

Analytical modelling for prediction and prevention of overflow occurrence in wire-based additive manufacturing

Alireza M. Haghighi, Jialuo Ding, Yongle Sun, Wojciech Suder, Chong Wang, Paul Poulain, Xin Chen and Stewart Williams

Welding and Additive Manufacturing Centre, Cranfield University, Cranfield, UK

ABSTRACT

Increasing deposition rate is essential for higher productivity of additive manufacturing (AM). However, a high deposition rate usually requires high heat input to fully melt the fast-fed material, which could lead to defects due to molten material overflow. This paper presents a thermo-capillary-gravity model for predicting the overflow occurrence based on the analytically calculated reciprocal Bond number, $1/Bo$. Comprehensive experiments show that when the $1/Bo$ is no greater than 0.74, or the bead height is no less than 1.16 times the capillary length, overflow is highly likely to occur. Two different steel wire-based AM processes were employed to validate the model, demonstrating an overall accuracy of 84%-93%. It is found that both energy and material inputs per unit length significantly affect the molten material overflow, and hence they can be adjusted to prevent overflow. The validated analytical modelling approach enables efficient prediction and control of overflow for a high deposition rate wire-based AM process.

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Directed energy deposition; wire arc additive manufacturing; analytical model; overflow defect

Nomenclature

κ	Capillary length
σ	Surface tension
Bo	Bond number
$1/Bo_c$	Critical value of reciprocal Bond number
ρ_m	Density at melting temperature
ρ_0	Density at room temperature
g	Gravitational acceleration
P_0	Pressure at origin point
P_z	Pressure at point z
R_0	Radius at origin point
R_z	Radius at point z
θ	Slope angle
φ	Contact angle
θ_p	Penetration angle
A_b	Cross-sectional area of bead
A_l	Cross-sectional area of layer
A_p	Cross-sectional area of penetration melted region
W_E	Effective wall width
$W_{Max.}$	Maximum wall width
h_b	Bead height
h_l	Layer height
h_p	Penetration melting height

Q_t	Total transferred power
Q_w	Power for melting wire
Q_p	Penetration power
I	Current
V	Voltage
S	Travel speed
S_w	Wire feed speed
S_{hw}	Hot wire feed speed
S_{cw}	Cold wire feed speed
D_w	Wire diameter
η_w	Wire melting efficiency
η	Power transfer efficiency
η_p	Penetration melting efficiency
E_{IL}	Energy input per unit length
M_{IL}	Material input per unit length

1. Introduction

Additive manufacturing (AM) is an advanced layer-by-layer manufacturing technology with many advantages over traditional manufacturing technologies, such as reductions in material waste, fabrication cost and lead time, and increases in design space and energy efficiency [1–3]. According to ASTM standard, directed energy deposition (DED) is a major category of metal

CONTACT Yongle Sun  Yongle.Sun@cranfield.ac.uk  Welding and Additive Manufacturing Centre, Cranfield University, Cranfield MK43 0AL, UK

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AM [4]. Wire-based DED (w-DED) is a metal AM process in which the wire feedstock is deposited using intense energy sources such as laser, electron beam, and electrical arc. Arc-based w-DED is also known as wire arc additive manufacturing (WAAM) [5]. The WAAM process is gaining popularity in various industries due to its potential capability to fabricate large-scale structures with medium geometric complexity at higher material deposition rate than other AM methods [6].

Different techniques have been explored to increase the deposition rate of w-DED processes. For instance, recent research at Cranfield University [7,8] developed a cold wire gas metal arc (CW-GMA) process, which achieved a deposition rate up to 14 kg/h for steel parts. However, a high deposition rate can cause various challenges. Overflow of molten material is one of the defects that can occur during the deposition process, leading to a low quality of the final part. Overflow refers to the phenomenon that molten material flows beyond the edges of the underlying layers, causing a geometrical defect and material waste. This results in high roughness of the deposited component surface, which demands greater material removal in subsequent finishing processes. Figure 1 shows the typical appearance of overflow in a deposited steel wall.

The shape of the deposit bead is largely determined by the balance between the surface tension close to melting temperature and the gravitational force acting on the molten material just before the solidification [9]. The gravitational force increases with the bead height, and if the volume of the molten material exceeds a critical threshold, the gravitational force is anticipated to become dominant over the surface tension on the edges of the melt pool. This causes the material to flow onto the underlying layers and produce waste. In some cases, the material is solidified before fully flowing onto the underlying layers, leading to a high waviness of the surface [10,11]. The heat accumulation and low heat dissipation at high inputs of material and energy promote the overflow, and the upper layers far from substrate are especially susceptible to overflow [12]. Figure 2 shows a schematical cross-sectional representation of the overflow defect on the top surface.

Previous research adopted different approaches to study and control the overflow, such as monitoring the deposition process, developing new deposition strategies, and predicting the overflow occurrence via data-driven models. Xi et al. [14] designed a deposition strategy to control the geometric properties and defects of deposit beads, employing arc oscillation and forced inter-layer cooling techniques. Their results indicate that arc oscillation improves the expansion of the melt pool and prevents overflow, thereby increasing

the accuracy of the deposited part geometry. Xiong et al. [2] investigated the geometric properties of single-pass walls deposited using a gas metal arc (GMA) process. Their study employed a passive vision sensor to analyse the impact of arc current, deposition velocity and heat input on the formation of layers. Their findings indicate that the main process parameter influencing the bead geometry is the arc current, and a higher arc current leads to melt pool instability and overflow of the molten metal. Ma et al. [12] created an artificial neural network using 7212 images for training, and developed a quality monitoring technique based on visual sensing to identify overflow during the deposition process. Despite the high accuracy of the data-driven model, the neural network demands a substantial amount of experimental data. Alhakeem et al. [13] developed an algorithm using a CAD model and a neural network to calculate the width and height of beads. This algorithm generated deposition paths while considering heat distribution, aiming to identify the optimal path with minimal temperature variance to prevent overflow. The experimental validation of the algorithm showed a reduction of overflow in thin walls by 21%.

In the research field allied with metal AM, the application of a liquid drop on a flat surface (known as sessile drop) attracted wide attention during the past decade [14]. Some of the previous studies were focused on the effects of different factors on the equilibrium of forces in a sessile drop. Zhang et al. [10] highlighted the role of the Bond number, Bo , in stability of sessile drop, which is a dimensionless variable depending on drop geometry, gravitational force and surface tension [10,15]:

$$Bo = \left(\frac{h_b}{\kappa} \right)^2 \quad (1)$$

where

$$\kappa = \sqrt{\frac{\sigma_m}{\rho_m g}} \quad (2)$$

In Eqs. (1) and (2), h_b is the drop height (or bead height in w-DED), σ_m is the surface tension at melting temperature, ρ_m is the material density at melting temperature, and g is the gravitational acceleration. The capillary length κ represents a characteristic length scale indicating the relative importance of surface tension versus gravitational force in determining the shape and behaviour of a sessile drop. According to previous studies [11,15,16], if the sessile drop height is less than the capillary length, the shape remains nearly spherical or hemispherical due to the dominance of surface tension. However, for a sessile drop with height exceeding the

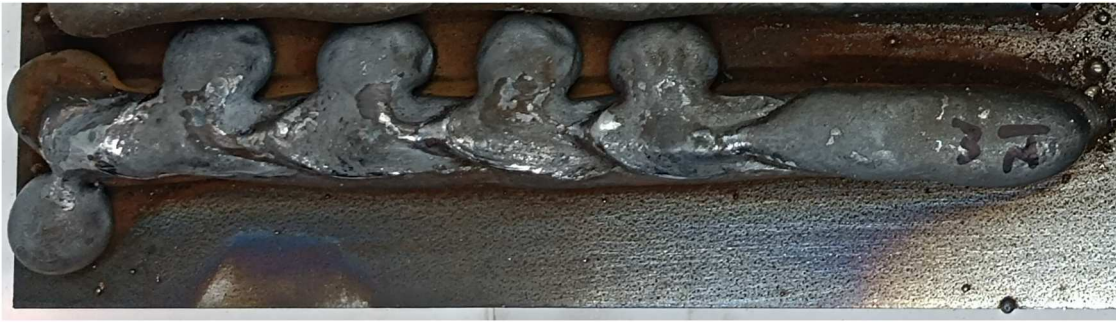


Figure 1. Typical overflow defect in a deposited steel wall.

capillary length, the shape becomes noticeably flattened as the gravitational effect becomes significant.

In this regard, the Bond number has been adopted by many researchers for studying the stability of sessile drop. For instance, Pozrikidis [11] obtained stability solution of sessile drop with respect to reciprocal Bond number and contact angle. It was found that there is a strong correlation between the volume and stability of the sessile drop. With exceeding a critical drop volume, the instability of the flow arises, and the liquid metal tends to reduce its volume to diminish the destabilising influence of gravity and surface tension. Zhu et al. [16] performed numerical analysis to examine the role of the Bond number in sessile and pendant drops. It was concluded that surface tension and Bond number influence the spreading behaviour of liquid drops.

The molten material in a w-DED process can be treated as a static sessile drop subjected to the equilibrium of the gravity and surface tension [17]. Therefore, here a thermo-capillary-gravity model, in conjunction with reciprocal Bond number, is developed to predict the overflow occurrence for w-DED deposited walls. It should be noted that this study does not intend to explain the full complexity of melt pool behaviour. Instead, it focuses on a practical goal: developing a physics-based method to identify when the overflow is highly likely to occur. The analytical model could be used to improve the quality of w-DED built parts. Since

the Bond number is a dimensionless variable, this approach, in principle, is universal and could be applied to any wire-based AM process and material.

2. Model development

2.1. Analytical modelling framework

A thermo-capillary-gravity model combined with the reciprocal Bond number $1/Bo$ is proposed here to predict the overflow occurrence, thereby guiding the selection of w-DED process parameters for preventing overflow defects. The model inputs are grouped into material properties and process parameters. Figure 3 illustrates the flowchart of the analytical model for w-DED wall deposition. First, the bead geometry is obtained through solving the governing thermo-physical equations using the thermo-capillary-gravity theory in order to predict the bead height [21]. Then, the occurrence of overflow is predicted based on the critical value of the reciprocal Bond number ($1/Bo_c$). In this study, the $1/Bo_c$ needs to be identified from a series of experiments, and the overflow is expected to occur when the reciprocal Bond number is below the critical value.

The key innovation of this research includes determining the reciprocal Bond number through the thermo-capillary-gravity model-derived bead height calculation and using the reciprocal Bond number to predict overflow occurrence in wire-based AM. Although the Bond number has been considered in the studies of the stability of sessile drops (Section 1), those previous studies were focused on the generic physics of fluids without providing specific approaches and insights to AM applications. In those previous studies, the sessile drop was usually positioned on a large flat surface, while in the context of AM, the sessile drop lies on the top of previously deposited layers. Based on the previous AM research (Section 1) and the experiments in this study (Section 3), it is found that AM overflow does not occur in the first few layers deposited on a flat substrate. Instead, it appears in the later stage of

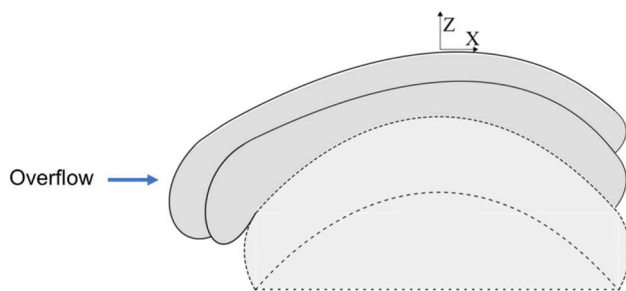


Figure 2. Schematic of molten material overflow on the upper layers during w-DED process.

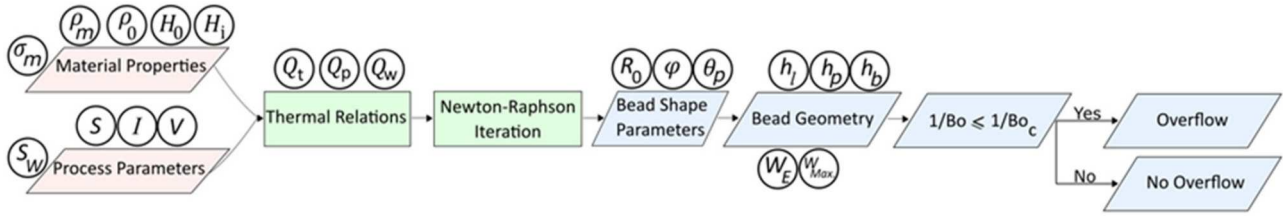


Figure 3. Flowchart of analytical model for prediction of the overflow occurrence in single-pass w-DED wall deposition.

the deposition, at the side edges of the deposited beads in the upper layers, where there is no material to support the molten metal flowing from the sides. In these regions, surface tension acts as the main force keeping the liquid metal from spilling over. Therefore, new considerations and insights to the stability of sessile drop are needed for AM applications.

2.2. Assumption, simplification and limitation

This model assumes uniform surface tension across the entire bead surface, since the surface tension gradient in the liquid metal is expected to be limited near the solidification temperature when the final bead is formed. Symmetrical geometry is also assumed for the single-pass wall deposition. Although uncertainties in AM system input and environment could introduce geometrical asymmetry, the deviation is usually small in a well-controlled process. For simplicity, the model does not consider detailed thermal profile and melt pool flows. The thermal effects are approximately accounted for through experimental calibration of the penetration melting efficiency. Regarding melt pool flow, although such flows – mainly driven by Marangoni convection and arc pressure – play a role in shaping the melt pool in the front region, our model specifically targets the rear region of the melt pool, where solidification occurs, and the molten metal behaviour is quasi-static. In the rear region, previous studies [17–20] have shown that the dominant forces are hydrostatic pressure and surface tension, while convective flows become negligible due to rapid cooling and increased viscosity. Therefore, by focusing on this rear solidifying region, with the aid of experimental calibration, the model can reasonably predict the final bead geometry and the onset of overflow without requiring explicit modelling of the complex flow of melt pool, which can cover the majority in practical applications.

There are some exceptional situations such as extreme arc pressure and varied material purity, which can affect the overflow occurrence beyond the capability of the thermo-capillary-gravity model. However, the proposed overflow criterion based on the reciprocal Bond number remains applicable, provided that the bead height can be determined for the calculation.

This is because, regardless of whether the deviation arises from arc fluctuation, material inconsistency, or other factors, its physical effect is ultimately reflected in changes to the bead geometry.

Another limitation of the analytical model for predicting the overflow occurrence is that it is unable to predict the shape of the overflowed material, which may be interesting for fundamental understanding but less relevant to engineering applications as overflow defects should be prevented.

2.3. Governing equations and solution

The bead profile equations have been formulated by establishing the equilibrium between capillary and gravity pressures in a two-dimensional configuration, employing the Laplace theorem [22]. For simplicity, the inter-layer temperature is set to be constant. Eqs. (3) and (4) represent the equations for the height (z) and the half width (x) at z for the deposited bead (the detailed derivation of the governing equations can be found in Ref. [21]).

$$\frac{0.5 \rho_m g z^2}{\sigma_m} - \frac{z}{R_0} + \left(\frac{\frac{dx}{dz}}{\sqrt{1 + \left(\frac{dx}{dz}\right)^2}} - 1 \right) = 0 \quad (3)$$

$$x = \pm \frac{1}{\sqrt{\left(\kappa^{-2} + \frac{0.25}{R_0^2}\right)}} \left[\left(2 + \frac{0.5\kappa^2}{R_0^2} \right) \left[E \left(\cos^{-1} \left(\sqrt{\frac{1}{1 + (\tan \theta)^2}} \right), \sqrt{\frac{\kappa^{-2}}{\kappa^{-2} + \frac{0.25}{R_0^2}}} \right) - E \left(\frac{\pi}{2}, \sqrt{\frac{\kappa^{-2}}{\kappa^{-2} + \frac{0.25}{R_0^2}}} \right) \right] \right. \\ \left. - \left(1 + \frac{0.5\kappa^2}{R_0^2} \right) \left[F \left(\cos^{-1} \left(\sqrt{\frac{1}{1 + (\tan \theta)^2}} \right), \sqrt{\frac{\kappa^{-2}}{\kappa^{-2} + \frac{0.25}{R_0^2}}} \right) - F \left(\frac{\pi}{2}, \sqrt{\frac{\kappa^{-2}}{\kappa^{-2} + \frac{0.25}{R_0^2}}} \right) \right] \right] \quad (4)$$

In above equations, R_0 stands for the curvature radius of bead surface at the origin, ρ_m is the density of the material at melting temperature, and g is the acceleration due to gravity, and θ is the slope angle, i.e. $\cot(\theta) = dx/dz$. The F and E in Eq. (4) are the first and second order elliptical integrals [19,20]. The κ represents the capillary length expressed in Eq. (2) [22].

A three-equation system is needed to find three unknown variables, including the curvature radius at the origin R_0 , the contact angle φ , and the penetration angle θ_p , as shown in Figure 4a. For the cross-sectional areas of the layer (A_l), the penetration (A_p) and the bead (A_b) (Figure 4a), we have:

$$\begin{cases} A_b = -2 \int_0^{z_\varphi} x \, dz \\ A_p = -2 \int_0^{z_{\theta_p}} x \, dz \\ x(R_0, \varphi) = x(R_0, \theta_p) \end{cases} \quad (5)$$

where

$$A_l = \frac{0.25 S_w \pi D_w^2}{S} \quad (6)$$

$$A_p = \frac{\eta_p \left(Q_t - \frac{0.25 \pi D_w^2 S_w \rho_0 H_0}{\eta_w} \right)}{H_i \rho_m S} \quad (7)$$

$$A_b = A_l + A_p \quad (8)$$

In Eqs. (6)-(8), D_w is wire diameter, S_w is wire feed speed, S is energy source travel speed, η_w is wire melting efficiency, and η_p is penetration melting efficiency. The Q_t is total transferred power, and for WAAM, we have $Q_t = \eta I V$ where η is power transfer efficiency, I is arc current, and V is arc voltage. The ρ_0 and ρ_m represent the densities of the material at room temperature and melting temperature, respectively. The H_0 represents the enthalpy difference of the material between the melting temperature and room temperature, and the H_i is the enthalpy difference of the material between the melting temperature and inter-layer temperature.

The Newton-Raphson iteration [23] is employed for solving the three equations and determining the three unknowns expressed in Eq. (5). After obtaining R_0 , φ and θ_p , the bead height for a given set of model input can be calculated using Eq. (3). Figure 4b and c show the comparison between the actual and predicted layer height h_l and bead profile, respectively, using the thermo-capillary-gravity model validated in a previous study [21].

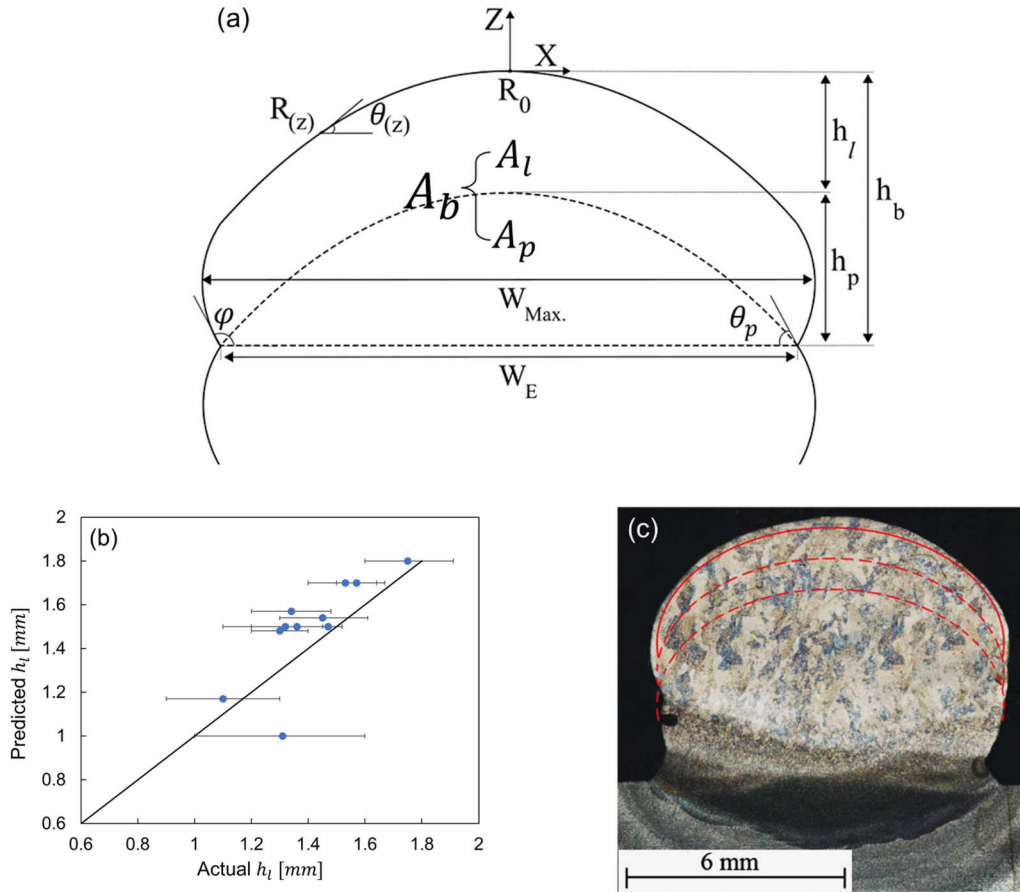


Figure 4. (a) Geometric parameters characterising the cross-sectional profile of a single-pass w-DED deposited wall (the dashed line shows the boundary of the penetration molten region). The comparison of predicted and actual layer height h_l for PTA deposition with ER90S-G steel wire is shown in (b), and the predicted bead profile (red lines) is superimposed in the etched macrograph (c) [21].

When the Bond number (Eq. 1) approaches one, the liquid metal reaches a critical height equal to the capillary length [15]. As the capillary length is a constant for the given material and deposition condition, a high Bond number means that the height of the liquid drop is near or reaching a critical value [16], wherein the gravitational force overwhelms surface tension and the molten material starts overflowing. A low Bond number means that the gravitational force is secondary compared to the surface tension, which governs the shape of the liquid drop [16,24]. As the occurrence of overflow requires the dominance of gravity, the Bond number should be larger than one. To impose two bounds of a variable for predicting overflow, the reciprocal of the Bond number ($1/Bo$) is adopted, which falls in the range of 0–1 for the gravity-dominated regime. This number can be calculated using Eqs. (1) and (2), viz.

$$\frac{1}{Bo} = \frac{\sigma_m}{\rho_m g h_b^2} \quad (9)$$

Usually, the surface tension of molten metallic material is small, no greater than 2 N/m [25]. In this study, we adopt $\sigma_m = 1.6 \text{ N/m}$ and $g = 9.8 \text{ m/s}^2$ for the steels used in WAAM deposition, while the density at the melting temperature, ρ_m , is 7280 kg/m^3 and 7240 kg/m^3 for the low-alloy steel and duplex stainless steel, respectively [25–27]. A critical value of the reciprocal Bond number, $1/Bo_c$, for overflow occurrence can be identified from the calibration experiments described in Section 3.

To validate the overflow occurrence prediction model, two different w-DED processes based on cold wire gas metal arc (CW-GMA) WAAM and plasma transferred arc (PTA) WAAM, respectively, were employed, which are described in detail in Section 3. These specific processes were selected as they exhibit very different deposition characteristics in terms of energy and material inputs. To enable better comparison and understanding of the results, both processes were characterised in terms of energy and material inputs per unit length, which are two generic physical factors applicable to different w-DED processes. The energy input per unit length, E_{IL} , is the ratio of the total transferred power, Q_t , to the travel speed, S , of the energy source, viz.

$$E_{IL} = \frac{Q_t}{S} \quad (10)$$

For a WAAM process, $Q_t = \eta I V$ where η is power transfer efficiency, I is arc current, and V is arc voltage. The E_{IL} indicates the power supplied to melt the wire feedstock and the underlying material. In the PTA process, the wire is fed externally into the arc, and the arc travel speed is lower, exhibiting a higher E_{IL} than the CW-GMA process. The E_{IL} can be used to select and control the

amount of energy input to various w-DED processes and materials.

The material input per unit length, M_{IL} , refers to the mass of the material fed to the deposition process per unit length, which is defined as follows:

$$M_{IL} = \frac{0.25 S_w \pi D_w^2 \rho_0}{S} \quad (11)$$

where S_w is the wire feed speed (the sum of all wire feeds if multiple wires are used), D_w is the wire diameter, ρ_0 is the wire material density at room temperature, and S is the energy source travel speed. The ratio of E_{IL}/M_{IL} indicates the specific energy of the deposit.

According to the previous study by Martina et al. [28], at constant E_{IL} the width of the deposited bead depends on M_{IL} . The GMA process usually achieves higher M_{IL} than the PTA process, and the difference is even greater for the CW-GMA process with dual-wire feeding. The M_{IL} can be used to control and optimise the deposition rate and the quality of the deposited beads [29].

The E_{IL} and M_{IL} characterise the w-DED processes in terms of energy and material inputs and allow comparison of different process variants of w-DED. Moreover, these two physical factors have a direct relation with layer geometry, as implied in Eqs. (6) and (7), which is important for predicting and preventing the overflow occurrence.

3. Experiments for model calibration and validation

For experimental calibration and validation of the analytical model described in Section 2, two distinctive w-DED processes, i.e. CW-GMA-based WAAM and PTA-based WAAM, with different wire materials, were employed. This section provides a detailed description of the experimental setups for these two processes. In the experiments, a wide range of material and energy inputs per unit length were selected to represent diverse deposition conditions. This variation ensures that the model is applicable within and around the inherent limits of both CW-GMA and PTA processes and remains relevant to practical industrial scenarios.

3.1. Low-alloy steel wire specification

The copper-coated high-strength low-alloy steel wire (ER90S-G) with a diameter of 1.2 mm was used for both the CW-GMA and PTA processes, and the chemical composition of the wire is shown in Table 1. A mild steel substrate with dimensions of $200 \times 300 \times 10 \text{ mm}$ was used for depositing ER90S-G steel walls. Figure 5a and b show the wire density and enthalpy versus temperature, respectively.

Table 1. Chemical composition of ER90S-G copper-coated low-alloy steel wire (Wt. %).

C	Cr	Cu	Mn	Mo	P	Si	S	Fe
0.08	2.50	0.12	0.60	1.00	0.01	0.60	0.01	Bal.

3.2. Duplex stainless steel wire specification

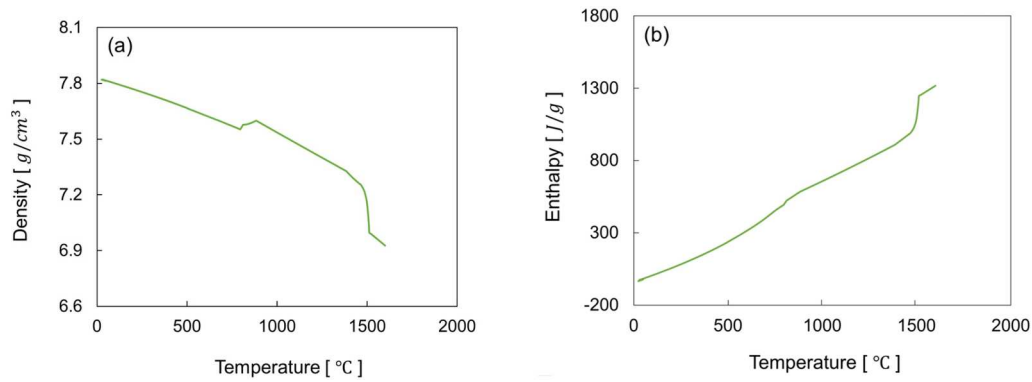
Duplex stainless steel (SS32906) walls were also deposited using the CW-GMA process to validate the analytical model. Table 2 and Figure 6 show the chemical composition and material properties of the SS32906 wire, respectively.

3.3. CW-GMA w-DED process

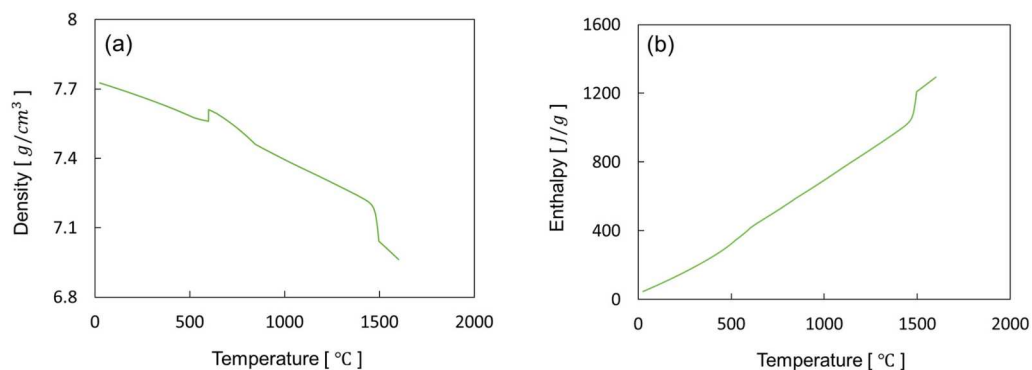
The recently developed CW-GMA w-DED process employs the feeding of an additional non-energised wire into a GMA process, resulting in a markedly increased deposition rate and better thermal control [7].

The two ER90S-G low-alloy steel wires, each with a diameter of 1.2 mm and spaced 2 mm apart, were used as the cold and hot wires, respectively. During the deposition, a shielding gas mixture consisting of 92% Ar and 8% CO₂, with a flow rate of 20 L/min was employed. Figure 7 illustrates the experimental setup for the CW-GMA process. A total of 50 walls using various process parameters were deposited to cover a wide range of E_{IL} and M_{IL} , from which overflow was observed in sixteen samples and the threshold of the reciprocal Bond number for overflow occurrence was determined. Among the samples, the bead geometry of six samples without overflow was used to calibrate the penetration melting efficiency in the analytical model [21].

In addition, to validate the model for different materials, twenty single-pass walls were deposited using the SS32906 duplex stainless steel for both the hot and cold wires with a diameter of 1.2 mm. The deposition was performed on the substrate with dimensions of

**Figure 5.** Variation of density (a) and enthalpy (b) of ER90S-G low-alloy steel wire with temperature.**Table 2.** Chemical composition of SS32906 duplex stainless steel wire (Wt. %).

C	Si	Mn	P	Cr	Ni	Mo	Cu	N	Co	Ti	Fe
0.01	0.36	0.97	0.02	29.27	6.72	2.18	0.14	0.39	0.05	0.002	Bal.

**Figure 6.** Variation of density (a) and enthalpy (b) of SS32906 duplex stainless steel wire with temperature.

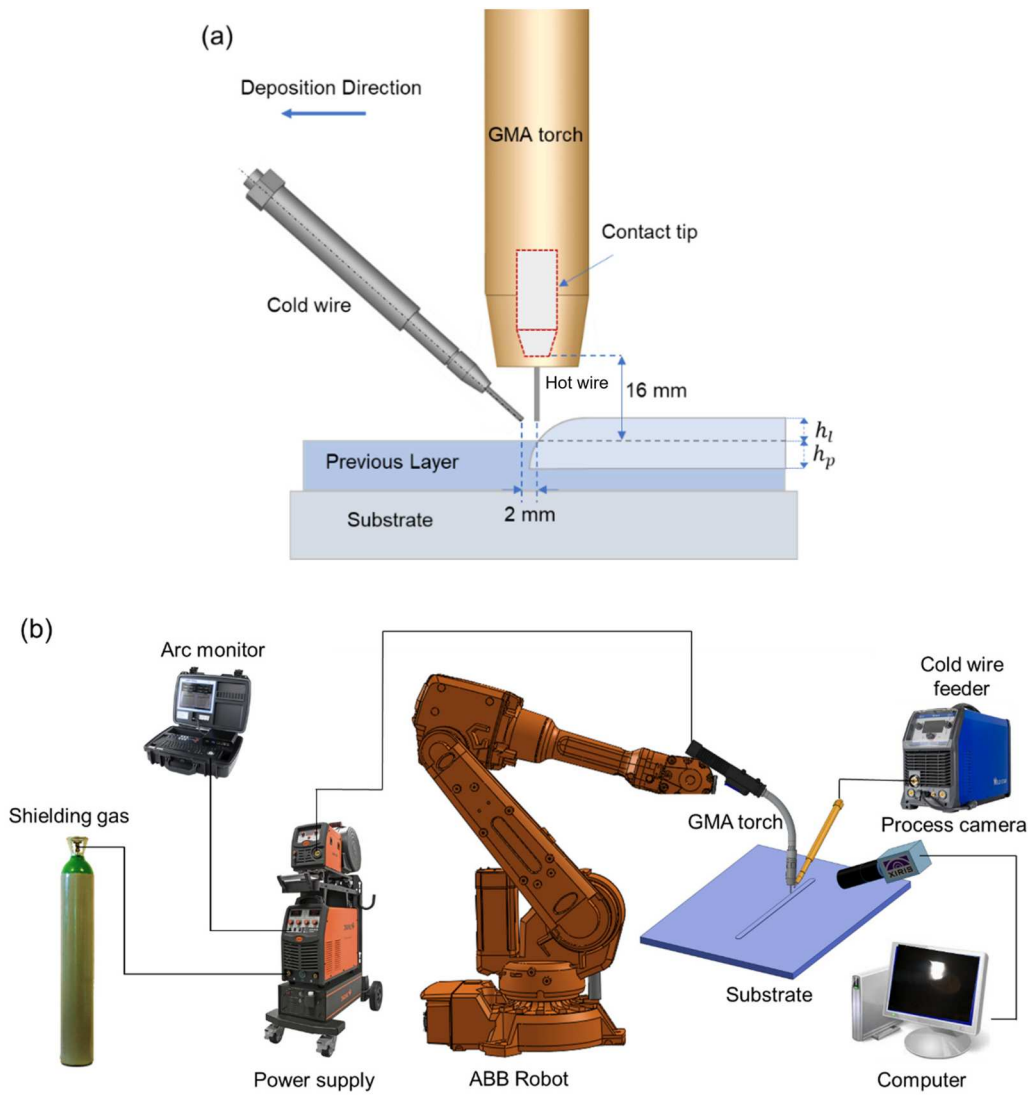


Figure 7. (a) The schematical configuration of the CW-GMA deposition process with different positions of two wires; (b) The schematical setup of the CW-GMA deposition process, along with the associated equipment.

$300 \times 60 \times 8$ mm, employing local shielding ($\text{Ar} + 2.5\% \text{CO}_2$) with a shielding gas flow rate of 20 L/min . Each wall consists of 12 layers and measured 260 mm in length. Various energy and material inputs per unit length were used for the deposition, with a constant inter-layer temperature of 75°C . Five of the samples were used for calibration of the penetration melting efficiency, while the remaining samples were used for validation purpose. In the deposition experiments, overflow of molten material occurred in six samples, while no overflow was observed in the other samples.

3.4. PTA w-DED process

The PTA w-DED process offers several advantages, including high deposition rate and low surface waviness [30]. A 3-axis CNC machine was used for the PTA process

with an 8 mm stand-off distance between the PTA nozzle and the substrate (Figure 8) to deposit twenty multi-layer ER90S-G low-alloy steel walls with a wide range of process parameters. A welding camera with a proper view angle was installed to observe the deposition process. Also, to ensure accurate recording of arc current and voltage, an arc power acquisition device was employed during the deposition. Overflow was observed in six samples, while the other samples were free from overflow defect.

4. Results and discussion

Through experimental tests using the CW-GMA process with ER90S-G low-alloy steel wire, it was observed that when the bead height exceeded the capillary length, surpassing a threshold corresponding to a critical value

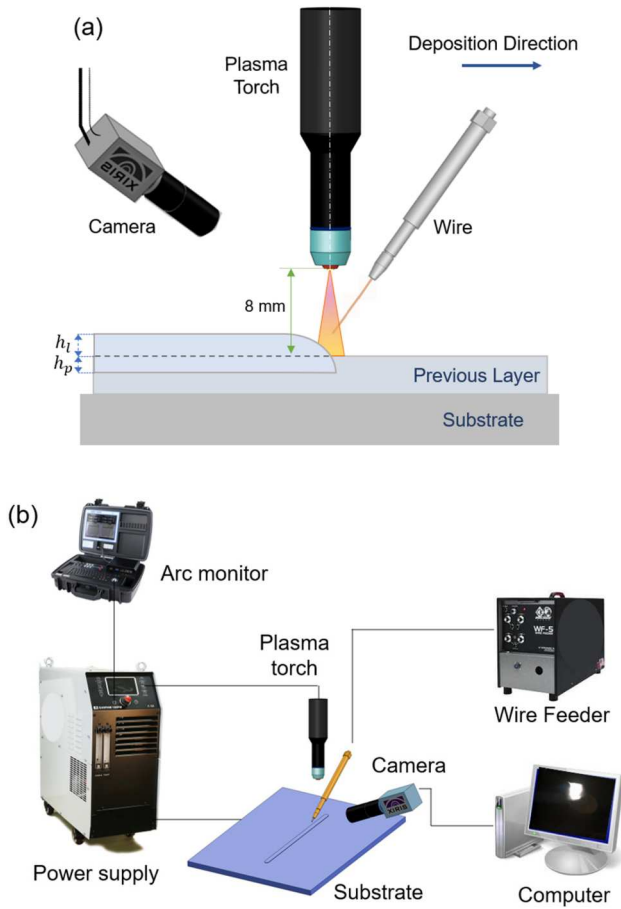


Figure 8. (a) The schematical configuration of the PTA deposition process with ER90S-G low-alloy steel wire from a side view; (b) the schematical setup of the PTA deposition process, along with the equipment used in the process.

of the reciprocal Bond number, i.e. $1/Bo_c = 0.74$, overflow occurred. This is because, before overflow takes place, the liquid metal is moved toward the bead's edges by different forces within the melt pool. It accumulates there, and the surface tension holds it in place. In the critical condition, the metal at the edge is almost still, and the main forces shaping the melt pool – such as arc pressure or Marangoni flow – no longer have much effect. For instance, in the PTA-WAAM process using a 200 A arc current, arc pressure can reach up to 1853 Pa at the centre of the arc, but it drops to below 100 Pa just 2 mm away [31]. Since the side edges are usually more than 3 mm away from the centre, they lie beyond the reach of these strong forces.

The process parameters affect how heat transfers and liquid metal moves, which in turn change how much metal accumulates at the edges. Overflow begins when the weight of the accumulated liquid metal becomes too much for the surface tension to hold. In theory, this could happen even when the reciprocal Bond number is just slightly smaller than one,

while in reality, the gravity needs to be sufficiently dominant to trigger a considerable overflow, and from the calibration experiments a critical value of 0.74 was identified, which were then further verified in the experiments of the CW-GMA deposition with SS32906 duplex stainless steel wire and PTA deposition with ER90S-G low-alloy steel wire.

The following sections present the reciprocal Bond number calculated using the thermo-capillary-gravity model and the detailed validation of the analytical model for predicting the overflow occurrence.

4.1. Overflow occurrence prediction for CW-GMA w-DED process

4.1.1. ER90S-G low-alloy steel walls

Forty-four walls deposited using the CW-GMA process with a wide range of energy and material inputs per unit length were examined to validate the overflow prediction model. Figure 9a–c show the $1/Bo$ obtained from the analytical model, as a function of material input per unit length M_{IL} , energy input per unit length E_{IL} , and their ratio (E_{IL}/M_{IL} , indicating specific energy). Most of the observed overflow cases (only three exceptions) fall in the regime below the dashed line for the critical $1/Bo$ of 0.74, indicating the correct prediction of the overflow occurrence by the model. Figure 9d shows the camera-observed overflow formation during the CW-GMA deposition. Figure 9e and f compare two deposited samples without and with overflow, respectively, along with the etched macrographs of the cross sections. From Figure 9a and b, it is seen that both M_{IL} and E_{IL} are influential on the magnitude of $1/Bo$. This is due to the dependence of the bead height h_b on the M_{IL} and E_{IL} , while the h_b affects the relative importance of the surface tension and gravitational force, which will be further discussed later.

Table 3 compares the correct and false predictions of overflow occurrence using the analytical model. There were sixteen deposited cases with overflow and twenty-eight cases without overflow, for which the analytical model had false predictions for three cases with overflow and four cases without overflow, achieving 84% overall prediction accuracy. The potential causes for the false predictions could be the inaccuracy in estimating the penetration melting efficiency using the analytical model and the assumption of a constant inter-layer temperature throughout the deposition process.

Figure 10a shows the variation of the reciprocal Bond number $1/Bo$ when the material input per unit length (M_{IL}) increases, while keeping the energy input per unit length approximately constant ($E_{IL} \approx 1114 \text{ kJ/m}$). Based on Figure 10a, an increase in M_{IL} means more

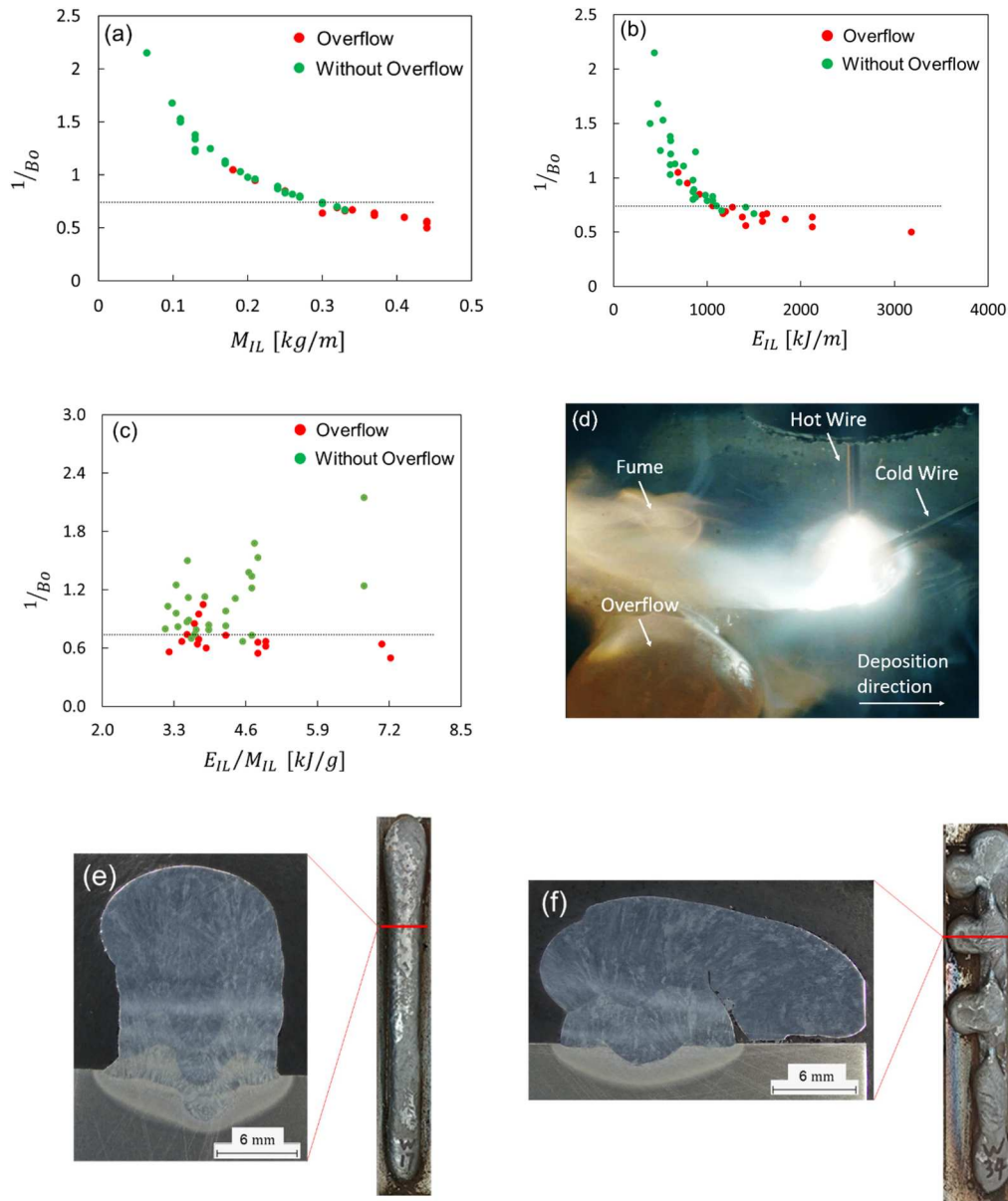


Figure 9. Comparison of the $1/Bo$ as a function of M_{IL} (a), E_{IL} (b) and E_{IL}/M_{IL} (c) for forty-four CW-GMA single-pass deposited ER90S-G low-alloy steel walls (the critical $1/Bo_c$ value of 0.74 is shown as a dashed line). The occurrence of overflow during the deposition process is shown in (d). Two samples without overflow (e) and with overflow (f) are also shown, along with etched macrographs of cross-sections.

material is deposited per unit length. This affects the forces imposed on the surface, resulting in the gravitational force becoming dominant over surface tension. Consequently, the $1/Bo$ steadily decreases until it drops below the critical value, leading to the overflow of molten material.

Similarly, Figure 10b shows the variation in $1/Bo$ when the E_{IL} increases at an approximately constant material input per unit length ($M_{IL} \approx 0.29 \text{ kg/m}$). Increasing the E_{IL} leads to higher energy input exceeding the required energy for a particular deposition rate, resulting in the increase of the molten material height.

Table 3. Number and percentage of correct and false predictions for all cases of CW-GMA single-pass deposited ER90S-G low-alloy steel walls with and without overflow.

Condition	Num. of cases	Correct prediction cases	Correct prediction %	False prediction cases	False prediction %
With Overflow	16	13	81	3	19
Without Overflow	28	24	86	4	14
Total	44	37	84	7	16

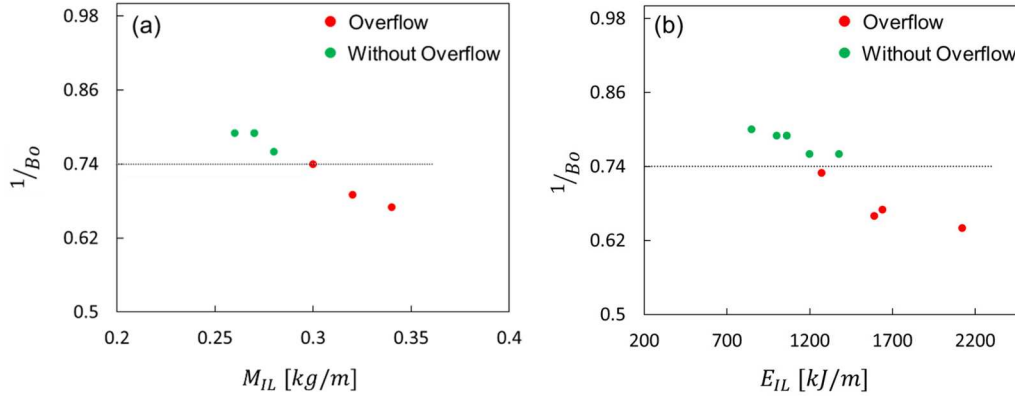


Figure 10. Plot of the $1/Bo$ as a function of M_{IL} at a constant E_{IL} ($E_{IL} \approx 1114$ kJ/m) (a), and plot of $1/Bo$ as a function of E_{IL} at a constant M_{IL} ($M_{IL} \approx 0.29$ kg/m) (b) for the CW-GMA deposition of single-pass ER90S-G low-alloy steel walls (the critical $1/Bo_c$ value of 0.74 is shown as a dashed line).

The increase in bead height leads to larger gravitational force that overwhelms the surface tension on the edges of molten material and causes the overflow of the top layer.

According to the above results, both material and energy inputs per unit length are pronounced influential factors for overflow occurrence, which have not been revealed in the literature (for instance, unlike the analysis in this study, Xiong et al. [2] considered basic process parameter of arc current specific to a WAAM process as the key influential factor of overflow occurrence). The material and energy inputs influence the overflow through changing the bead height term in the reciprocal Bond number (Figure 11). Figure 12 shows the model predictions for layer height h_l , penetration height h_p and bead height h_b of the CW-GMA deposition at $M_{IL} \approx 0.2$ kg/m and at $E_{IL} \approx 1129$ kJ/m for ER90S-G low-alloy steel walls. On one hand, an increase in the energy input at a constant material input hardly changes h_l , but leads to a marked

increase in the h_p , therefore an overall increase in the h_b of the deposition. On the other hand, increasing the material input at a constant energy input results in a significant increase in h_l , but it results in a marginal reduction in the h_p , thus an overall increase in h_b . Although higher energy and material inputs per unit length can both increase the h_b , thereby reducing the reciprocal Bond number and promoting the overflow, the mechanism is different (Figure 12). Furthermore, it is found that h_l and h_p (and hence h_b as their sum) have a stronger correlation with M_{IL} than E_{IL} . This is because at a constant M_{IL} , the E_{IL} mostly affects the h_p , but at a constant E_{IL} , the M_{IL} affects both h_l and h_p , leading to stronger influence on h_b .

4.1.2. SS32906 duplex stainless steel walls

To further test the model for different materials, fifteen SS32906 duplex stainless steel walls were built using the CW-GMA w-DED process. Figure 13a–c present the model prediction of overflow occurrence for all the samples. It is found that $1/Bo$ has a stronger correlation with M_{IL} than E_{IL} , and a clear trend of decrease in $1/Bo$ with increasing M_{IL} is evident. This is because the bead height h_b increases as a result of the strong positive correlation between the M_{IL} and layer height h_l (Figure 12b). The correlation to E_{IL} is weaker, and the results are more scattered. However, the overall trend is that $1/Bo$ decreases when M_{IL} and E_{IL} increase. Figure 13c also shows that overflow mainly occurred when the E_{IL}/M_{IL} ratio was low, in contrast to the result for the ER90S-G low-alloy steel for which overflow occurred at both low and high values of E_{IL}/M_{IL} . The etched samples without and with overflow are shown in Figure 13d and e, respectively. Compared to the ER90S-G low-alloy steel wall (Figure 9d and e), the SS32906 duplex stainless steel wall exhibits larger surface waviness, but the overflow defects appear similar. Table 4 compares

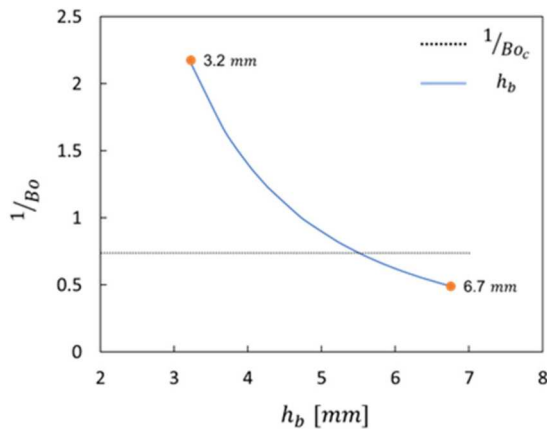


Figure 11. Dependence of $1/Bo$ on h_b according to Eq. (9) for ER90S-G low-alloy steel. The minimum and maximum h_b values (i.e. 3.2 mm and 6.7 mm) are identified from the CW-GMA experiments with ER90S-G low-alloy steel wire (the critical $1/Bo_c$ value of 0.74 is shown as a dashed line).

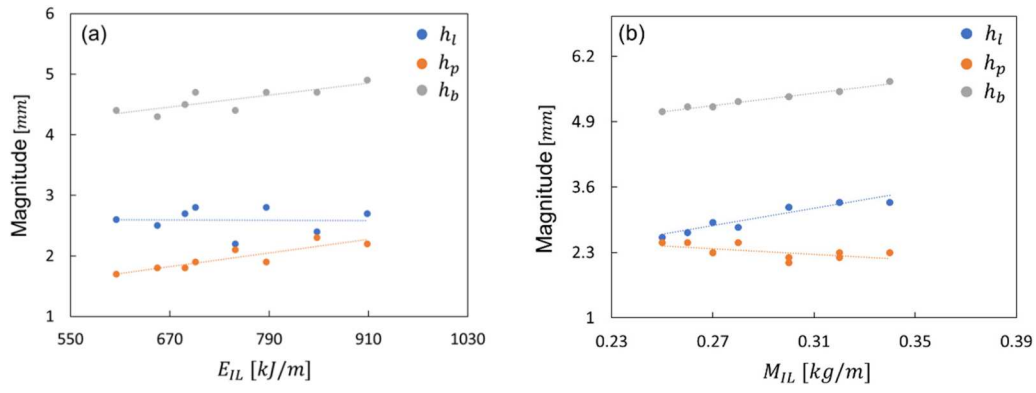


Figure 12. The comparison of layer height h_l (blue), penetration height h_p (orange) and bead height h_b (grey) as a function of energy input per unit length at a constant material input per unit length ($M_{IL} \approx 0.2$ kg/m) (a) and as a function of material input per unit length at a constant energy input per unit length ($E_{IL} \approx 1129$ kJ/m) (b).

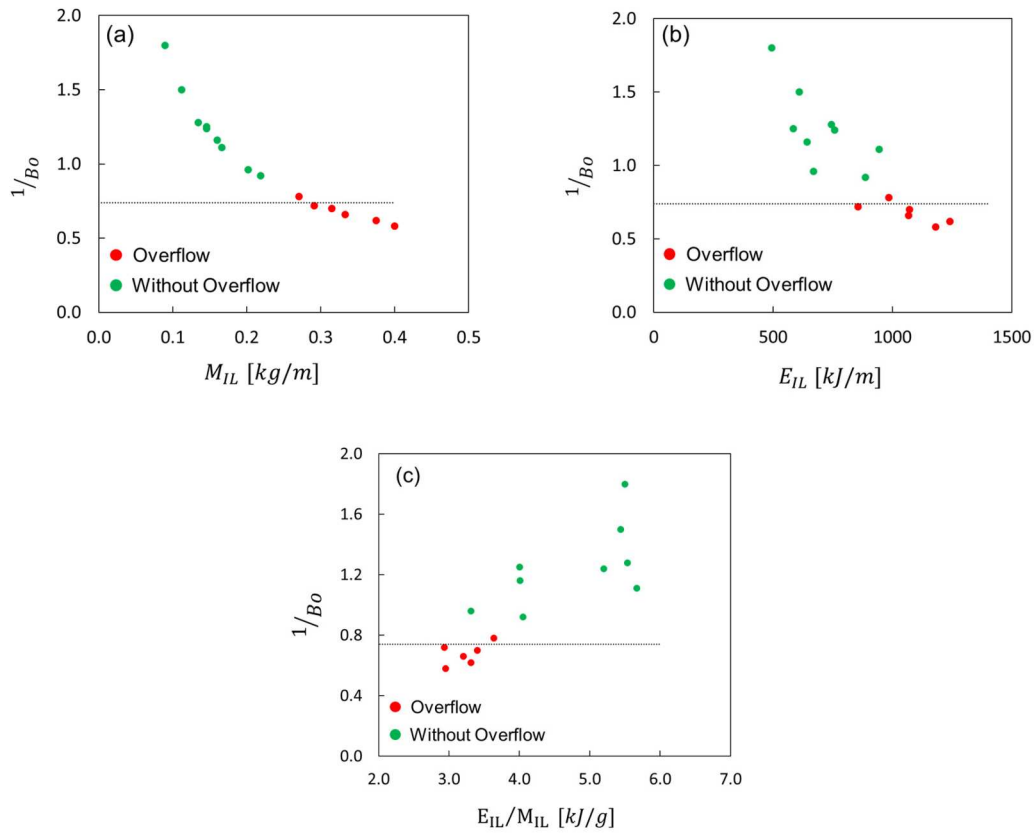
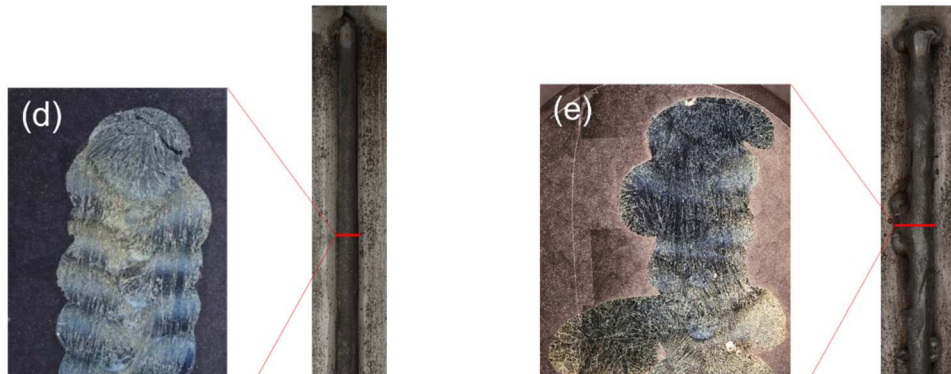
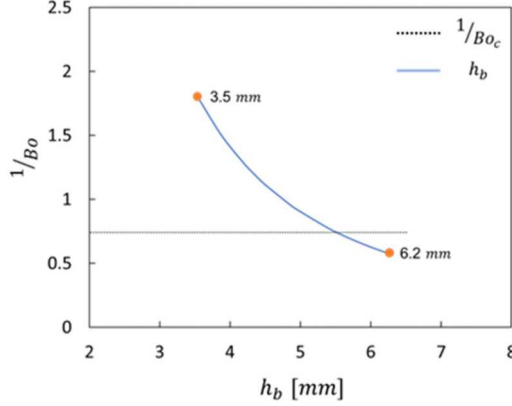


Figure 13. Comparison of $1/B_o$ as a function of M_{IL} (a), E_{IL} (b) and E_{IL}/M_{IL} (c) for fifteen CW-GMA single-pass deposited SS32906 duplex stainless steel walls (the critical $1/B_{oc}$ value of 0.74 is shown as a dashed line). Two samples without overflow (d) and with overflow (e) are also shown, along with the etched macrographs of cross sections.

Table 4. Number and percentage of correct and false predictions for all cases of CW-GMA single-pass deposited SS32906 stainless steel walls with and without overflow.

Condition	Num. of cases	Correct prediction cases	Correct prediction %	False prediction cases	False prediction %
With Overflow	6	5	83	1	17
Without Overflow	9	9	100	0	0
Total	15	14	93	1	7

**Figure 14.** Dependence of $1/Bo$ on h_b according to Eq. (9) for SS32906 duplex stainless steel. The minimum and maximum h_b values (i.e. 3.5 mm and 6.2 mm) are identified from the CW-GMA experiments with SS32906 wire (the critical $1/Bo_c$ value of 0.74 is shown as a dashed line).

the predicted and observed overflow occurrence for the duplex stainless steel walls, summarising the number of cases examined and the percentages of correct and false predictions. According to the results, six deposited samples had overflow, and five of the overflow cases were correctly predicted by the model, while all the deposited samples without overflow were correctly predicted by the model. The findings indicate that the overall percentage of overflow prediction error for all cases is only 7%.

Figure 14 depicts the relation between the $1/Bo$ and h_b for the SS32906 duplex stainless steel walls. According to Eq. (9), the $1/Bo$ is inversely related to the square of h_b , while the capillary length (κ) remains constant for a given material. In other words, when h_b increases, the $1/Bo$ decreases, leading to a reduction in the influence of surface tension and the dominance of gravitational force. So, h_b is the key variable for predicting the overflow of molten material in the w-DED deposition for a given material.

4.2. Overflow occurrence prediction for PTA w-DED process

Concerning the applicability of the model to different w-DED processes, fourteen ER90S-G low-alloy steel walls were deposited using the PTA w-DED process with a

broad range of parameters. Among these walls, six samples exhibited overflow, while the other eight samples were free from defect. Figure 15a–c show comparison between the model predictions and experimental results. The overall trend for the dependence of the reciprocal Bond number on the material and energy inputs per unit length and their ratio for the PTA process is consistent with the trend for the CW-GMA process (Figure 9), despite the E_{IL}/M_{IL} ratio is markedly larger for the PTA process. Figure 15d shows the formation of overflow during the PTA deposition. Furthermore, Figure 15e and f show the typical appearance of the PTA samples without and with overflow, respectively. The overflow defect for the PTA samples appears less severe than for the CW-GMA samples (Figure 9), presumably because the material input per unit length is lower for the PTA process. Table 5 reports the model prediction accuracy for all the samples with and without overflow. The overall error of the prediction is 7.1%. The false predictions can stem from different factors, such as modelling errors in the analytical prediction of bead height and experimental errors in measurement for the model calibration.

The average computational time by the analytical model's solution algorithm for the bead geometry prediction and calculating the reciprocal Bond number is about eighteen seconds, which is significantly lower than other physics-based modelling methods, such as CFD. For example, in the recent CFD study by Chen et al. [32] the average prediction error for bead dimensions in the PTA-based WAAM process was 12%, and the simulation of a single-layer deposition with 5-second duration took approximately 5 days using 32 CPU cores. Additionally, Cadiou et al. [33] showed that simulating just 6-second deposition of the cold metal transfer-based WAAM process took 15 days using 7 CPU cores. Similarly, Zhao et al. [34] showed that a simulation of 2-second deposition of GMA-based WAAM process took around 4 days using 56 CPU cores. Therefore, it is deemed that the analytical model has achieved remarkable accuracy with significantly lower computational time in predicting overflow occurrence.

4.3. Model generalisation for predicting overflow occurrence

The overflow cases for different steels and w-DED processes (Sections 4.1 and 4.2) transpire that the critical

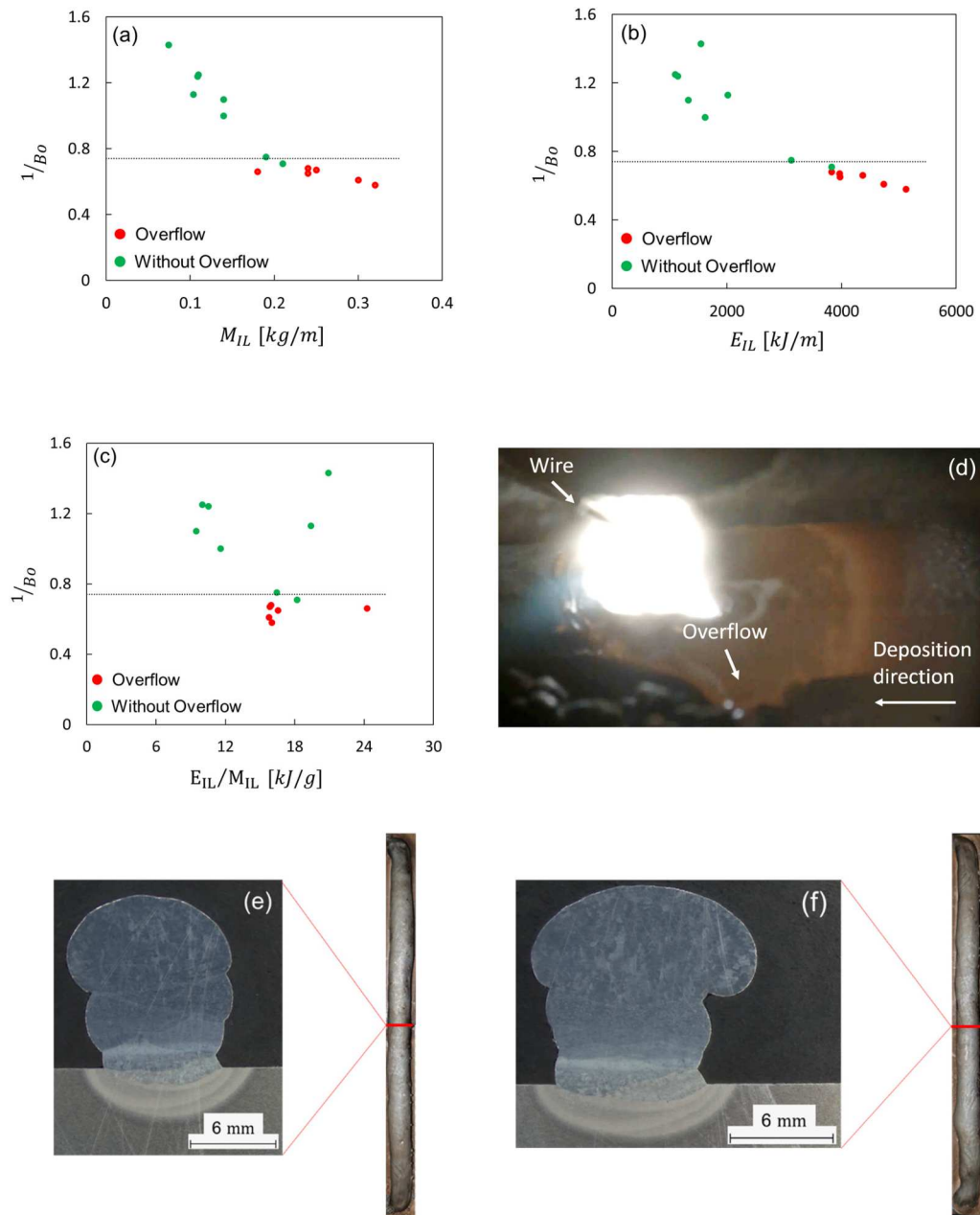


Figure 15. Comparison of $1/Bo$ as a function of M_{IL} (a), E_{IL} (b) and E_{IL}/M_{IL} (c) of PTA deposited single-pass ER90S-G low-alloy steel walls (the critical $1/Bo_c$ value of 0.74 is shown as a dashed line). The occurrence of overflow during the deposition is shown in (d). Two samples of the PTA process without overflow (e) and with overflow (f) are also shown, along with etched macrographs of cross sections.

$1/Bo$ value for overflow occurrence in the w-DED applications is much lower than one. The $1/Bo$ close to one indicates that the relative importance of surface tension and gravitational force is similar. A value of

$1/Bo$ less than one indicates that the bead height is greater than the capillary length, which reduces the effect of the surface tension. A sufficiently low $1/Bo$ indicates the dominance of gravitational force and enables

Table 5. Number and percentage of correct and false predictions for all cases of PTA single-pass deposited ER90S-G low-alloy steel walls with and without overflow.

Condition	Num. of cases	Correct prediction cases	Correct prediction %	False prediction cases	False prediction %
With Overflow	6	6	100	0	0
Without Overflow	8	7	87.5	1	12.5
Total	14	13	92.9	1	7.1

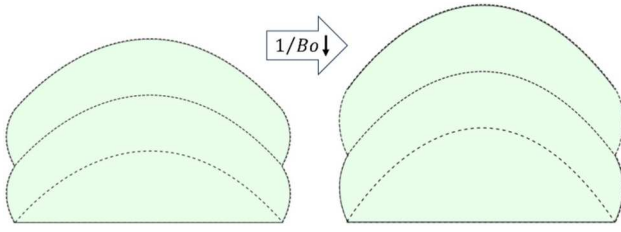


Figure 16. Comparison of two w-DED deposited walls with higher $1/Bo$ (left) and lower $1/Bo$ (right) for a given material at a constant inter-layer temperature.

the overflow to occur. Figure 16 illustrates a schematic of two w-DED walls with different $1/Bo$ values.

From this study, it is found that when the $1/Bo$ is lower than 0.74, there is a high probability of overflow occurrence. So, based on Eq. (9), we have:

$$0.74 h_b^2 = \kappa^2 \quad (12)$$

$$h_b = 1.16 \kappa \quad (13)$$

Eq. (13) gives the critical bead height at which overflow is likely to occur in the w-DED process. Specifically, if the bead height exceeds 1.16κ , there is a significant risk of molten metal overflowing from the top layer. In principle, the modelling approach is applicable to different w-DED processes and materials, as demonstrated in sections 4.1 and 4.2. Rios et al. [17] conducted a study on the prediction of bead geometry of w-DED built Ti-6Al-4V walls. They adopted the cylindrical layer assumption for beads with a height smaller than 6 mm and predicted the bead geometry. Their model has limitations due to the inability to deal with a bead having a larger radius. In their study, the bead height is less than κ (for Ti-6Al-4V, $\kappa = 5.9 \text{ mm}$ [17]), and the $1/Bo$ is greater than one. This indicates that surface tension dominates over gravitational force, resulting in deposits exhibiting a semi-circular shape in the cross-section without overflow. This is also the reason why Rios et al.'s [17] model based on cylindrical layer assumption gave good prediction of the bead geometry for Ti-6Al-4V. However, due to variations in κ , the critical bead dimensions for different materials can fall in a broad range. For Ti-6Al-4V, we have $\kappa = 5.9 \text{ mm}$, and based on Eq. (13), the critical bead height for overflow is 6.84 mm, while for steel, the $\kappa = 4.7 \text{ mm}$ and the critical bead height is 5.38 mm, meaning that steel is more vulnerable to overflow than Ti-6Al-4V. The critical bead height is material specific, since the capillary length depends only on material properties, and the vulnerability to overflow differs between materials. In contrast, the bead height depends on both material properties and process conditions, meaning that the larger bead

height a w-DED process produces, the more likely overflow occurs.

5. Conclusion

The overflow of molten material during a w-DED process causes geometric defects and adversely impacts the quality of an AM-built part. A thermo-capillary-gravity model was created to predict the bead height, and then the reciprocal Bond number ($1/Bo$) was calculated to provide an index for predicting overflow occurrence. The $1/Bo$ indicates the relative importance of gravitational force versus surface tension, and a critical $1/Bo$ value of 0.74 was identified as a threshold for overflow occurrence, below which the overflow is anticipated to occur. This threshold implies dominance of gravitational force over surface tension, corresponding to a critical bead height (h_b) that is 1.16 times the capillary length.

The analytical model was validated for two w-DED processes, i.e. PTA-based WAAM and CW-GMA-based WAAM, which have different material and energy inputs, and for two materials, i.e. ER90S-G low-alloy steel and SS32906 duplex stainless steel. The model predictions of overflow occurrence achieved an overall accuracy of 84% and 93% for the deposited walls using the CW-GMA process with low-alloy steel and duplex stainless-steel wires, respectively. The prediction accuracy was overall 93% for the PTA process with low-alloy steel wire. In addition, the energy input per unit length (E_{IL}) and material input per unit length (M_{IL}) were defined to examine how process condition affects the overflow occurrence. There is a trend that the $1/Bo$ decreases when E_{IL} and M_{IL} increase. This is because the h_b increases with both E_{IL} and M_{IL} , while the higher the h_b , the lower the $1/Bo$. It is also found that the correlation of h_b with M_{IL} is stronger than with E_{IL} , since the M_{IL} influences both the layer height (h_l) and penetration height (h_p), and $h_b = h_p + h_l$, while the E_{IL} mainly influences the h_p . The validated analytical model is generic, efficient and useful for predicting the overflow occurrence during a w-DED process, thereby guiding optimisation of process conditions to prevent overflow and enhance the quality of the final part.

While the current model is designed for single-material wall deposition, incorporating a multi-material deposition process or more complicated part geometry presents an interesting challenge for future work, as the interaction between different material properties, such as varying surface tensions, and the geometric effect on heat dissipation, could introduce additional complexities in accurately predicting overflow occurrence.

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Author contributions

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Data availability statement

Data underlying this study can be accessed through the Cranfield University repository at <https://doi.org/10.57996/cran.ceres-2611>.

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Haghighi, Alireza M.; Ding, Jialuo; Sun, Yongle; Suder, Wojciech; Wang, Chong ...

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