



Characterising and modelling plasma transferred arc for additive manufacturing

Guangyu Chen, Yongle Sun , Chong Wang ^{*}, Jialuo Ding, Wojciech Suder , Zhiyong Li, Stewart Williams

Welding and Additive Manufacturing Centre, Cranfield University, Bedfordshire, MK43 0AL, UK

ARTICLE INFO

Keywords:

Additive manufacture
Directed energy deposition
Plasma transferred arc
Power density distribution
Heat source model

ABSTRACT

The thermal characteristics of a plasma transferred arc (PTA) and its mathematical representation are primary considerations when designing and modelling PTA-based wire arc additive manufacturing (WAAM). However, most of the currently used PTA thermal characteristics are derived from welding processes, which are not directly applicable to WAAM. In this study, the power density distribution, arc diameter and arc efficiency of PTA in the WAAM process were measured using the split anode calorimetry (SAC) method. The effects of key process parameters, including current intensity, plasma gas composition, plasma gas flow rate, and arc length, on the PTA power profile were systematically examined. The results show that for a typical PTA used in WAAM, the arc diameter ranged from 9.6 mm to 10.8 mm, with an arc efficiency of approximately 60 % within the tested parameter range. The PTA power becomes more concentrated as power density increases with higher current intensity and plasma gas flow rates. Additionally, a softer plasma was achieved by increasing helium content in the plasma gas or by using a longer nozzle-to-workpiece standoff distance, both of which are beneficial for avoiding keyhole defects. To accurately represent PTA power distribution, a binomial Gaussian heat source model was proposed, which captures the details of the arc power profile with a high accuracy of over 99.94 %, outperforming the conventional monomial Gaussian heat source model. The PTA calorimetry characterisation and the proposed binomial Gaussian model can be useful in establishing a better understanding of the PTA power profile and enhancing process control for high-precision WAAM.

1. Introduction

Additive manufacturing (AM) has become an increasingly adopted net/near-net shaping technology that boosts the industrial applications of rapid prototyping and sustainable manufacturing. AM offers numerous advantages over conventional subtractive manufacturing, including reduced material waste, shorter lead times, and higher design flexibility [1]. Among the various AM techniques, wire arc additive manufacturing (WAAM) is particularly suited for producing large metallic components owing to its higher deposition rate compared to other processes such as powder bed fusion. Plasma transferred arc (PTA) is one of the most widely used heat sources in the WAAM process due to the advantages of its high energy density, stable arc condition and wide working envelope, which ensure a higher deposition rate and better deposition quality compared to other heat sources such as gas tungsten arc (GTA) and gas metal arc (GMA). Recognising the benefits of the PTA,

many researchers have focused on the study of the PTA-based WAAM process. For example, Martina et al. [2] introduced a PTA-based WAAM method for the deposition of Ti-6Al-4V. Wang et al. [3] studied the correlation between wire diameter and deposition rate in the PTA-based WAAM of Ti-6Al-4V.

To achieve high accuracy and good process prediction in PTA-based WAAM, the mechanism behind the process, especially the thermal behaviour, needs to be studied. A numerical approach is one of the most effective ways to study the mechanism of the PTA deposition process. In this way, a mathematical model of the energy distribution of the heat source is essential for simulating the WAAM process. Chen et al. [4] simulated the coupling behaviours of wire melting, metal transfer and melt pool dynamics of a PTA-based WAAM process. Wang et al. [5] developed a three-dimensional (3D) steady-state finite element model with two independent circular surface heat sources for a hybrid PTA-laser AM process. Despite the innovative contributions, most of the

^{*} Corresponding author.

E-mail address: chong.wang1@cranfield.ac.uk (C. Wang).

<https://doi.org/10.1016/j.ijheatmasstransfer.2025.126735>

Received 22 November 2024; Received in revised form 1 January 2025; Accepted 18 January 2025

Available online 23 January 2025

0017-9310/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

previous studies used empirical heat source models, such as the Gaussian model and double ellipsoid model. Although these models have evolved over decades to improve accuracy, they often fall short of representing the actual energy distribution. Rosenthal [6] first proposed a series of simplified point and line heat source models for welding processes. The simplification of the heat source enabled the derivation of an analytical solution to the temperature field generated by welding. However, these models had limited accuracy due to the oversimplification of the energy distribution. To overcome the limitation, Pavelic et al. [7] presented a surface Gaussian distribution model for welding arc energy, which achieved better agreement with experimental measurements and hence was widely applied in welding simulations [5]. Subsequently, the Gaussian distribution model was extended from 2D to 3D. For instance, Goldak et al. [8] introduced a double ellipsoidal heat source model based on a 3D Gaussian distribution of power density for modelling high-penetration arc welding. Wang et al. [9] further proposed a Gaussian-based conical heat source model to better represent deep-penetration welding processes, such as the keyhole PTA process. However, the heat source models presented in the previous research relied on fitting temperature measurements to determine the empirical parameters included in the models, meaning that the heat source model is not necessarily a representation of the actual energy distribution but rather an empirical tool providing the basis of a thermal model for reproducing the temperature field associated with a welding process. Consequently, these empirical models are not useful for understanding the characteristics of the heat source. This issue is also pertinent to the WAAM process, the simulations of which usually adopt the welding heat source models.

To establish a realistic heat source model, an accurate measurement of the energy distribution is needed. Many researchers have conducted studies to characterise the power profiles of electric arcs. Haddad et al. [10] measured the temperature distribution in a free-burning argon arc at atmospheric pressure using spectroscopic techniques. Thornton [11] used the normalised spectroscopic method to measure the temperature distribution of a GTA with a number of different spectral lines. Langmuir et al. [12] introduced a Langmuir probe method, named after its inventor, to allow researchers to measure low-pressure plasma using an electrostatic probe from the inside of its plasma body. Fanara et al. [13] introduced a simple apparatus for the study of low-current GTA. Nestor [14] proposed a split anode calorimetry (SAC) method to measure high-current GTA. Due to its non-invasive nature and high feasibility compared to other arc measurement techniques, the SAC method has become widely adopted for measuring energy distributions in various types of electric arc sources.

Most of the previous research focused on the measurement of GTA, and few of them focused on the measurement of PTA. The presence of the restricted plasma gas in PTA plays a critical role in concentrating the energy of the arc. As a result, the energy distributions of the GTA and PTA are significantly different. Richardson [15] examined the influence of ambient pressure on the behaviour and characteristics of the constricted gas tungsten (plasma) welding arc using the SAC method. The influence of process parameters on arc structure and energy transfer at the anode was investigated. Chen et al. [16] developed a modified SAC device for the measurement of the PTA power profile. The modified SAC has ground positions located underneath the centre of the arc that can reduce the arc distortion during measurements. These researchers have made great contributions to the energy distribution measurement of PTA. However, further characterisation is still needed to reveal the effects of various parameters (e.g., plasma gas flow rate and torch stand-off distance) on the energy distribution of the PTA. In particular, a limited number of studies have been conducted on the energy distribution of the PTA for the WAAM process, which is different from PTA welding in various aspects. For example, in welding, a focused arc is necessary to achieve high penetration and efficiency. In WAAM, however, a soft plasma with a wider profile is preferred to prevent the formation of keyhole defects.

From the above review of the literature, we identified a need for the PTA energy profile as a function of process parameters and the implications for characterisation and modelling of a PTA being used for WAAM. In this study, the SAC method was utilised to measure the power distribution of a PTA typically used in WAAM. The power profiles were characterised under varying current intensities, plasma gas compositions (PGC), plasma gas flow rates (PGFR) and arc lengths, and the effects of these factors on the power distribution were analysed. Furthermore, the energy source modelling for PTA was carried out based on the typical parameters adopted in WAAM applications. The limitations of the conventional monomial Gaussian heat source model were assessed. A binomial Gaussian heat source model was introduced to provide a more accurate description of the PTA power distribution, and its generic form could be incorporated into numerical simulations of WAAM processes. The findings from this PTA characterisation and modelling can benefit the melt pool control in WAAM for facilitating high-precision deposition and improving the numerical simulations. Apart from the WAAM process, the results of this study could also be valuable for low-penetration PTA welding and cladding applications.

2. Experimental and modelling methods

2.1. SAC for PTA characterisation

2.1.1. Materials and equipment setup

Fig. 1 illustrates the central grounded SAC setup used for measuring the PTA power profile. Two cooling water slots were machined in separate aluminium holder bases as the lower halves of two cooling channels (Fig. 1c). Two oxygen-free copper anodes with dimensions of 95 mm × 90 mm × 10 mm were fixed onto the aluminium bases. Two more water slots were machined at the bottom of the copper plates as the upper halves of the two cooling channels. Two Viton O-ring seals were placed between the copper anodes and the aluminium bases to prevent water from leaking. Two separate cooling channels were formed when placing the copper anodes on the top of the aluminium bases. A set of brass screw baffles was mounted in the copper slots to increase turbulence and mixing of water. A gap between those two anodes was set using a 75 µm thick heat and electrically resistant polyamide film (DuPont® KAPTON® HN' 3 mil'). Four K-type thermocouples were placed at the inlets and outlets of the cooling channels to measure the temperature changes of the cooling water. Two turbine flow meters were placed within each water circuit to monitor the flow rate of the cooling water. A chiller with refrigeration was used to pump and cool down the water for both cooling circuits. The inlets of the cooling circuits were placed close to the anode interface to provide a lower water temperature for the arc section. Two ground wires were placed at the bottom of the aluminium bases under the position of the arc. By using this configuration, the distance difference between the ground wires and the arc section was minimised, and arc distortion can be reduced [16]. The arc current flows through the SAC from the upper surface of the copper anode to the ground connectors at the bottom of the aluminium base.

2.1.2. Methods

The power profiles of the PTA with different current intensities, PGCs, PGFRs and arc lengths were measured. The arc length is primarily determined by the nozzle-substrate distance (NSD), as shown in Fig. 1b. The electrode setback was kept fixed at 2.4 mm. Four types of shielding gas were used to provide different PGCs: Pureshield argon gas was used as pure argon, Alushield Light, Alushield Universal and Alushield Heavy welding gases were used as argon/helium composite gas with helium compositions of 30 %, 50 % and 75 %, respectively. Table 1 lists the fixed parameters used in the measurements, while Table 2 lists the variable parameters of which the effects were investigated.

Two National Instruments NI 9211 and NI 9361 data logger modules were used to acquire temperature and water flow data. A Triton P349 data logger was used to collect current and voltage data. All

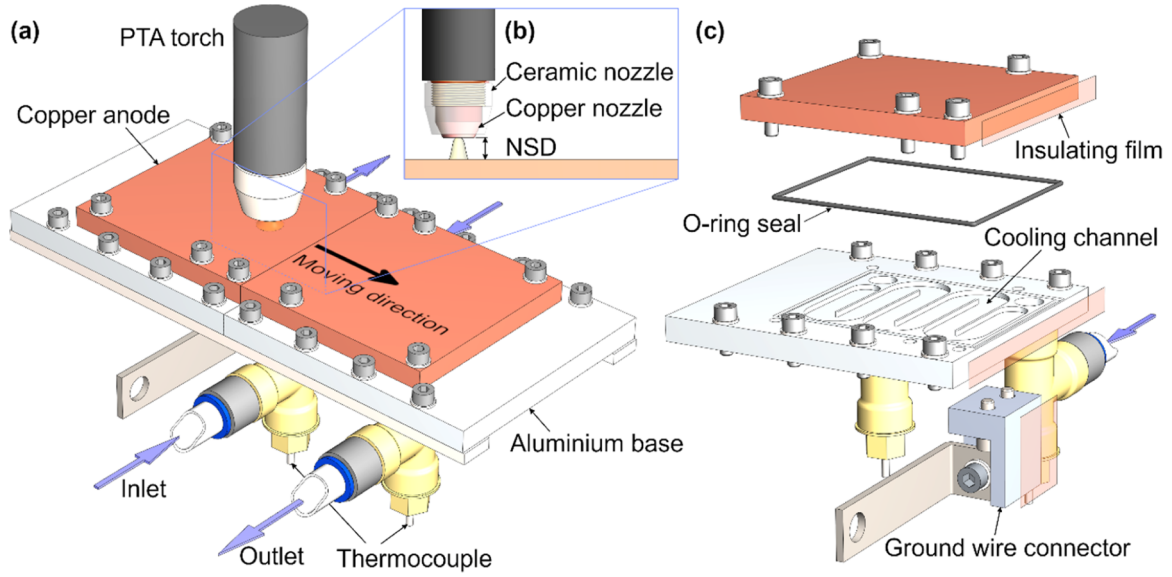


Fig. 1. (a) Configuration of the SAC setup for PTA power profiling, (b) illustration of the nozzle-substrate distance (NSD), and (c) exploded view of the inner cooling channel and the ground connector underneath.

Table 1

Fixed parameters for the PTA measurement.

Shielding gas / (L/min)	15
Orifice size / (mm)	3.9
Electrode diameter / (mm)	4
Electrode Tip Angle / (degree)	40
Electrode Tip Set-back / (mm)	2.4

Table 2

Variable parameters for the PTA measurement.

Current / (A)	PGFR / (L/min)	PGC	NSD / (mm)
110	0.8	Pure Ar	8
130			
150			
130	0.2		
	3.0		
	5.0		
	0.8	75 % Ar + 25 % He	
		50 % Ar + 50 % He	
		25 % Ar + 75 % He	
		Pure Ar	6
			8
			10

experimental data were collected and recorded using LabVIEW software and processed using Excel and Matlab software on a personal computer. During the measurements, the PTA torch moved across the interface between the copper anodes with an increment of 0.2 mm. The whole interface traversing of the arc was divided into 100 increments. 30 s was applied for each increment keeping the PTA torch stationary and allowing stabilisation of water temperature. Measurement of the water temperature was taken from the 15th second to the 30th second of each increment to ensure that a stabilised temperature was taken.

The power that each copper anode received at each increment can be calculated using either Eq. (1) with the temperature data or Eq. (2) with the current data:

$$Q_{temp} = (T_{out} - T_{in})C_{water}M_{water} \quad (1)$$

$$Q_{current} = IU \quad (2)$$

In Eq. (1), Q_{temp} represents the power that each anode receives at each

increment calculated from the temperature data, T_{out} and T_{in} are the water temperatures at the outlet position and the inlet position, C_{water} is the specific heat of water and M_{water} is the mass flow rate of the cooling water. In Eq. (2), $Q_{current}$ represents the power that each anode received at each increment calculated from the current data, I is the split current that flows through each of the copper anodes, and U is the voltage of the arc. It is noteworthy that the power amount calculated by Eqs. (1) and 2 is the partial power received by each anode. The total power amount should be the summation of the power amounts received by two anodes.

The power per increment ΔQ_i was measured using Eq. (3). Q_i represents the power that one of the copper anodes received, as calculated from Eq. (1) or 2, in each increment.

$$\Delta Q_i = Q_{i-1} - Q_i \quad (3)$$

By associating each ΔQ_i with the position of the corresponding increment, the distribution of the energy profile was generated. It is worth noting that this profile is a 1D profile directly converted from the acquired data. This profile represents the power distribution along the arc advancing direction, and each point means the power integrated along the split anode interface direction at each increment. The power profile generated from the current data could be considered as the theoretical power profile of the PTA before being absorbed by the substrate, and the power profile generated from the temperature data could be considered as the profile of the power absorbed by the substrate surface [16]. Repeated measurements were applied when measuring a single PTA to get an averaged result.

Before the modelling of the PTA power profiles, the profiles measured by the SAC were symmetrised based on the axial symmetric assumption. A central line for each measured profile was determined by dividing the power into two equal parts, and the symmetrised profile was then obtained by averaging two sides of the central line. The symmetrised profile was then processed and smoothed using a Savitzky-Golay smoothing filter [17] in Matlab software.

The size of the PTA can be defined by the area that contains 86.6 % of the total power, as shown in Fig. 2, which is also known as D86 [18]. Arc efficiency η was determined by dividing the absorbed power by the input power, which can be calculated by dividing the temperature data-calculated power Q_{temp} with the current data-calculated power $Q_{current}$, as shown in the following equation:

$$\eta = \frac{Q_{temp}}{Q_{current}} \quad (4)$$

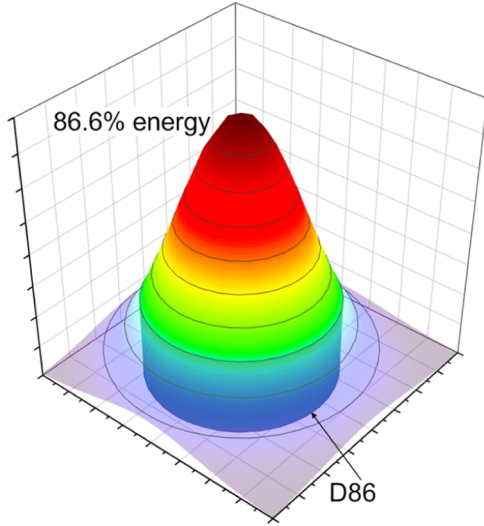


Fig. 2. Illustration for the definition of the D86 profile diameter.

2.2. Modelling of PTA power profile

The measurement of the PTA power profile is based on the temperature and current on the planar copper surface. Therefore, the planar surface heat source model was analysed and modelled in this study. After the measurement of the PTA power profile, heat source modelling was performed by adopting the conventional monomial Gaussian distribution and proposing a new binomial Gaussian distribution, and the accuracy of the two heat source models for representing a PTA was compared. The modelling was focused on a typical set of PTA-based WAAM process parameters, as shown in Table 3. Pearson correlation coefficient (PCC) [19] was calculated to evaluate the efficacy of the heat source model for fitting the measured PTA power profile.

2.2.1. Monomial Gaussian model

The Gaussian distribution, also known as the normal distribution, has been widely used by the welding community to represent the power distribution of an electric arc. Eq. (5) expresses the function of a 2D axial symmetric Gaussian heat source distribution:

$$Q(x, y) = \frac{Q}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \quad (5)$$

where x and y are the relative position coordinates to the centre of the distribution, and σ is the standard deviation factor that determines the domain size of the distribution. When using the Gaussian distribution to represent a heat source model, a multiplier Q can be added to define the total power amount.

Another variant of the Gaussian distribution heat source model is also widely used in the numerical simulation of welding, as presented below:

$$Q(x, y) = \frac{3Q}{\pi r^2} \exp\left(-3\frac{x^2 + y^2}{r^2}\right) \quad (6)$$

$$r = \sqrt{6}\sigma \quad (7)$$

Table 3

Process parameters used for the modelling of PTA power profile.

Current / (A)	PGFR / (L/min)	PGC	NSD / (mm)
110	0.8	Pure Ar	8
130			
150			

where the standard deviation σ is replaced by a spot size factor r and the power density drops to 5 % peak density when the distance to the centre is equal to r . When using a Gaussian function, the standard deviation σ , or the spot size factor r , determines the concentration of power distribution. Therefore, it is essential to find a proper range of σ or r for the heat source modelling. For the expression in Eq. (5), the values within the range of $(-1.5\sigma, 1.5\sigma)$ account for 86.6 % of the total integral. In other words, D86 is equal to 3σ , or $\sqrt{6}/2r$.

The power profile measured using the SAC method is not a 2D distribution, but rather an integrated 1D distribution along the moving direction of the arc. Assuming that the arc body is axially symmetrical, an Abel inversion could be applied to convert a 1D profile to a 2D profile [14]. However, the Abel inversion might not be necessary when using a 2D Gaussian model to represent an electric arc energy source because its integrated 1D profile would still be a 1D Gaussian distribution, as shown in Eq. (8):

$$Q(x) = \frac{Q}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad (8)$$

In this 1D Gaussian distribution, the standard deviation σ and the total power amount Q remain unchanged. This means that the measured 1D profile could be directly fitted by a 1D Gaussian model, and its 2D counterpart could be calculated accordingly. Therefore, in this study, the measured power profiles were not converted by Abel inversion.

2.2.2. Binomial Gaussian model

To overcome the limitations of the monomial Gaussian model, which will be discussed in Section 3.2.1, a binomial Gaussian model was introduced to achieve a more precise fitting of the PTA energy source. Eqs. (9) and 10 express the functions of the 2D and integrated 1D binomial Gaussian model:

$$Q_{c2d}(x, y) = \frac{1}{2\pi} \left[\frac{Q_1}{\sigma_1^2} \exp\left(-\frac{x^2 + y^2}{2\sigma_1^2}\right) + \frac{Q_2}{\sigma_2^2} \exp\left(-\frac{x^2 + y^2}{2\sigma_2^2}\right) \right] \quad (9)$$

$$Q_{c1d}(x) = \frac{1}{\sqrt{2\pi}} \left[\frac{Q_1}{\sigma_1} \exp\left(-\frac{x^2}{2\sigma_1^2}\right) + \frac{Q_2}{\sigma_2} \exp\left(-\frac{x^2}{2\sigma_2^2}\right) \right] \quad (10)$$

$$Q_{c2d} = Q_{c1d} = Q_1 + Q_2 \quad (11)$$

Here, Q_{c2d} is the 2D binomial Gaussian model, and Q_{c1d} is the integrated 1D binomial Gaussian model. The binomial Gaussian model consists of two Gaussian terms which are defined respectively as the major term and the secondary term. The total power amount (Q_{c2d} or Q_{c1d}) was divided into two parts, which are Q_1 and Q_2 . These two parts can be adjusted accordingly and provide higher flexibility for profile fitting.

3. Results and discussion

3.1. Measured PTA thermal characteristics

Among the various thermal characteristics of PTA, power density distribution is a fundamental aspect for understanding PTA-based WAAM processes, as it directly influences the thermal behaviour, material deposition quality, and microstructural characteristics of the deposits. Arc diameter is another critical factor, which significantly influences the bead width of the deposited track. Additionally, arc efficiency is essential for defining the heat source conditions in numerical simulations of PTA-based WAAM processes. Therefore, the analysis in this section will focus on examining the power density distribution, arc diameter, and arc efficiency of PTA under varied process parameters. Moreover, the theoretical input power of an electric arc is determined by the product of the arc current intensity and the voltage. In a non-consumable-electrode process, the arc voltage serves as an indicator of arc input power, given that the current intensity remains constant. This

aspect will also be discussed in this section.

3.1.1. Effect of current intensity

Fig. 3a and b show the power density distributions of PTA at three different current intensity levels generated from current and temperature data, respectively. Overall, the profiles obtained from both methods expanded with higher peak and wider out-reaching when increasing the current intensity from 110 A to 150 A. Specifically, both the current and temperature-generated power profiles show irregular top shapes, where the power peak deviated from the centre of the arc and presented in a ramp shape at a current intensity of 110 A. As the current intensity increased, the power peak was gradually centralised, and the top shape turned from a ramp shape to a symmetric conical shape. This indicates that the stiffness of the plasma column was enhanced with higher current intensity and voltage [20], and the arc distortion was eased. The stiffness of the PTA is important in the WAAM process to ensure consistency of the deposition and guarantee the geometric accuracy of the printed products.

Fig. 4 shows the correlation between the current intensity and arc diameter. The diameter of both the current and temperature-generated profiles show an increase with increasing current intensity. Specifically, the arc diameter calculated from temperature data ranges from 9.6 mm to 10.8 mm, while the arc diameter derived from current data ranges from 6.8 mm to 7.6 mm. In Richardson's work [15], the arc diameter calculated from current data in PTA welding increased from 6 mm to 7.6 mm with current intensity increased from 60 A to 100 A. The arc diameter was calculated by encompassing 90 % of the total current, which is larger than the D86 diameter that includes 86.6 % of the current. Despite this difference in calculation method, the arc diameters closely aligned with the measurements obtained in the present study.

The arc efficiencies at different current intensities are shown in Table 4. Within the tested range, arc efficiency slightly decreased from 62 % to 59 % as current intensity increased. Previous studies on PTA and GTA processes have reported similar findings. Evans et al. [21] studied the arc efficiency of plasma arc welding with variable polarity, observing a decrease in arc efficiency from 66 % to 53 % as current intensity increased from 110 A to 130 A. Niles et al. [22] examined the power density distribution in the GTA process, finding that arc efficiency dropped from 60 % to 30 % as current levels rose from 125 A to 225 A. There are two main reasons for the decrease in arc efficiency at a higher current intensity. First, a higher current intensity leads to a higher arc temperature. The energy loss to the surroundings by convection and radiation is thereby increased with a higher thermal gradient. Second, the size of the power profile can be expanded. Consequently, a larger arc area can further cause faster energy loss through convection and radiation. It should be mentioned that the arc efficiency has no direct correlation with the distortion of the power density distribution. The improvement of the uniformity of the power density distribution is

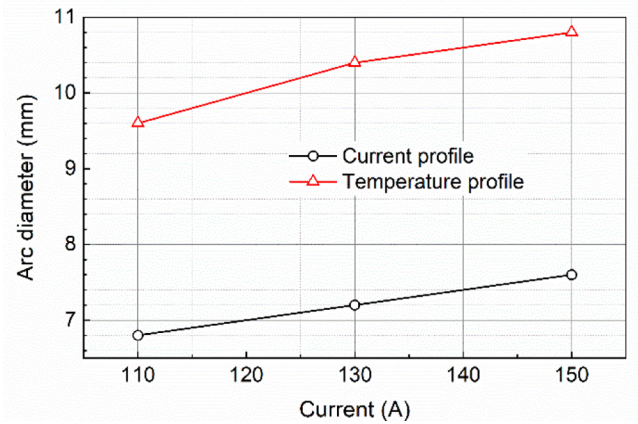


Fig. 4. Arc diameter as a function of current intensity.

Table 4

The voltage level and arc efficiency with varying current intensity.

Current / (A)	Voltage / (V)	Arc efficiency
110	22.0	62 %
130	23.2	61 %
150	24.4	59 %

attributed to the increased current density and arc stiffness, while the reduced arc efficiency at higher current is due to the higher thermal loss to the surroundings through radiation and convection.

3.1.2. Effect of plasma gas composition

Fig. 5 shows the power density distributions at four different PGCs derived from both current and temperature data. As the helium content in the plasma gas increases, the profiles transition from a cone shape to a rounded-top shape, indicating a decrease in arc power concentration. In the study by Zijp et al. [23], the electron density profile of a helium-containing arc was reported to be flatter compared to that of a pure argon arc, which aligns with the variation in power density distribution obtained in the present study. The possible explanation of the variation of electron density was also given by Zijp et al., which is that helium tends to concentrate at the centre of the arc, and this effect has been corroborated by previous studies using light and mass spectroscopic experiments [24,25]. Tsai [26] studied the characteristics of a helium-argon tungsten arc in comparison to a pure argon tungsten arc. The arc power profiling results indicated that a 50 % Ar + 50 % He mixture produced a broader heat distribution than a pure argon arc, particularly when the arc length exceeded 4 mm. These findings are in agreement with the measurements obtained in the present study.

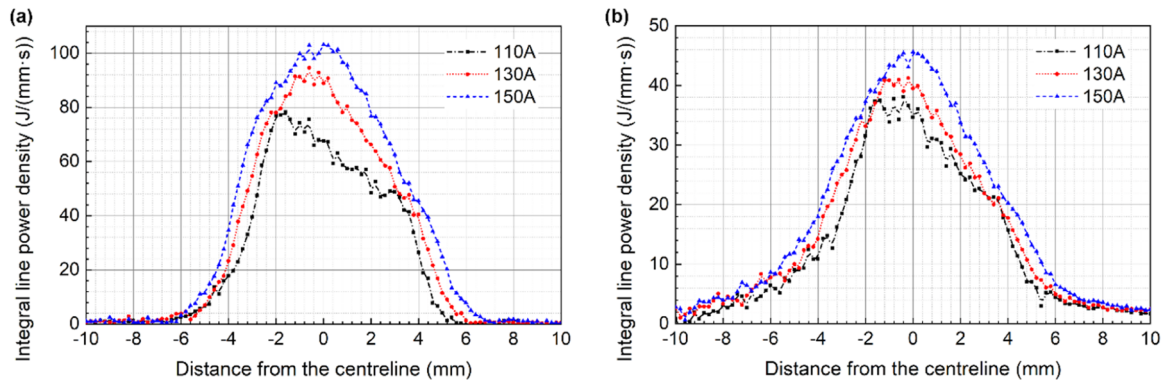


Fig. 3. PTA power profiles with varied current intensity ranging from 110 A to 150 A: (a) current data generated profiles, and (b) temperature data generated profiles.

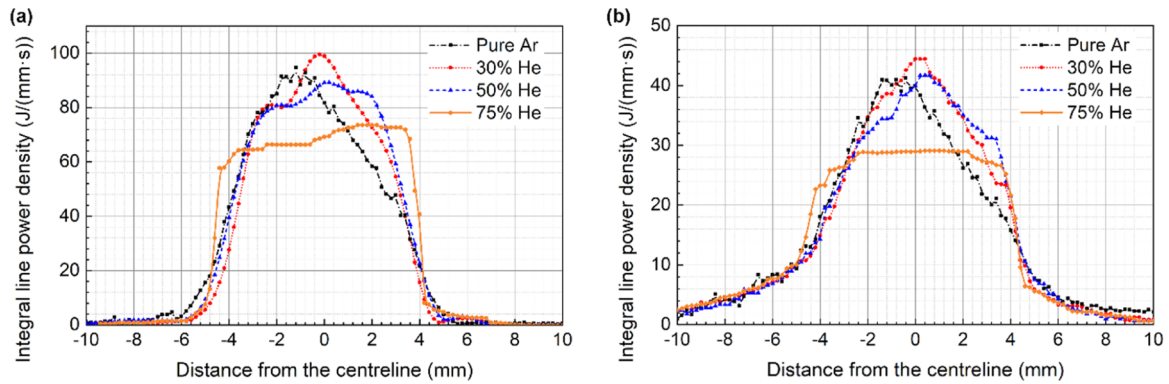


Fig. 5. PTA power profiles with helium content ranging from 0 % to 75 %: (a) current data generated profiles, and (b) temperature data generated profiles.

Fig. 6a shows the effect of helium content on arc diameter. For both current and temperature data-generated profiles, the arc diameter decreases slightly with helium addition to the plasma gas, though the overall change remains minimal. The peak power density is a key factor in determining the keyhole formation in PTA-based WAAM. Fig. 5 shows a decreasing trend in peak power density with the increase in helium content. The correlation between the peak power density and helium content is further detailed in Fig. 6b. The power density increased slightly from 0 % to 30 % helium content, but showed a substantial decrease from 30 % to 70 %, dropping from 100 J/(mm·s) to 73 J/(mm·s) in the current-derived data, and from 44 J/(mm·s) to 30 J/(mm·s) in the temperature-derived data. This indicates that adding more than 30 % helium to the plasma gas reduces the peak power density of PTA, thereby decreasing the likelihood of keyhole defect formation in PTA-based WAAM.

Table 5 presents the voltage and arc efficiency at different PGC levels. During the tests, the current intensity remained constant, while the voltage increased with higher helium content. This increase can be attributed to the higher ionisation potential of helium, which requires a greater voltage drop across the arc column compared to an argon plasma body [27]. Similarly, in Tsai's study [26], the voltage of a GTA increased with the helium content in helium-argon shielding gas mixtures. The arc efficiency of the PTA was also influenced by the PGC, decreasing as helium content increased. This could be attributed to the fact that the thermal conductivity of helium is higher than that of argon, and the energy loss through convection is higher.

In WAAM, surface waviness is a critical factor as it dictates the amount of material that must be machined off to achieve the desired surface quality. It has been reported that adding helium to the plasma gas increases heat input and reduces arc pressure, causing the melt pool to spread laterally [28]. This results in a wider and flatter bead geometry, which helps reduce surface waviness and enhances material utilisation efficiency.

Table 5

The voltage level and arc efficiency with varying PGC.

PGC	Voltage / (V)	Arc efficiency
Pure Ar	23.2	61 %
30 % He	23.3	57 %
50 % He	24.3	55 %
75 % He	24.8	51 %

3.1.3. Effect of plasma gas flow rate

Most previous studies on PTA power profile have primarily focused on welding applications with high PGFR. However, in the PTA-based WAAM process, a lower PGFR is typically chosen to reduce arc pressure and prevent the formation of keyhole defects, thereby ensuring stable deposition [2]. Therefore, it is essential to understand how low PGFR affects the PTA thermal characteristics in WAAM.

Fig. 7 shows the power density distributions generated from both current and temperature-generated data across five different PGFRs. The shape of the power profiles expanded in radial direction in both graphs when increasing the PGFR from 0.2 to 5.0 L/min. Fig. 8 shows images of the PTA to understand the influence of PGFR on the arc power profiles. It can be observed that the bottom of the plasma body was spread by the solid-state water-cooled copper surface when increasing the PGFR. However, in Fig. 7, the peak levels of the current data-generated profiles were barely changed, while the peak levels of the temperature data-generated profiles increased almost linearly with PGFR. This difference occurs because the temperature-derived results account for arc efficiency, which rises with higher PGFR. The increase in arc efficiency will be introduced later in this section.

During testing, no melt pool was formed due to the relatively low current and the use of water cooling device. It is important to note that in actual WAAM applications, where a liquid melt pool forms, the power density distribution may differ, especially if a keyhole forms, causing a

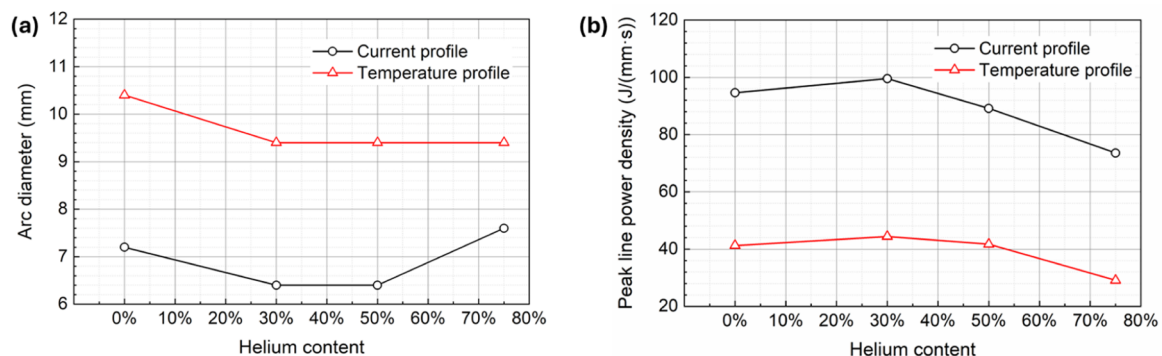


Fig. 6. (a) Arc diameter and (b) peak power density as a function of helium content in plasma gas.

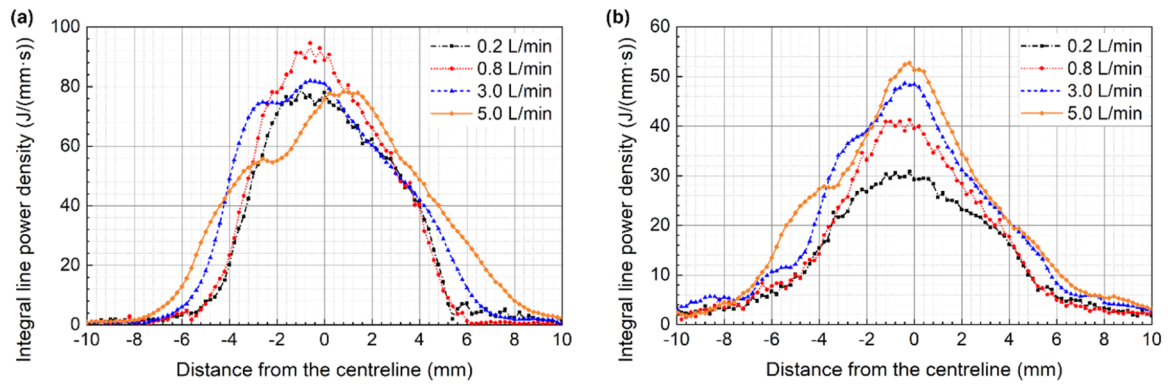


Fig. 7. PTA power profiles with varied PGFR ranging from 0.2 L/min to 5.0 L/min: (a) current data generated profiles, and (b) temperature data generated profiles.

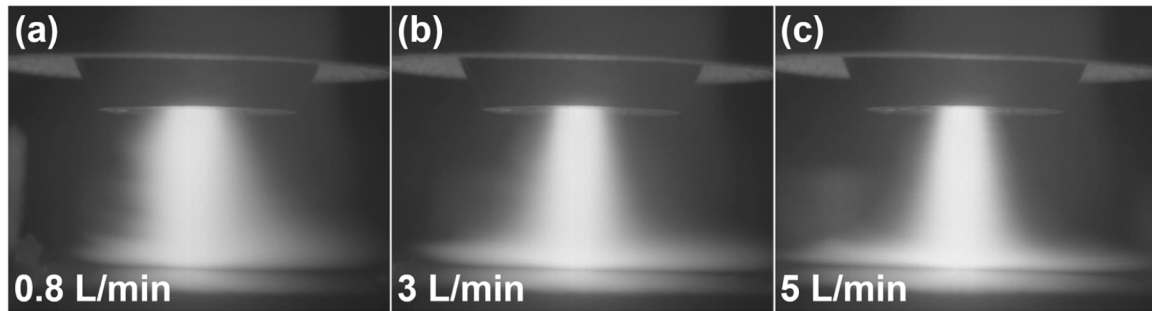


Fig. 8. Images of the PTA with different PGFR: (a) 0.8 L/min, (b) 3 L/min, and (c) 5 L/min.

depression in the melt pool. However, the melt pool surface geometry is closer to a flat solid surface with a lower arc pressure when using low PGFR. Therefore, the results with lower PGFR presented in this study are feasible to meet the conditions in the WAAM practice. The arc diameter of both current and temperature generated profiles measured by the SAC slightly decreased when the PGFR increased from 0.2 to 0.8 L/min, and then increased when the PGFR increased from 0.8 L/min to 5 L/min, as shown in Fig. 9.

As shown in Table 6, the arc voltage increased from 22.5 V to 27.2 V as the PGFR increased from 0.2 L/min to 5.0 L/min. Correspondingly, the total power also increased significantly with the increased PGFR. In addition, the arc efficiency increased almost linearly from 55 % to 69 %. This effect is due to the contraction of the arc column as PGFR increases, as observed in Fig. 8, which reduces the convection area with its surroundings and decreases heat loss. This explains the notable rise in peak power density values from the temperature data derived profiles as

Table 6

The voltage level and arc efficiency with varying PGFR.

PGFR / (L/min)	Voltage / (V)	Arc efficiency
0.2	22.5	55 %
0.8	23.5	61 %
3	25.2	67 %
5	27.2	69 %

discussed earlier. Therefore, when studying WAAM applications with a relatively low PGFR, it is important to adopt a lower arc efficiency than that typically used in conventional welding applications.

3.1.4. Effect of arc length

The arc length could be altered due to the inconsistent layer height during the PTA-based WAAM process. This could lead to changes in power density distribution and result in inconsistent melt pool shapes, which can negatively impact the overall deposition quality. Therefore, understanding the influence of arc length on the PTA power profile is crucial for maintaining process stability and ensuring high-quality deposition.

Fig. 10 shows the effect of arc length on the power density distribution of the PTA. The arc profile changes noticeably with arc length, with both current and temperature data-derived results showing lower peak values and broader profile ranges as the arc length increases from 6 mm to 10 mm. This indicates that the PTA power density becomes less concentrated and more widely distributed as the electrode moves farther from the substrate.

Fig. 11 shows that as the arc length increases from 6 mm to 10 mm, the arc diameters calculated using the current data and temperature data increased from 6.8 mm to 10.2 mm and from 9.6 mm to 13.2 mm, respectively. Fig. 12 shows the corresponding arc profiles at different NSDs. Tsai [26] reported that the diameter of a GTA increased rapidly with arc length, which is consistent with the PTA results achieved in this

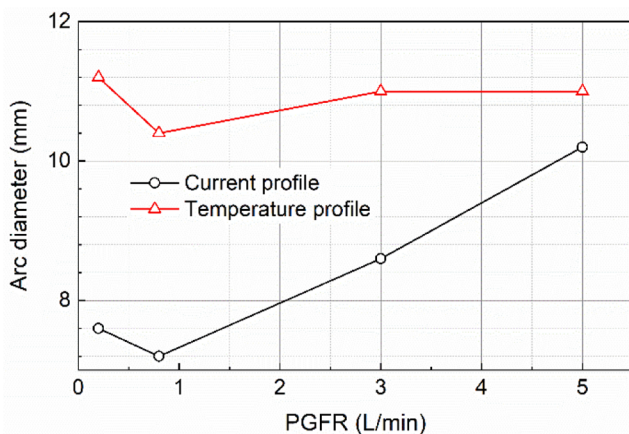


Fig. 9. Arc diameter as a function of PGFR.

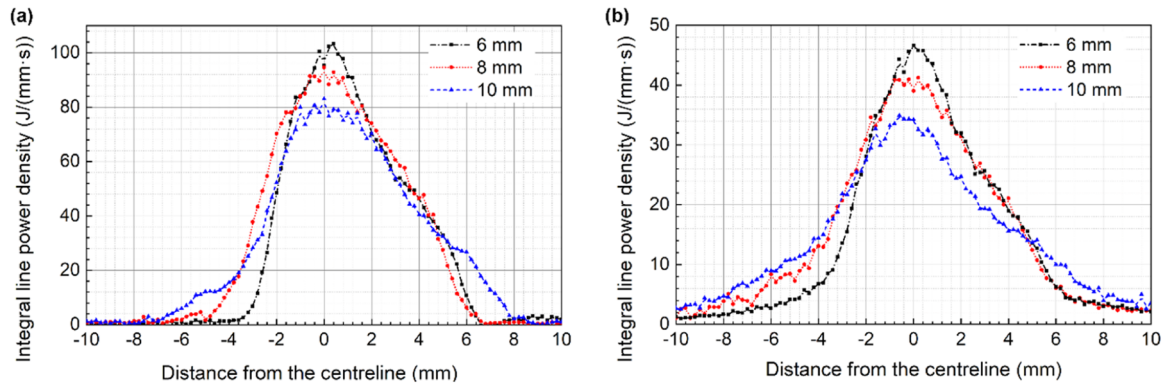


Fig. 10. PTA power profiles with varied arc lengths ranging from 6 mm to 10 mm: (a) current data generated profiles, and (b) temperature data generated profiles.

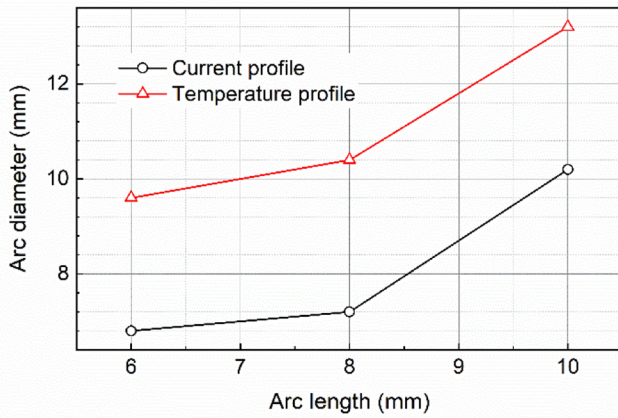


Fig. 11. Arc diameter as a function of arc length.

study. In addition, the trends of the arc diameter as a function of arc length reported in the previous studies show that the root of the arc expanded when moving the electrode away from the substrate, which matches the results in this study. In PTA-based WAAM, having a wider and lower energy density arc is highly beneficial as it reduces the likelihood of keyhole formation. In addition, a longer arc provides more wire feeding space, which increases the process tolerance and stability.

Table 7 shows the voltage and arc efficiency as a function of arc length. In general, arc voltage increased with an increasing arc length, while arc efficiency showed a slight decrease from 61 % to 60 %. Previous studies on GTA showed that the arc efficiency decreased with increasing arc length, as reported by Fuerschbach and Knorovsky [29]. This effect can be attributed to the lower radiation heat loss in a shorter arc. However, measurements on PTA indicate that the reduction in arc efficiency with increasing arc length is less pronounced than in GTA. Richardson [15] reported only about a 1 % decrease in arc efficiency

when increasing the PTA arc length from 4 to 10 mm. The difference in the effect of arc length on arc efficiency between PTA and GTA can be explained by the presence of plasma-restricting gas in PTA, which re-directs heat loss back toward the substrate [21], making it more significant than radiation heat loss.

In this study, power profiles for PTA were calculated using both temperature and current data. As discussed in Section 2.1, the power density distribution derived from current data represents the input power profile of the arc prior to any energy absorption by the substrates. In contrast, the power density distribution based on temperature data reflects the power absorbed by the copper plates in the SAC device. Consequently, these two methods yield differing power density values due to variations in the energy absorption efficiency of the substrates. Specifically, the power density obtained from temperature data is consistently lower than that derived from current data, as some energy is inevitably lost in the process (i.e., arc efficiency is always less than unity). In practical applications, the power profile from the workpieces is more relevant for both experimental and numerical analyses in WAAM, as it reflects conditions present in the actual setup. However, the power profile obtained from current data remains essential for understanding the intrinsic properties of the PTA process.

In addition, when depositing materials with low boiling temperature, e.g. Al and Mg, the metal vapour has a large effect in both arc energy distribution and arc efficiency. In non-consumable electrode processes, i.e. PTA and GTA, the metal vapour produced tends to be present in the lower temperature regions near the anode, which extends the conducting region of arc plasma to higher radii. This has the effect of

Table 7

The voltage level and arc efficiency with varying arc lengths.

Arc length / (V)	Voltage / (V)	Arc efficiency
6	21	61 %
8	23.2	61 %
10	23.3	60 %

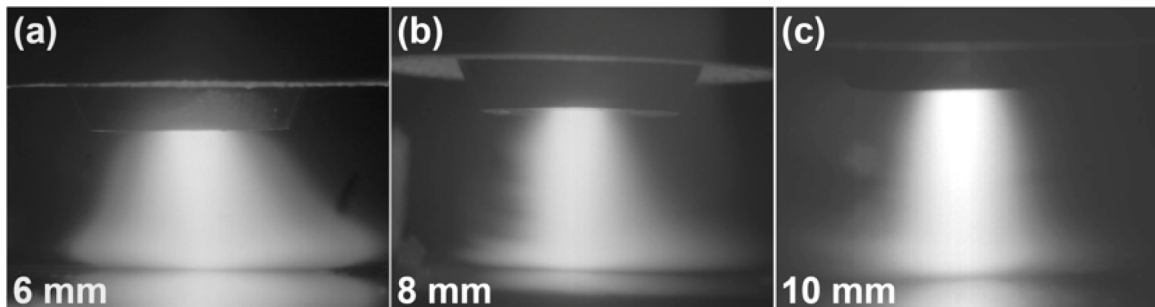


Fig. 12. Images of the PTA with different arc lengths: (a) 6 mm, (b) 8 mm, and (c) 10 mm.

decreasing the current density, and therefore the heat flux density, near the centre of the anode [30]. Moreover, metal vapour also reduces the arc efficiency due to the high radiative coefficient and therefore thermal loss [31].

3.2. Modelling of the PTA power profile

The accuracy of the heat source model used in numerical simulations, such as finite element analysis or computational fluid dynamics, is crucial for determining the precision of simulated results in the WAAM process. In this section, the conventional monomial Gaussian heat source model is compared with the measured power profiles, and its limitation on representing the PTA heat source will be demonstrated. The advantages of the newly proposed binomial Gaussian heat source model are also examined. Furthermore, a generalised form of the binomial Gaussian heat source model is presented.

3.2.1. Monomial Gaussian model fitting and analysis

Two types of monomial Gaussian profiles were analysed. One is the best-fitted profiles generated by the optimisation algorithm, and the other is the conventional Gaussian heat source model (Eq. (6)) adopted by the measured power amount (Q_m) and the measured standard deviation (σ_m). The measured power amount (Q_m) was calculated by integrating the area of the measured power profiles. The measured standard deviation (σ_m) was converted from the measured D86 based on Eq. (7). Fig. 13 compares the two types of profiles with the measured profiles. Both the best-fitted Gaussian model and the Gaussian model using measured parameters generally match the measured profile. It can be observed that the conventional Gaussian profiles have lower peaks and wider outlines, while the peaks of the best-fitted Gaussian profiles are closer to the measured profiles. Especially, the measured profiles have a gentler decrease at the edge compared to both the best-fitted Gaussian and conventional Gaussian heat source profiles.

Table 8 shows the parameters of the best-fitted monomial Gaussian

profiles for each PTA power profile, along with the correlated measured power amount (Q_m), measured standard deviation (σ_m), and PCCs between the measured profiles and two types of Gaussian profiles. Both the power amount (Q_f) and standard deviation (σ_f) of the best-fitted profiles were slightly lower than the measured data. The deviation of the monomial power amount, especially in the power amount, could have a negative effect on the numerical analysis by reducing the power input to the model. On the other hand, the overall shape of the profile deviated from the measured profiles when the actual power amount (Q_m) and standard deviation (σ_m) was adopted with lower PCCs compared to the best-fitted profiles. These results reveal the limitation of the monomial Gaussian model, i.e., it can only compensate between high accuracy of fitting or correct energy characteristics.

3.2.2. Binomial Gaussian model fitting and analysis

The above discussion has demonstrated that the conventional monomial Gaussian model has limitations in depicting the details of arc power profiles. Therefore, a binomial Gaussian model was introduced to overcome the shortcomings of the monomial Gaussian profile. The binomial Gaussian model consists of two Gaussian terms which are defined respectively as the major term and the secondary term. To match the shape of the measured PTA power profiles, the major term was designed that consists of a majority amount of the arc power Q_1 with a standard deviation σ_1 slightly larger than the measured standard deviation.

Table 8

The voltage level and arc efficiency with varying PGC.

Current intensities / (A)	110	130	150
Fitted Q_f / (J)	1325.2	1514.3	1775.7
Fitted σ_f / (mm)	3.0	3.1	3.2
Fitted profiles PCC	99.90 %	99.81 %	99.84 %
Measured Q_m / (J)	1370.0	1590.4	1844.9
Measured σ_m / (mm)	3.2	3.5	3.6
Conventional profiles PCC	99.18 %	99.12 %	99.16 %

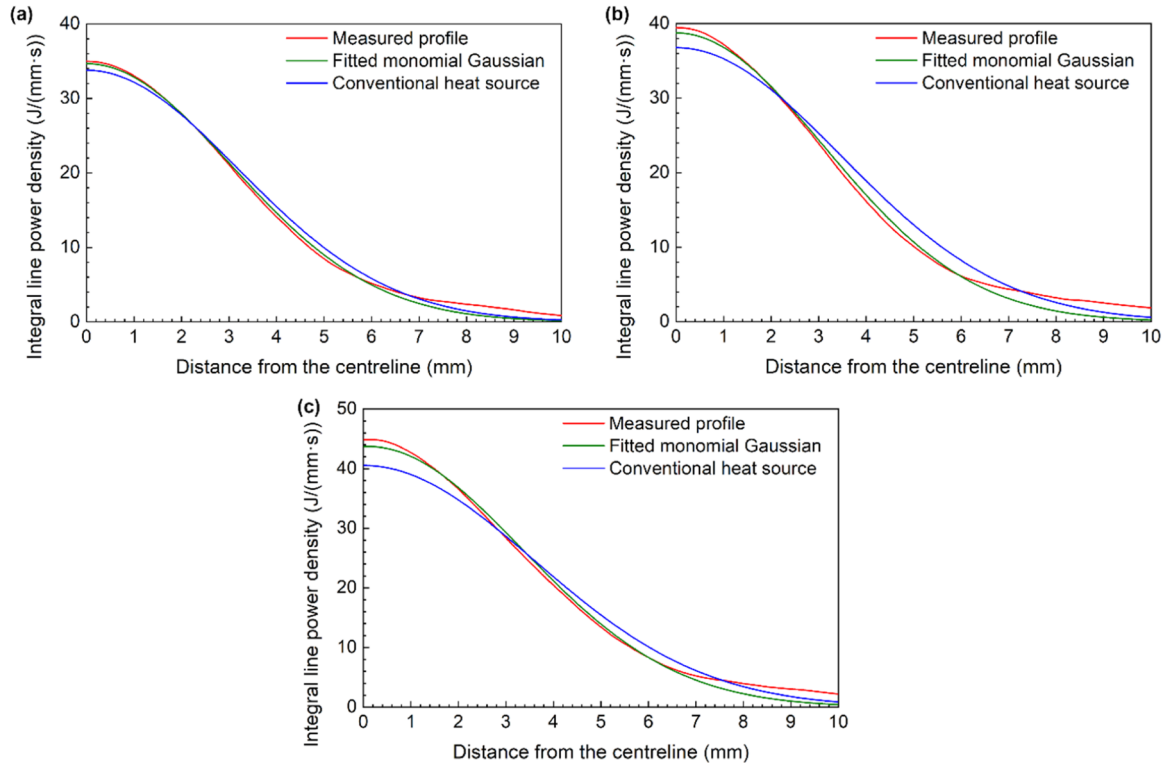


Fig. 13. Comparisons among SAC measured profiles (red), best-fitted monomial Gaussian profiles (green), and conventional Gaussian heat source model using parameters measured from the SAC experiments (blue) with different current intensities: (a) 110 A, (b) 130 A, and (c) 150 A.

ation σ , and the secondary term was designed that consist of a minority amount of the arc power Q_2 with a standard deviation σ_2 significantly larger than the measured standard deviation σ . The power amount of the second term represents the power at the edge of the measured profile. Fig. 14 shows the shapes of each term in a binomial Gaussian profile as a demonstration. It can be seen that the first term of the profile has a concentrated shape with a high peak, while the second term of the profile is rather flat with a wide range.

Table 9 shows the parameters of the best-fitted binomial Gaussian models along with the correlated PCCs. The total power amount of the best-fitted binomial Gaussian profiles is closer to the measured power amount compared to the best-fitted monomial Gaussian model. Not only that binomial Gaussian profiles have a more accurate power amount, but the PCCs also show that binomial Gaussian profiles have a better accuracy of fitting compared to monomial Gaussian profiles with a 99.98 % correlation. This further indicates that a binomial Gaussian model can better represent the power distribution of PTA with a more accurate shape and power amount.

To apply the binomial Gaussian for general use in a wide range of future PTA process simulations, a general form of the binomial Gaussian heat source model that represents a range of current intensities is desired. It can be calculated from Table 9 that the ratios between the major deviations σ_1 of the best-fitted profiles and the measured deviations σ_m are kept generally consistent. Therefore, the major deviation σ_1 could be defined as a multiple of the measured deviation σ_m of the arc profile with a fixed ratio of 0.8 (shown in Eq. (13)). The best-fitted binomial Gaussian profiles also show stable ratios between the major and secondary deviations (σ_1 and σ_2), and two partial power amounts (Q_1 and Q_2). Similarly, the secondary deviation (σ_2) and the two partial power amounts of the heat source model (Q_1 and Q_2) can be determined by the major deviation σ_1 and the measured power amount (Q_m) (shown in Eqs. (14) and 15). Accordingly, a generic formula of a binomial Gaussian heat source model could be given as Eq. (16) in one-dimensional form, and Eq. (17) in two-dimensional form:

$$\sigma_1 = 0.8\sigma_m \quad (13)$$

$$\sigma_2 = 2.3\sigma_m \quad (14)$$

$$Q_1 = 0.8Q_m \quad (15)$$

$$Q_{b1d}(x) = \frac{Q_m}{\sqrt{2\pi}\sigma_m} \left[\exp\left(-1.56\frac{x^2}{2\sigma_m^2}\right) + 0.087\exp\left(-0.19\frac{x^2}{2\sigma_m^2}\right) \right] \quad (16)$$

$$Q_{b2d}(x,y) = \frac{Q_m}{2\pi\sigma_m} \left[\exp\left(-1.56\frac{x^2+y^2}{2\sigma_m^2}\right) + 0.087\exp\left(-0.19\frac{x^2+y^2}{2\sigma_m^2}\right) \right] \quad (17)$$

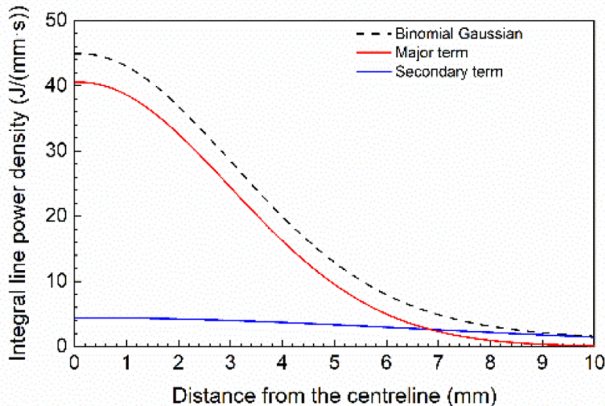


Fig. 14. Illustration of each term in a binomial Gaussian profile.

Table 9

Parameters of the best-fitted binomial Gaussian profiles.

Current intensities / (A)	110	130	150
Major partial power Q_1 / (J)	1085.2	1249.5	1392.5
Secondary partial power Q_2 / (J)	290	404	489.8
Total power Q_c / (J)	1375.2	1653.5	1882.3
Major standard deviation σ_1 / (mm)	4.0	3.9	3.9
Secondary standard deviation σ_2 / (mm)	9.6	12.0	8.4
Best-fitted profiles PCC	99.98 %	99.98 %	99.99 %

In this way, a binomial Gaussian heat source model could be determined by a power amount Q_m and a standard deviation σ_m measured from the experiment.

Fig. 15 shows the comparison between different Gaussian models and experimental measurements. The measured profiles with three current intensities were then fitted by the optimisation algorithm using the binomial Gaussian model. The overall shape of the best-fitted binomial Gaussian profiles matches the measured profiles both at the peaks and the edges, while the best-fitted Gaussian profiles does not match the edge of the measured profiles. It can be observed that despite a slight difference at the edge, the generic binomial Gaussian heat source model shows better matching to the measured profiles compared to the conventional monomial Gaussian heat source model.

The PPCs between the generic binomial Gaussian heat source profiles and the measured profiles are calculated and listed in Table 10. The PCCs of the generic binomial Gaussian heat source profiles are slightly lower than the best-fitted binomial Gaussian profiles. However, they are higher than the best-fitted monomial Gaussian profiles. This is evidence that the generic binomial Gaussian model is more accurate than the conventional monomial Gaussian heat source model.

With a high accuracy to the measured profile, the binomial heat source model can enable a precise prediction in the WAAM numerical simulation. This could further enhance the optimisation study for the WAAM to assist in the design of a novel AM process. In addition, the binomial heat source model can potentially be applied in the numerical study of other PTA processes such as welding and cladding. However, it should be mentioned that the feeding wire in WAAM has a large effect on the arc energy distribution due to its shading effect on heat transfer. It was found that the region on the workpiece surface shaded by the wire receives much less energy than the area directly exposed to the arc, resulting in a lower temperature in the shaded region [32]. This phenomenon is critical and should be considered in practical WAAM applications.

4. Conclusions

In this study, the thermal characteristics of PTA, including power density distribution, arc diameter and arc efficiency, were systematically measured for the WAAM process using the SAC device. The effects of key process parameters, such as current intensities, PGC, PGFR and arc length on these thermal characteristics were thoroughly examined, offering valuable insights for optimising part fabrication in WAAM. Furthermore, the limitations of the conventional monomial Gaussian model for representing the PTA energy source were evaluated. Based on these observations, a binomial Gaussian model was introduced to more accurately capture the PTA energy distribution in WAAM applications. The following conclusions were drawn:

1. For a typical PTA adopted in WAAM, the arc diameter ranges from 9.6 mm to 10.8 mm, and the arc efficiency is approximately 60 % as the current intensity increases from 110 A to 150 A. The power density distribution expanded with higher peak and wider out-reaching when increasing the current intensity. The stiffness of the PTA increased with current intensity, as indicated by a more symmetric power density profile.

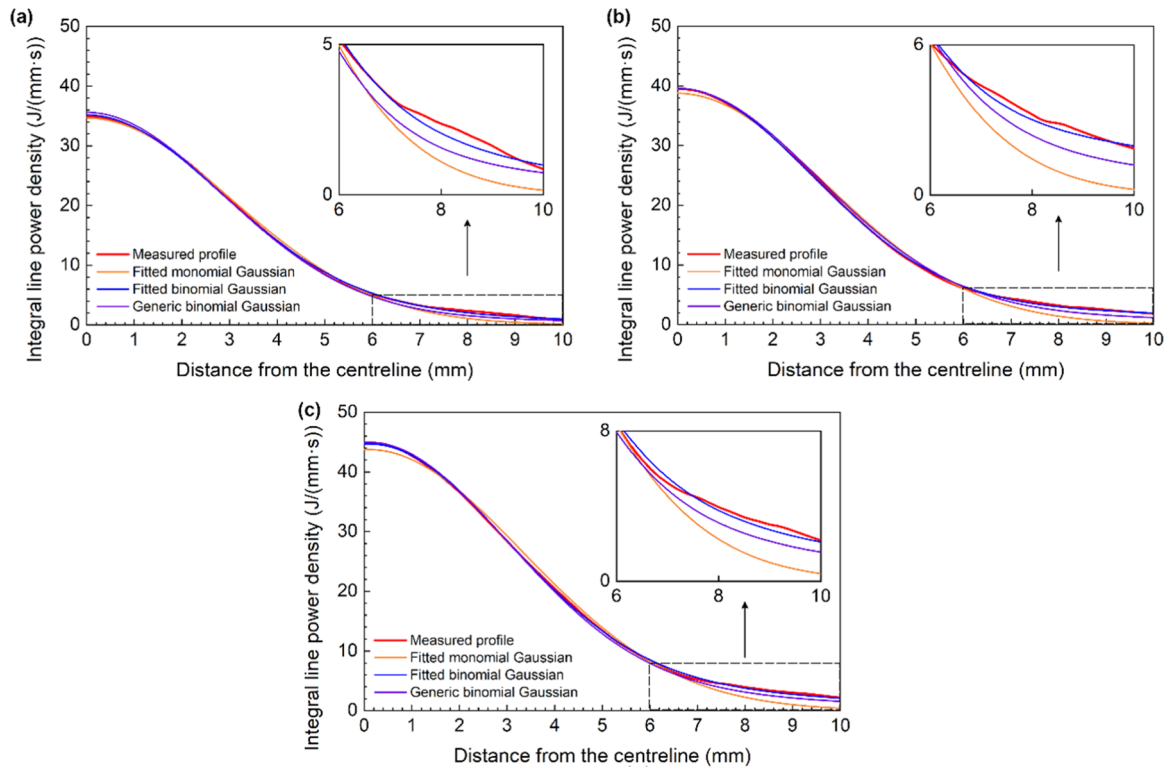


Fig. 15. SAC measured profiles (red), best-fitted monomial Gaussian profiles (orange), best-fitted binomial Gaussian profiles (blue) and generic binomial Gaussian heat source model (purple) with different current intensities: (a)110 A, (b)130 A, and (c) 150 A.

Table 10

PCC of generic binomial Gaussian profiles with varying current intensities.

Current intensities / (A)	110	130	150
Generic binomial Gaussian PCC	99.97 %	99.94 %	99.98 %

- Adding helium to the plasma gas transformed the power density distribution from a cone shape to a top-hat shape, indicating a less concentrated arc power, which is beneficial for avoiding keyhole defects. As helium content increased from 0 to 75 %, the arc diameter showed minimal overall change, while the arc efficiency reduced from 61 % to 51 % due to increased energy loss to the surroundings, driven by the high thermal conductivity of helium.
- Both power density and arc diameter increases as the PGFR increased from 0.2 to 5 L/min. The arc efficiency increased almost linearly from 55 % to 69 %, attributed to the contraction of the arc column and reduced thermal loss to the surroundings. In WAAM processes, a lower arc efficiency should be adopted compared to welding application due to the typically lower PGFR used.
- The power density distribution showed lower peak values and broader profiles as the arc length increased from 6 mm to 10 mm, indicating that PTA power becomes less concentrated and more widely distributed as the electrode moves farther from the substrate. This suggests that a softer plasma can be achieved by increasing the torch stand-off distance. The arc diameter increased from 9.6 mm to 13.2 mm, while arc efficiency showed a slight decrease from 61 % to 60 % within the tested range of NSD.
- The binomial Gaussian model provides a more accurate representation of PTA power profiles compared to the conventional monomial Gaussian model. The generic binomial Gaussian heat source model introduced in this study achieved over 99.94 % correlation coefficient to the measured profile, which is more accurate than the best-fitted monomial Gaussian model.

CRediT authorship contribution statement

Guangyu Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yongle Sun:** Writing – review & editing, Visualization, Supervision, Investigation, Formal analysis. **Chong Wang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Jialuo Ding:** Writing – review & editing, Supervision, Formal analysis. **Wojciech Suder:** Writing – review & editing, Supervision, Formal analysis. **Zhiyong Li:** Writing – review & editing, Methodology, Investigation. **Stewart Williams:** Writing – review & editing, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Guangyu Chen would like to express his gratitude to Cranfield University, United Kingdom and China Scholarship Council, China (No. 201706680064) for funding his research studies. The authors would like to thank New Wire Additive Manufacturing (NEWAM), United Kingdom (EP/R027218/1) programme for financial support. The authors also would like to thank Flemming Nielsen, Nisar Shah and John Thrower for the technical support.

Data availability

Data underlying this study can be accessed through the Cranfield

University repository at <https://doi.org/10.57996/cran.ceres-2717>.

References

- [1] S.W. Williams, F. Martina, A.C. Addison, J. Ding, G. Pardal, P. Colegrove, Wire + Arc additive manufacturing, *Mater. Sci. Technol.* (U.K.) 32 (2016) 641–647, <https://doi.org/10.1179/1743284715Y.0000000073>.
- [2] F. Martina, J. Mehnen, S.W. Williams, P. Colegrove, F. Wang, Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V, *J. Mater. Process. Technol.* 212 (2012), <https://doi.org/10.1016/j.jmatprotec.2012.02.002>.
- [3] C. Wang, W. Suder, J. Ding, S. Williams, The effect of wire size on high deposition rate wire and plasma arc additive manufacture of Ti-6Al-4V, *J. Mater. Process. Technol.* 288 (2021), <https://doi.org/10.1016/j.jmatprotec.2020.116842>.
- [4] X. Chen, C. Wang, J. Ding, R. Qu, Y. Wang, G. Pardal, et al., Thermal fluid dynamics of the effect of filler wire on deposition rate and bead formation intending plasma arc-based DED, *J. Manuf. Process.* 107 (2023) 199–209, <https://doi.org/10.1016/j.jmapro.2023.10.020>.
- [5] C. Wang, Y. Sun, G. Chen, X. Chen, J. Ding, W. Suder, et al., A simplified modelling approach for thermal behaviour analysis in hybrid plasma arc-laser additive manufacturing, *Int. J. Heat. Mass. Transf.* 195 (2022) 123157, <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123157>.
- [6] D. Rosenthal, Mathematical theory of heat distribution during welding and cutting, *Weld. J.* 20 (1941).
- [7] V. Pavelic, R. Tanbakuchi, O.A. Uyehara, P.S. Myers, Experimental and computed temperature histories in gas tungsten-arc welding of thin plates, *Weld. J.* 48 (1969).
- [8] J. Goldak, A. Chakravarti, M. Bibby, A new finite element model for welding heat sources, *Metallurg. Transact. B.* 15 (1984), <https://doi.org/10.1007/BF02667333>.
- [9] H.G. Wang, C.S. Wu, M.X. Zhang, Finite element method analysis of temperature field in keyhole plasma arc welding, *Hanjie. Xuebao/Transact. China Weld. Institut.* 26 (2005).
- [10] G.N. Haddad, A.J.D. Farmer, Temperature determinations in a free-burning arc. I. Experimental techniques and results in argon, *J. Phys. D. Appl. Phys.* 17 (1984), <https://doi.org/10.1088/0022-3727/17/6/015>.
- [11] M.F. Thornton, Spectroscopic determination of temperature distributions for a TIG arc, *J. Phys. D. Appl. Phys.* 26 (1993), <https://doi.org/10.1088/0022-3727/26/9/014>.
- [12] I. Langmuir, Electric discharges in gases at low pressures, *J. Franklin. Inst.* 214 (1932) 275–298, [https://doi.org/10.1016/s0016-0032\(32\)90932-6](https://doi.org/10.1016/s0016-0032(32)90932-6).
- [13] C. Fanara, I.M. Richardson, A Langmuir multi-probe system for the characterization of atmospheric pressure arc plasmas, *J. Phys. D. Appl. Phys.* 34 (2001), <https://doi.org/10.1088/0022-3727/34/18/302>.
- [14] O.H. Nestor, Heat intensity and current density distributions at the anode of high current, inert gas arcs, *J. Appl. Phys.* 33 (1962), <https://doi.org/10.1063/1.1728803>.
- [15] I.M. Richardson, Properties of the Constricted gas Tungsten (Plasma) Welding Arc at Elevated Pressures, Cranfield Institute of Technology, School of Industrial and Manufacturing Science, 1991.
- [16] G. Chen, S. Williams, J. Ding, Y. Wang, W. Suder, Split anode calorimetry for plasma arc energy density measurement with laser calibration, *J. Manuf. Process.* 78 (2022) 71–81, <https://doi.org/10.1016/j.jmapro.2022.04.003>.
- [17] A. Savitzky, M.J.E. Golay, Smoothing and differentiation of data by simplified least squares procedures, *Anal. Chem.* 36 (1964), <https://doi.org/10.1021/ac60214a047>.
- [18] W.J. Suder, Study of Fundamental Parameters in Hybrid Laser Welding, 2011.
- [19] K. Pearson, Mathematical contributions to the theory of evolution, *Proceed. Roy. Soc.* 60 (1896).
- [20] J.F. Lancaster, The physics of fusion welding Part 1: the electric arc in welding, *IEEE Proceed. B: Electr. Power Applic.* 134 (1987), <https://doi.org/10.1049/ip-b.1987.0040>.
- [21] D.M. Evans, D. Huang, J.C. McClure, A.C. Nunes, Arc efficiency of plasma arc welding, *Weld. J. (Miami, Fla)* (1998) 77.
- [22] R.W. Niles, C.E. Jackson, Weld thermal efficiency of the GTAW process, *Weld. J. (Miami, Fla)* (1975) 54.
- [23] J. Zijp, K. Hiraoka, Basic parameters in heat transport in argon-helium mixed gas arcs, *Q. J. Jpn. Weld. Soc.* 12 (1994).
- [24] K. Hiraoka, Local plasma compositions at anode surface in mixed gas shielding GTA. Study on characteristics of gas tungsten arc shielded by mixed gases. I, *Q. J. Jpn. Weld. Soc. (Jpn.)* 10 (1) (1992) 58–64.
- [25] K. Hiraoka, Evaluation of local plasma composition and temperature in mixed gas tungsten arc plasma column by light spectroscopy-study on characteristics of gas tungsten arc shielded by mixed gases (report 2-), *Q. J. Jpn. Weld. Soc.* (1993), 11–1.
- [26] N. Tsai, Heat Distribution and Weld Bead Geometry in Arc Welding, Massachusetts Institute of Technology, 1983.
- [27] S.S. Glickstein, Arc Modeling for Welding Analysis, 1978.
- [28] Y. Wang, J. Ding, S. Williams, B. Cong, Effect of plasma gas composition on deposition characteristics in plasma arc directed energy deposition of Ti-6Al-4 V, *Weld. World* (2024) 1–13.
- [29] P.W. Fuerschbach, G.A. Knorovsky, A study of melting efficiency in plasma-arc and gas tungsten arc-welding, *Weld. J.* 70 (1991).
- [30] Murphy, B. Anthony, The effects of metal vapour in arc welding, *J. Phys. D. Appl. Phys.* 43 (43) (2010) 434001.
- [31] L.I. Z, W.U. D, S. Tashiro, M. Tanaka, J. Xin, H. Wang, et al., Influence mechanism of metal vapor in plasma arc lap welding: metal vapor decreases arc energy efficiency in conduction plasma arc lap welding, *Weld. J.* (2022).
- [32] X. Chen, C. Wang, J. Ding, P. Bridgeman, S. Williams, A three-dimensional wire-feeding model for heat and metal transfer, fluid flow, and bead shape in wire plasma arc additive manufacturing, *J. Manuf. Process.* 83 (2022) 300–312.



DSPACE

<https://dspace.org/>

Characterising and modelling plasma transferred arc for additive manufacturing

Chen, Guangyu; Sun, Yongle; Wang, Chong; Ding, Jialuo; Suder, Wojciech ...

2025-05-15

Elsevier

<https://doi.org/10.1016/j.ijheatmasstransfer.2025.126735>

Chen G, Sun Y, Wang C, et al., (2025) Characterising and modelling plasma transferred arc for additive manufacturing. International Journal of Heat and Mass Transfer, Volume 241, May 2025 Article number 126735