding bead (Mai et al., 2021). The other parameters include the distance of the torch from the substrate, the angle of the torch, the speed of welding, the rate of filler feed, and the method of cooling. In the current study, the parameters of interest are displayed in Table 3. Each parameter has distinct effects on mechanical properties, surface finish, and defect formation in parts produced through WAAM. The key is to find the right balance for each parameter based on material characteristics, process requirements, and desired outcomes. Achieving the desired mechanical properties and surface finish and minimizing defects in the final WAAM parts requires careful experimentation, optimization, and continuous monitoring. The radar chart depicted in Figure 9 displays each parameter's significance in producing a satisfactory WAAM part.

Table 3
Welding parameters to be controlled in the WAAM process

Parameters	Effect	Welding Technique	Materials	Reference
Voltage	Controlled voltage: Width of the structure becomes uniform	GMAW	Mild steel	Abe et al., 2020
Current	High current flow: Instability and overflow of the molten pool	GMAW	Copper coated steel	Xiong et al., 2015)
Torch angle	Different torch angles: Change fluid flow stress and pattern flow of the weld pool	GTAW	SS304 stainless steel	Parvez et al., 2013
	Different torch angles: Different sizes of deposited beads	NA	NA	Gao et al., 2017
Welding speed	Speed increase: Fusion zone size decrease	NA	H13 tool steel	Ou et al., 2018
Filler feed rate	Constant filler feed rate: Double-wire surface morphology is better than single-wire process	CMT	Al-Cu-Sn alloy	Wang et al., 2019
	High filler feed rate speed: Overflowing molten pool	Tandem GMAW-WAAM	NA	Shi et al., 2019
Cooling	The cooling system helps to maintain the size of the molten pool.	GMAW	NA	Reisgen et al., 2020

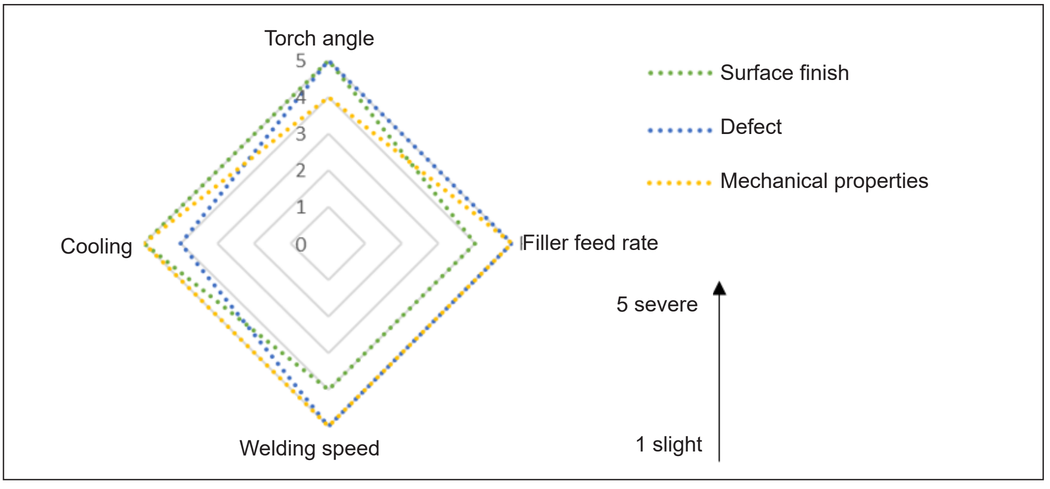


Figure 9. Effect of welding parameters on mechanical properties, surface finish and defects on deposited bead

Torch Angle

Torch angle is an important parameter that can significantly influence the quality of the deposited material and the overall printing process. The torch angle refers to the angle at which the welding torch is positioned relative to the workpiece surface during the deposition of each layer. Typically, a welding torch is moved by a gantry, which can be a machine or a Kuka robot arm. In the case of a simple or straight-line profile, it is customary for the welding torch angle to be perpendicular to the substrate. On the other hand, the position of the torch is determined by the part to be manufactured. The angle of the torch affects both the direction and angle of the heat input into the material. Since heat input is a crucial variable that influences the behavior of pool flow, alterations in torch angle have a noteworthy effect on the dynamics of the weld pool, encompassing the flow of the molten pool and the geometry of the bead. As the heat input increases, the contact area between the substrate and the welding metal also increases.

In their study, Lee et al. (2020) found that a small contact angle results in low heat input. The maximal heat flow from conduction and convection was located at the head of the electrode tip in accordance with the welding direction. As a result, the greatest total heat flux is symmetric along the center of the arc. When the torch angle decreases, the heat flux from conduction and convection also decreases, which leads to a shallow weld pool. The angle of the torch influences both the rate of melting and the size of the weld pool. Incorrect torch angles can lead to uneven heat distribution, resulting in residual stresses within the part. The stresses mentioned may impact mechanical properties, resulting in distortion, warping, or cracking. The shape of the weld, the generation of porosity, and the flow of the weld pool are all affected by different torch angles. Additionally, the deposited beads exhibit varying flaws depending on the torch angle (Bai et al., 2018). Moving in the same deposition direction, the space between the torch and the substrate may vary depending on the angle set. As a result, the space for heat accumulation and the molten pool produced may change.

According to Bai et al. (2018), it is suggested that a torch with a range of 0–10° can be adjusted from its vertical position in the deposition direction. This adjustment can produce well-formed deposited beads with reduced porosity and other flaws. The mobility of liquid metal causes hydrogen bubbles and molecules from the solidification front in the molten pool to travel together (Chen et al., 2020). The generated structures may fluctuate if the interlayer temperature is too low or too high for a particular lead angle. In order to avoid fluctuation effects, it is recommended to push the WAAM technique with a slightly inclined lead angle (Hauser, Reisch, Breese et al., 2021). Selecting the optimal torch angle in WAAM requires striking a balance between achieving the desired part geometry, ensuring good interlayer adhesion, minimizing distortion, and optimizing build speed. As the optimal angle can vary based on factors such as the material, part geometry, and equipment setup, it is essential to conduct systematic testing and optimization to determine the optimal torch angle for a particular WAAM application.

Welding Speed

The welding speed in WAAM refers to the rate at which the welding torch or arc travels along the substrate while depositing material to build up a part. This crucial process parameter directly affects the deposition rate, part quality, and overall efficiency of the additive manufacturing process. The welding speed in WAAM is typically measured in units of length per unit of time, such as millimeters per minute. The optimal welding speed depends on several factors, such as the material being deposited, the wire feed rate, the torch configuration, the part geometry, and the desired quality of the printed part. The speed at which welding occurs is an important factor that influences the quality of the weld—a faster throughput results in a faster welding speed. However, the maximum achievable welding speed is limited for a variety of reasons when it comes to producing a quality weld. The welding torch moves at a speed that the user sets to create a 3D profile. Defects such as porosity, humping, and cracking may occur when an insufficient welding speed is used. The defect known as the humping bead, for instance, is caused by partial solidification occurring in the rear of the bead. When the deposition speed is slow, ineffective heat is supplied to the molten pool.

Welding speeds that are either too fast or too slow may lead to fluctuations in the flow and size of the molten pool, as well as the geometry of the welding bead. Fast welding can cause the weld pool to become excessively large and run ahead of the arc. Additionally, the arc might not have sufficient time to fully melt the substrate, leading to a thin and narrow weld, exhibiting inadequate fusion and penetration. As the welding speed increases, the higher heating frequency raises the substrate temperature while decreasing the heat flux. On the other hand, slow welding speeds may result in excessive bead formation and the arc forming directly above the center of the molten weld pool. The increase in welding speed leads to an increase in weld penetration. The increase in welding speed leads to an increase in weld penetration. The arc causes the penetration of depth; if the penetration is too close to the leading edge of the weld pool, the metal transfer droplets will strike portions of the substrate immediately. The determination of the appropriate welding speed for a specific WAAM application involves the process of experimentation and optimization. Manufacturers and researchers frequently conduct test builds at various speeds to discover the optimal range that offers the finest blend of part quality, deposition rate, and process stability. It is important to consult material-specific guidelines, equipment manufacturer recommendations, and expertise in the field to make informed decisions about welding speed in WAAM.

Filler Feed Rate

The filler feed rate in WAAM refers to the rate at which the filler material, typically in the form of a wire, is fed into the welding process during the additive manufacturing process. The electric arc melts the filler material and is then deposited onto the workpiece to build up the desired part layer by layer. The filler feed rate, a critical process parameter in WAAM, can impact various aspects of the additive manufacturing process and the quality of the printed parts. It is necessary to adjust the feed rates based on the specific welding setups and wire compositions to achieve optimal melting efficiency. Proper feed rate control helps ensure that the filler material is completely melted. A higher filler feed rate typically results in a faster deposition rate, accelerating the build process. However, a high feed rate can lead to issues, such as inadequate melting and fusion of the filler material, which results in poor layer bonding and compromised part quality. According to Ou et al. (2018), the wire feed rate and wire diameter do not significantly affect the heat transfer from the molten pool to the substrate.

However, it was discovered by Xiong et al. (2018) that the stability of the molten pool decreased, and a low-quality welding bead resulted when the filler feed rate was increased. Maintaining a consistent and stable feed rate is essential to achieve a stable welding arc and consistent deposition. Fluctuations in the feed rate may result in irregular deposition and defects. Optimizing material usage and minimizing waste is achieved by balancing the feed rate, welding speed, and other process parameters. Increasing the feed rate allows greater mixing in the additive layer, preventing the filler from melting properly (Paskual et al., 2018). In their study, Hejripour et al. (2018) discovered that the travel speed and feed rate impact mass transport, heat transfer, and fluid flow in different substrates. In order to determine the optimal filler feed rate for a specific WAAM application, it is necessary to conduct experiments and optimize various factors, including welding speed. Manufacturers and researchers frequently conduct tests on builds at different rates to ascertain the optimal combination of part quality, deposition rate, and process stability. When defining filler feed rate selections in WAAM, it is important to consider material-specific concerns, equipment manufacturer guidelines, and field expertise.

Cooling

Implementing a cooling system in WAAM can result in different outcomes that affect both the fabrication process and the properties of the deposited material. The specific outputs of implementing a cooling system depend on various factors, including the cooling method employed, the material utilized, process parameters, and the desired properties of the final part. Cooling, which affects the microstructure, mechanical properties, and overall quality of the printed parts, is an important aspect of any additive manufacturing process, including WAAM. In the WAAM process, the deposited metal layers undergo rapid heating and cooling. Proper part cooling is essential for controlling the thermal gradient and reducing the risk of thermal distortion, cracking, and residual stress buildup. Part cooling can be achieved through various methods, such as fans, water-based cooling systems, or controlled ambient conditions. The cooling effect in WAAM has been extensively studied because it reduces the time required for producing a 3D part. Cooling strategies can be integrated into the planning of the toolpath. Designing toolpaths that incorporate controlled cooling periods makes it possible to regulate the temperature distribution within the part during the deposition process. There are two types of cooling in WAAM, namely free cooling and active cooling (Le et al., 2020).

Natural air is utilized for free cooling, while a cooling system is specifically designed for active cooling. Researchers discussed the cooling effect in molten pool flow to reduce thermal accumulation during the WAAM process. Some of the former cooling systems discussed are cold metal transfer (Scotti et al., 2020; Teixeira et al., 2021; Zhong et al., 2021), the thermoelectric cooling device (Li, Chen et al., 2018), water cooling tank (Kozamernik et al., 2020; Montevecchi et al., 2018), air-jet cooling (Hackenhaar et al., 2020; Montevecchi et al., 2021), and integrated water-cooling channel's substrate (Ogino et al., 2018). Each type of cooling system has a distinct effect on the flow of the molten pool. Heat conduction models have been utilized to predict the shape of weld pools, temperature ranges, and cooling rates of solidified structures. Ogino et al. (2018) created a multilayer 3D model to investigate deposited strategy and cooling conditions in terms of heat input and arc pressure. In their study, Hauser, Reisch, Breese et al. (2021) discovered a relationship between the cooling effect and both the gas flow rate and porosity defect. Specifically, they observed that a higher gas flow rate leads to faster hardening of molten pools, primarily due to enhanced convective cooling. Additionally, this increased gas flow rate also results in the formation of more pores. It is critical to use the proper cooling method because insufficient cooling can disrupt the flow of the molten pool. According to Rodrigues et al. (2019), air cooling can destabilize the arc, and liquid cooling may necessitate additional liquid circulation. Proper cooling aids in attaining uniform solidification and minimizes surface irregularities, thereby resulting in a smoother surface finish.

Adding a post-weld cooling gas improves bead geometry accuracy, improving layer geometry and mechanical properties. This improvement is achieved through grain refinement and the attainment of homogeneous hardness. The width and height of the welding bead vary due to the additional cooling effect. A welding bead with a cooling effect produces a larger bead and aids in grain size refinement compared to one without a cooling effect. It is important to note that WAAM processes can vary depending on the specific equipment, materials, and applications. Cooling strategies, as such, may need to be tailored to the specific requirements of each use case. Proper cooling can result in better part quality, fewer defects, and enhanced mechanical properties in parts produced through WAAM. However, careful planning and tailoring of the implementation of a cooling system are necessary to meet the specific requirements of the WAAM process, material properties, and part design. The optimization of the choice of cooling method, the intensity of cooling, and the placement of cooling devices should be done to achieve the desired outcomes while also avoiding potential challenges such as excessive cooling rates or uneven cooling distribution.

The parameters discussed in this review impact the flow of the molten pool, as well as the geometry and size of the welding bead, either directly or indirectly. However, the research has gaps in considering other factors during developing the WAAM technique for molten pool flow to achieve smooth welding bead geometry and size. Studying other aspects is necessary to optimize specific bead geometry based on requirements. It is important not to focus solely on the addressed parameter but to be proficient in addressing all problems. Various factors, including the physical configuration of the welding table, the surface condition of the substrate, the position of the nozzle, and the presence of nozzle accessories, such as the contact tip and tip holder, can influence the molten pool flow. When the distance between the substrate and the welding torch is adjusted improperly, the contact tip and tip holder adversely affect the welding bead, causing it to clog. The process could benefit from a study that would lengthen the nozzle's useful life. Future WAAM experiments should consider incorporating a reference table. Having such a reference would assist new research in achieving good bead geometry, as opposed to initiating and conducting all experiments from scratch to determine the optimal parameters for wire feed rate, voltage, current, and travel speed. The existing research primarily focuses on a specific material, and some parameters only apply to that specific material and machine. Therefore, the reference tables should include, at the very least, the machine type, range of setup parameters, and material type. Orientation and built strategy should also be well discussed in relation to the other welding parameters.

CONCLUSION

The flow of molten pools and the geometry of beads are inextricably linked, and controllability improves process efficiency. A good molten pool flow will lead to an excellent deposited bead in shape, size, and quality. The parameters that influence bead geometry and molten pool flow are generally similar. During the review, the following issues were discovered:

1. The space of the molten pool changes depending on the position of the welding torch. Applying a slight welding angle to the direction of welding movement results in a more stable flow of the molten pool and produces a high-quality weld bead.
2. If the welding travel speed is not configured correctly, the flow of the molten pool and the formation of the weld pool are improper. As the welding travel speed increases, the welding bead becomes thinner and narrower, leading to less penetration.
3. An unstable pool flow may occur due to a higher wire feed rate, as the molten pool has not yet formed while the filler wire continues to be dispensed. Poor welding bead geometry is typically produced due to an unstable filler feed rate, which results in inadequate melting of the filler material.

4. Recently, cooling methods have been widely introduced to shorten cooling time. Although the cooling effect slightly influences the molten pool flow and the bead geometry, it assists the WAAM process in reducing the number of defective parts produced.
5. The demands for bi-metal WAAM may pose more challenges as the material behavior may differ and require greater attention.

Based on the review, a few recommendations can be made for improving the quality and efficiency of the deposited bead, such as the following:

1. Implementing automated systems like machine learning and artificial intelligence aims to control bead geometry. It is done to meet the requirements of profile complexity and process repeatability.
2. It is crucial to have reliable and efficient optimization tools for tackling various parameters in the unique applications of part repair, where the part profile may not be standard.

ACKNOWLEDGEMENT

The authors thank Universiti Sains Malaysia (USM) for the technical and providing facilities for this experiment to be conducted successfully. The authors also gratefully acknowledge USM for being supported under the research project RUI Grant and Short-Term Grant (Grant No: 1001/PMEKANIK/8014031 and 304/PMEKANIK/6315332).

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