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The Effects of Gravity on Track Integrity During Collaborative Robot-Assisted Wire Arc Additive Manufacturing

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Abstract

Metal deposition against gravity is crucial for additive manufacturing of complex overhangs and curved surfaces. Gravity significantly impacts the metal transfer process, affecting track integrity and quality. While some insights from upward and overhead arc welding are applicable, a clear understanding of the influence of gravity on track integrity is lacking, despite its importance for ensuring the dimensional accuracy of additively manufactured parts. Here, we employ an experimental approach utilizing an in-house collaborative robot-assisted wire arc deposition system to study the gravity effects on the integrity of stainless steel tracks. Real-time monitoring of waveform, molten pool behavior, and metal transfer mode is conducted during the deposition process. This investigation provides unique findings in four directions. First, deposition against gravity during upward scanning deteriorates the track integrity compared to the downward scanning along the gravity. Upward scanning results in humps and bulges because of the lack of support for the depositing materials and molten pool instability. Second, the track integrity for both upward and downward scanning degrades with the increase in the deposition angle with the horizontal plane. Third, deposition on a curved surface that includes a gradual variation of deposition angle with the horizontal plane as well as both upward and downward scanning, can be achieved by precisely controlling the fabrication process. Finally, for all cases, metal deposition using a pulsed arc metal transfer results in better tracks than that using a short circuit metal transfer. These preliminary findings will provide a basis for further investigation into the effects of gravity on the part geometry during wire arc additive manufacturing of large and complex components.

Introduction

Wire arc deposition is an additive manufacturing process where a metallic wire is melted by an electric arc, and the molten metal is deposited layer by layer to form a part [1]. This technique is widely used for its rapid deposition rates, cost-effective equipment, high material utilization, and environmentally sustainable characteristics [2, 3]. The integration of collaborative robots (COBOTs) into wire arc deposition has further enhanced its versatility, enabling complex deposition procedures, path planning, and adaptive adjustments to varying operational constraints [4,5]. COBOTs offer precise control over deposition parameters through their accurate movements, ensuring the quality and consistency of the deposited beads [6-8]. A critical challenge in wire arc deposition, particularly for fabricating complex geometries such as overhangs and curved surfaces, lies in countering the effects of gravity on the molten metal deposition [9]. Gravity significantly influences the metal transfer process, impacting the integrity and quality of the deposited tracks [10]. Understanding how gravity affects track integrity is essential for maintaining dimensional accuracy and ensuring the structural soundness of additively manufactured components.

Some insights from upward and overhead arc welding [11] are applicable to understand the gravity effects during wire arc deposition. For example, gravity caused issues like surface distortion during upward welding, pulling liquid metal away from the arc column [11,12]. High-speed gas metal arc welding also contributed to humping defects against gravity by creating a backward flow of molten metal [13,14], which was mitigated with the twin wire method [15,16]. While many studies have focused on molten pool characteristics on horizontal surfaces in wire arc deposition [17], research on deposit formation on non-horizontal or curved surfaces is limited due to the disruptive effect of gravity on the molten pool [12,18-20]. For example, downward deposition method was found to reduce defects like humping in multi-directional wire arc-directed energy deposition processes [19]. Optimizing deposition parameters like travel speed and current is crucial for mitigating gravity's negative effects on droplet transfer and stability [21]. Understanding gravitational influences can enhance metal transfer dynamics and improve the quality of deposited tracks [22]. Consequently, adjustments to these parameters can improve molten pool characteristics and reduce defects from gravitational forces [23]. What is needed and currently not available is an understanding of the effects of gravity on metal deposition for non-horizontal and curved geometries using different scanning directions and metal transfer modes.

In this study, we employ an in-house collaborative robot-assisted wire arc deposition system to investigate the effects of gravity on the integrity of stainless steel tracks. Metal transfer and molten pool behavior are monitored using a high-speed camera, enabling detailed visualization of dynamic interactions at the wire tip and pool interface. Simultaneously, the waveform is monitored using the system’s in-built waveform analyzer, providing real-time voltage and current signal data. These observations offer comprehensive insights into the physical and electrical phenomena that govern track formation and stability under varying gravitational conditions. Based on these scientific understandings, successful deposition on curved surfaces is achieved.

Materials & Methods

Figure 1 schematically represents the experimental methodology used in this study. An in-house COBOT-based wire arc system [24] is employed to conduct depositions on three different inclined plates set at angles of 30º, 60º, and 90º, utilizing both pulse and short-circuit metal transfer modes with two distinct deposition directions. When deploying a COBOT system, it is possible to implement deposition techniques such as pulse and short circuit, which adjust the deposition parameters in relation to the workspace's orientation. The upward direction refers to the movement of the arc torch from the bottom to the top, while the downward direction indicates movement from the top to the bottom. In both methods, the deposited tracks are created using ER308 wires of 0.8 mm diameter on stainless steel 304 substrates with a thickness of 12.7 mm. The process parameters include a scanning speed of 7 mm/s, a wire feed speed of 180 mm/s. The primary difference between the pulse and short circuit methods lies in the variations in current and voltage during the metal deposition cycle. These temporal variations, known as waveforms, are monitored (0.25 ms time resolution) using an in-built waveform analyzer controlled using Lincoln Electric Power Wave Manager software. Cavitar C300 welding camera was used to monitor the metal transfer and molten pool behavior in real-time (500 fps). The process parameters remain constant throughout the experiment for each respective deposition technique. For each angle, both upward and downward directions were investigated multiple times, and a consistent trend was identified: as the angle increased from 30° to 90°, the degree of irregularity became more pronounced.

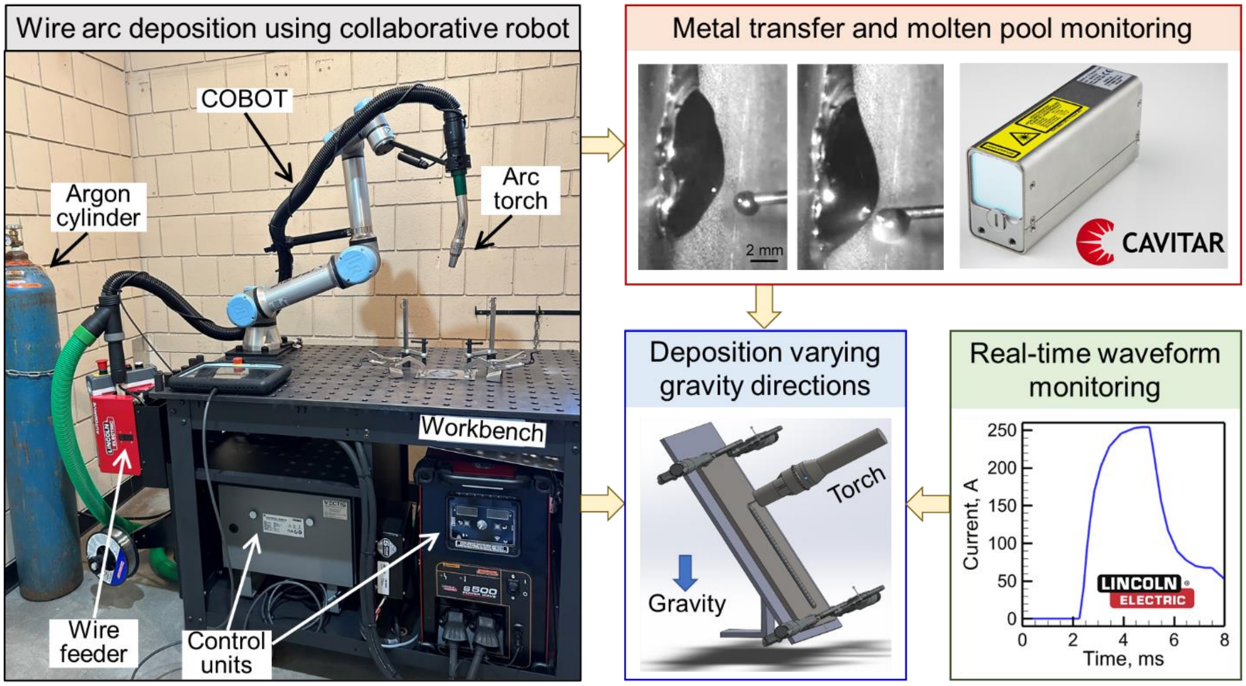

Figure 1: The detailed experimental methodology used in this research.

Results & Discussion

Figure 2 includes CAD models of flat plates oriented at 30°, 60°, and 90° to the horizontal plane, as well as a curved plate representing a continuous variation between these angles. To minimize potential distortions during deposition, all flat plates and the curved surface are securely fixed at their corners. This fixture strategy is particularly critical for curved surfaces, where the risk of deposition disintegration and the inherent complexity of the fabrication process can amplify the effects of distortion, increasing gravity-induced and process-related defects such as sagging, and humping. In all scenarios, the welding torch is held perpendicular to the plate at a fixed 90º angle. The influence of gravity on deposition quality is evaluated in this study by comparing pulse and short-circuit metal transfer modes at different deposition orientations. Short-circuit transfer occurs at relatively low currents. In this mode, droplets solidify quickly, adhere effectively against gravity, and minimize sagging during deposition. However, as the substrate angle increases from the horizontal to a 90-degree angle, the gravitational effect on droplet transfer becomes more pronounced, diminishing the advantages of short-circuit transfer.

Figure 3 illustrates the droplet transfer behavior in short-circuit mode, combining synchronized electrical waveforms and high-speed imaging. In **Figure 3 (a)**, the current increases sharply due to a sudden reduction in electrical resistance during the short circuit when the molten metal at the tip of the electrode wire comes into direct contact with the molten pool. Concurrently, **Figure 3 (b)** illustrates a corresponding voltage drop. This voltage drop occurs because the arc is momentarily extinguished during the short circuit, reducing the arc gap to nearly zero and causing the arc voltage to fall rapidly. These concurrent current and voltage behaviors are the indicators of the cyclical nature of short-circuit metal transfer. In **Figure 3 (c)**, a molten droplet begins to form at the tip of the continuously fed wire electrode. The stable arc provides consistent thermal energy, which facilitates the formation and gradual growth of the droplet. As this molten droplet increases in size and mass, it approaches the pool. **Figure 3 (d)** captures the moment just before the droplet makes contact with the pool, initiating a new short circuit. This event is evidenced by a sudden drop in voltage (**Figure 3 (b)**). The formation of the short circuit effectively creates a low-resistance path for current flow, causing a significant current surge (**Figure 3 (a)**).

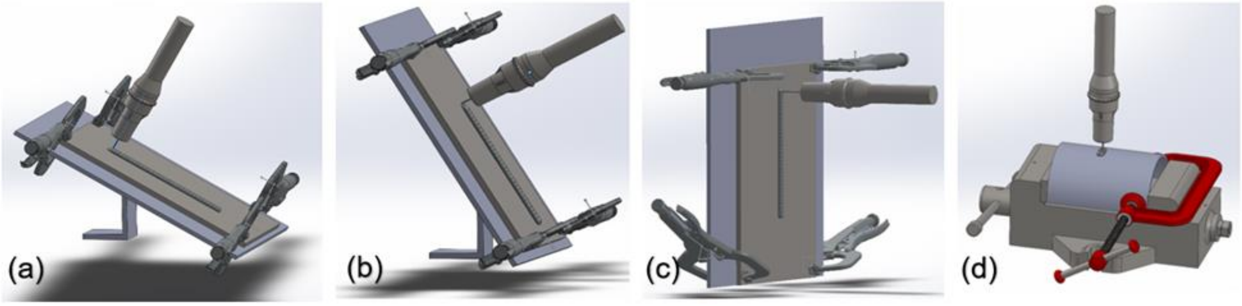

Figure 2: CAD models of flat plates oriented at (a) 30°, (b) 60°, and (c) 90° to the horizontal, and (d) a curved plate representing a continuous angular variation. All plates are clamped with appropriate fixtures to minimize distortion. The welding torch is held perpendicular to each plate at a constant 90° angle.

In **Figure 3 (e)**, the current reaches near its peak, providing enough force to detach the droplet from the wire. In **Figure 3 (f)**, the droplet is fully transferred to the molten pool, and the arc is re-established, corresponding to the increase in voltage and decrease in current in **Figures 3 (a) and (b)**. This sequence captures the cyclic nature of short-circuit transfer and highlights the correlation between waveforms and physical droplet behavior. Moreover, since short-circuit transfer is inherently prone to arc instability due to repeated arc extinction and re-ignition, the direction of deposition plays a crucial role. In this case, the downward movement of the arc, especially toward a 90-degree vertical plate, allows gravity to assist the molten droplet, promoting smoother flow into the molten pool.

Figure 4 illustrates the short-circuit metal transfer during bottom-to-top deposition, where the deposition direction is opposite to gravity. Note that the current and voltage waveforms do not depend on the orientation and remain the same as in **Figure 3**. In contrast to **Figure 3 (c-f)**, where gravity assists the molten droplet's movement and promotes smooth transfer, the upward deposition in **Figure 4** faces gravitational opposition. As shown in **Figure 4 (a–e)**, the molten droplet resists detachment and the pool sags downward due to gravity, causing accumulation at the base of the bead and leading to a bulging or humping effect. In **Figure 4 (a)**, the molten droplet begins to form at the wire tip. Gravity pulls molten droplet downward, away from the intended path, as shown in **Figure 4 (b)**. The droplet enlarges further due to delayed detachment and arc instability (**Figure 4 (c)**). Then, gravitational force prevents proper fusion, causing the droplet to sag (**Figure 4 (d)**), and the droplet eventually detaches but shifts downward, leading to bulging at the base of the track and compromised deposition consistency (**Figure 4 (e)**). This behavior highlights the increased instability in droplet transfer and molten pool behavior in upward short-circuit welding, as gravity pulls the molten metal away from the arc column and disrupts fusional consistency.

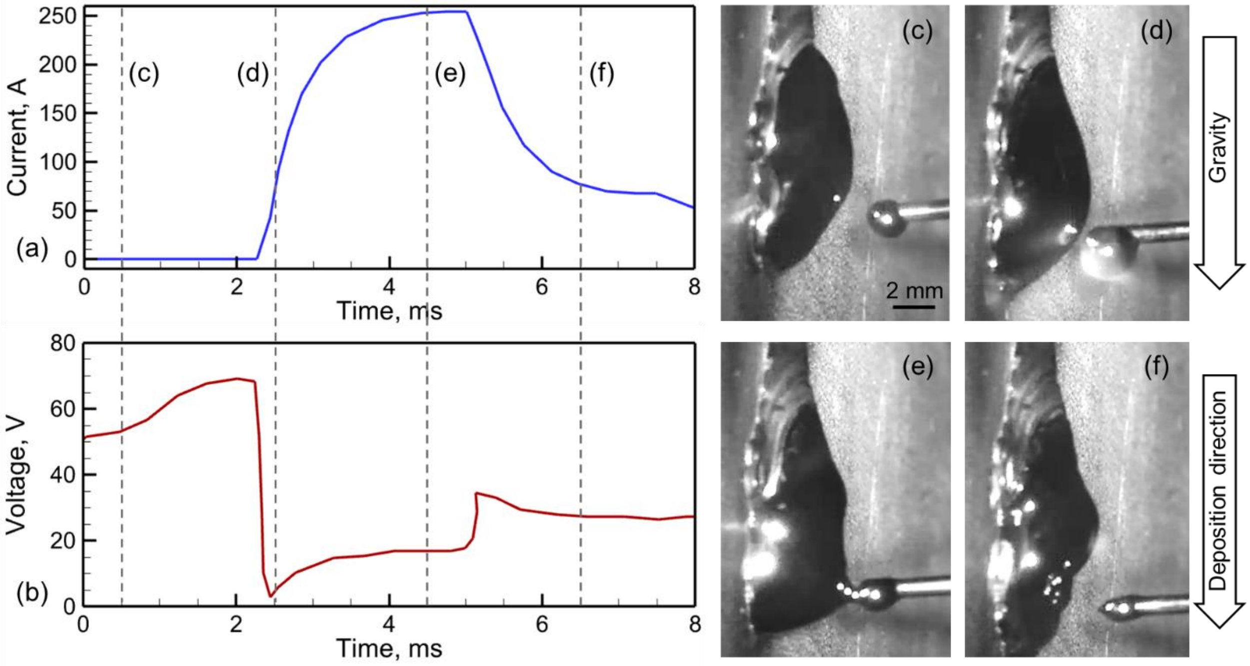

Figure 3: (a) Current and (b) voltage waveforms during wire arc deposition at 90° to the horizontal plane using short-circuit mode metal transfer, where the deposition direction is downward along the gravity. Real-time imaging showing (c) droplet formation, (d) short-circuit initiation and arc extinction, (e) droplet detachment is about to happen, and (f) droplet transfer with arc re-ignition.

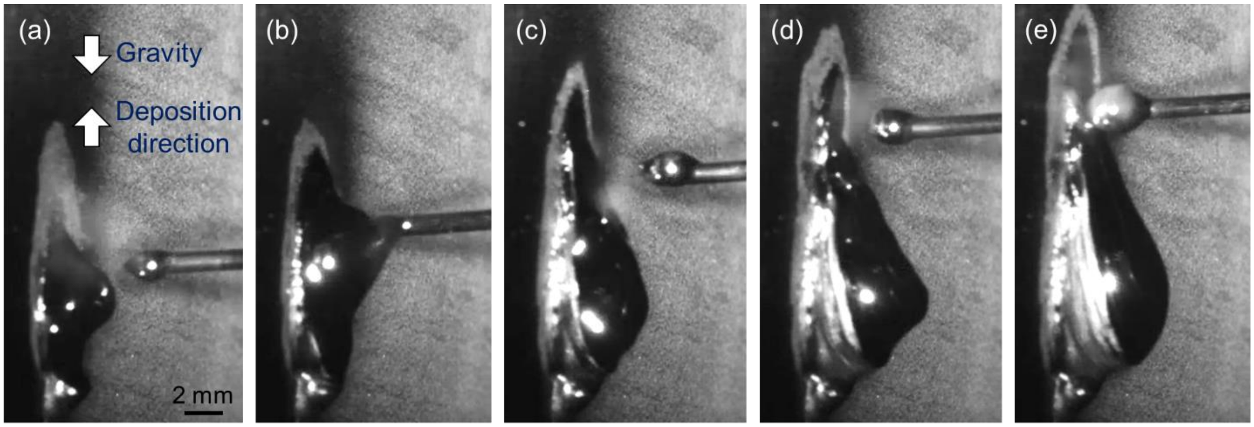

Figure 4: High-speed imaging of short-circuit transfer during bottom-to-top deposition, where gravity acts opposite to the deposition direction. (a) The molten droplet begins to form at the wire tip, (b) gravity pulls molten droplet downward, away from the intended path, (c) the droplet enlarges further due to delayed detachment and arc instability, (d) gravitational force prevents proper fusion, causing the droplet to sag, and (e) the droplet eventually detaches but shifts downward, leading to bulging at the base of the track and compromised deposition consistency.

Figure 5 shows short-circuit mode deposition for 30°, 60°, and 90° plates in the upward and downward direction, which are shown by the red and blue arrows, respectively. As illustrated in **Figure 5,** the gravitational force in the upward deposition pulls each deposited droplet downward before solidification. This effect can cause the droplet to shift or slide before fully fusing with the previous layer, leading to poor bonding and irregular deposition. This phenomenon results in material accumulation at the initial section of the bead, forming a noticeable bulge for all three angled plates due to the lack of support at the beginning of the track, which causes material to pile up. In **Figure 5 (a),** the 30º angled plate allows the molten pool to maintain a relatively stable position against gravity, minimizing the risk of dripping of molten metal compared to steeper angles. With the scanning speed set at 7 mm/s, consistent deposition can be achieved for both upward and downward directions.

As the plate angle increases to 60º in **Figure 5 (b),** the gravity component acting on the molten pool also increases, directly affecting the stability of the depositing track. Uneven depositions become more likely due to the increased gravitational effect on the molten pool, particularly in the upward direction. The results also indicate that the upward deposition direction exhibits greater irregularity compared to the downward direction. This occurs because, in short-circuit transfer, the control over droplet detachment is insufficient, leading to sagging and sliding of the droplet along the substrate surface before it fully fuses with the underlying bead. Consequently, poor bonding and irregular deposition are observed. Then, deposition at a 90° angle has the highest impact of gravity. The molten pool is almost free to flow down (**Figure 4 (e)**), leading to significant potential for bulging as shown in **Figure 5 (c),** especially at the start of the bead during upward scanning. Therefore, by increasing the plate angle to 90 degrees, the effect of gravity in disrupting the molten flow and providing a discontinuous track is increased. As shown in **Figure 4**, at a 90° angle, humping occurs during deposition due to the strong gravitational pull on the molten droplet, which causes it to sag downward. To address this limitation, an alternative deposition method with improved droplet transfer control and arc stability is required to prevent excessive molten fluidity. Pulse mode enables stable track integrity even at steep angles where short-circuit transfer is ineffective.

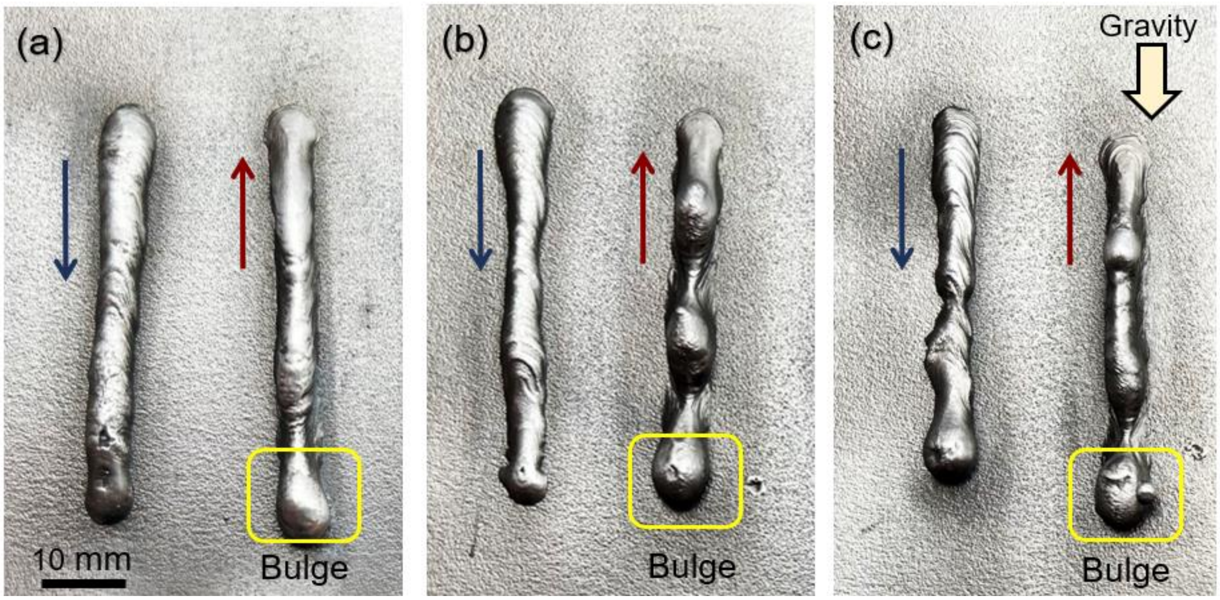

Figure 5: Experimental cases for short circuit deposition are shown for (a) 30-degree, (b) 60-degree, and (c) 90-degree angles. The blue line represents the downward scanning direction, while the red line indicates the upward direction.

Figure 6 illustrates the current and voltage waveforms along with high-speed imaging for pulse metal transfer mode during deposition. In **Figure 6 (a)**, the current alternates between a low current and a high peak pulse, enabling one controlled droplet transfer per cycle. Correspondingly, **Figure 6 (b)** shows that the arc voltage remains relatively stable, confirming the continuous arc condition characteristic of pulse mode. In **Figure 6 (c)**, a molten droplet begins to form at the wire tip during the background current phase. As the pulse current rises in **Figure 6 (d)**, the droplet grows under increasing electromagnetic force. In **Figure 6 (e)**, the peak current is reached, providing enough force to detach the droplet cleanly. Finally, in **Figure 6 (f)**, the droplet is transferred into the molten pool, and the cycle resets. Pulse transfer allows precise control of droplet size, detachment timing, and thermal input. During downward deposition, gravity acts in the same direction as droplet motion, aiding droplet delivery and improving wetting behavior. This synergy between gravity and controlled arc force results in more uniform tracks and consistent deposition.

During upward deposition, gravity opposes molten metal flow and can destabilize the process. However, as shown in the **Figure 7,** pulse mode still helps maintain track integrity due to fast droplet transfer, reduced heat input, and minimal pool disturbance, unlike short-circuit mode which is more prone to humping and instability in such orientations. **Figure 7 (a)** shows that a molten droplet forms. Eventually, the droplet begins to detach under pulse current, as shown in **Figure 7 (b)**. The detachment completes as the droplet moves toward the pool (**Figure 7 (c)**), and finally, the droplet successfully fuses with the molten pool (**Figure 7 (d)**).

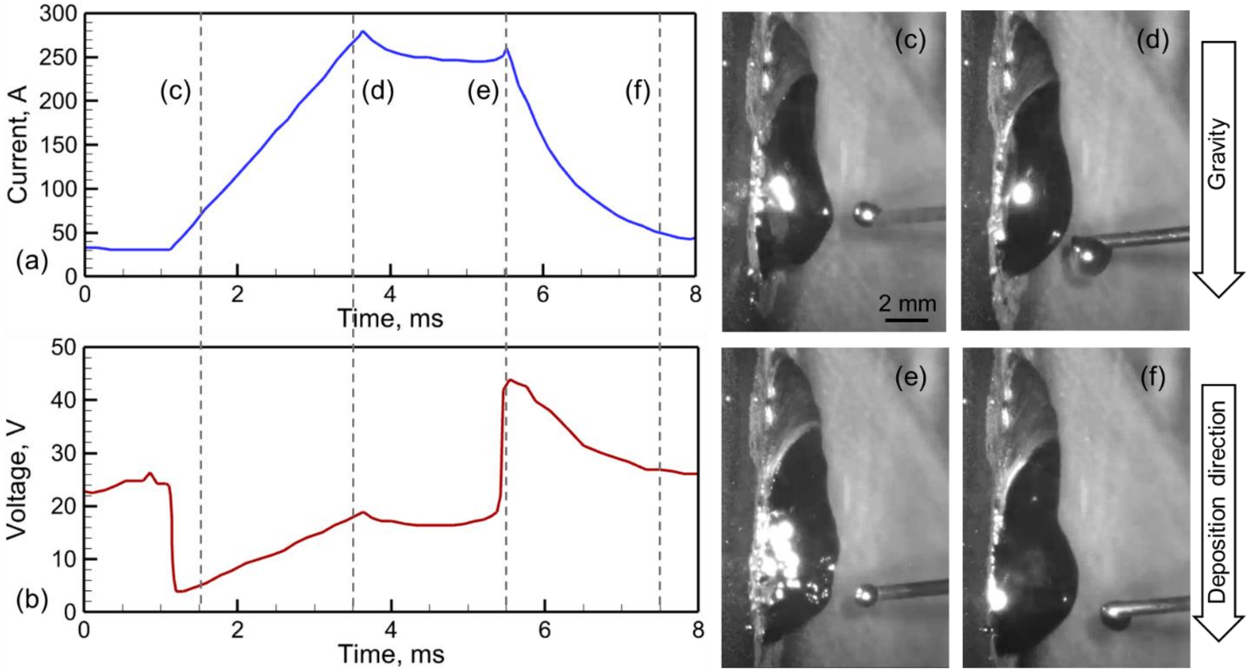

Figure 6: (a) Current and (b) voltage waveforms during wire arc deposition at 90° to the horizontal plane using pulse mode metal transfer, where the deposition direction is downward along the gravity. Real-time imaging showing (c) droplet formation at the wire tip, (d) droplet growth under increasing current, (e) droplet detachment and impingement into the molten pool at peak current, and (f) molten pool behavior immediately after the droplet transfer.

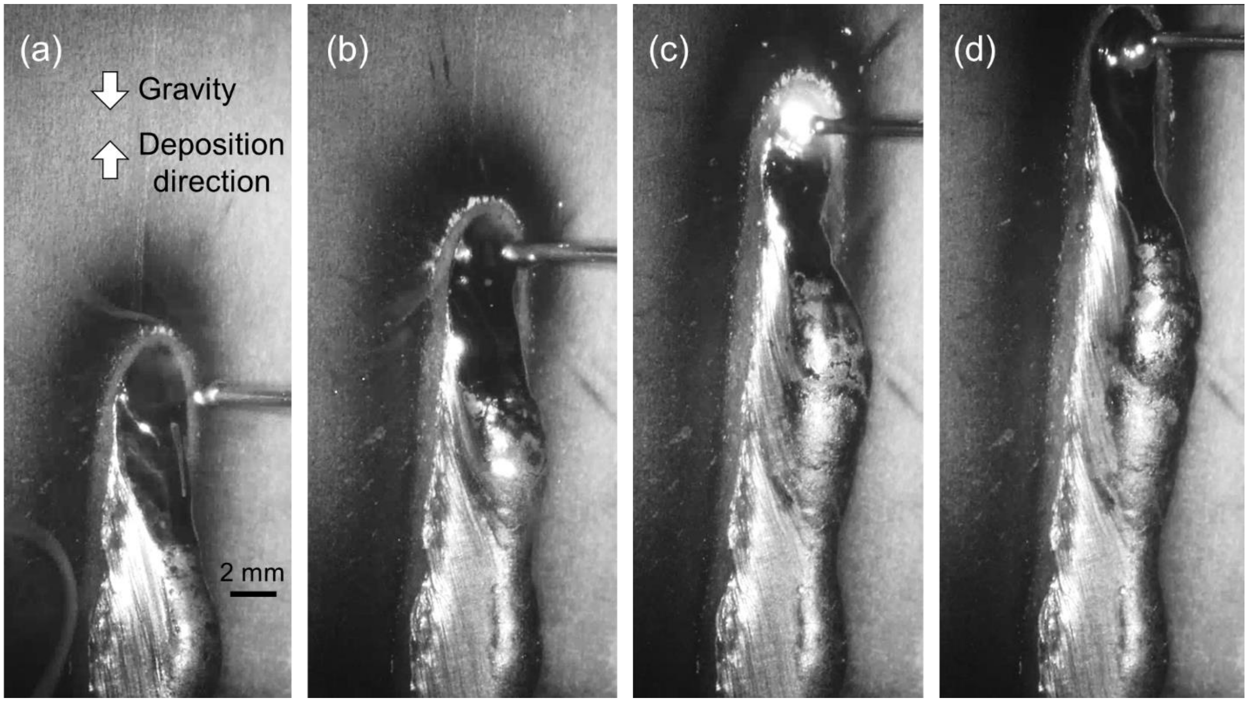

Figure 7: High-speed imaging of pulse transfer during bottom-to-top deposition, where gravity acts opposite to the deposition direction. (a) A molten droplet forms, (b) the droplet begins to detach under pulse current, (c) detachment completes as the droplet moves toward the pool, and (d) the droplet successfully fuses.

Figure 8 compares pulse and short-circuit modes in both upward and downward deposition, indicated by red and blue arrows, respectively. The results show that pulse mode provides better control over deposition behavior, leading to improved overall track integrity. However, the short-circuit mode can lead to irregular bead shapes and sizes due to the fluctuation in metal transfer. In doing upward deposition at an angle of 60 degrees, there is a higher likelihood of creating bulges in the deposited bead due to inadequate control and the tendency of molten metal to accumulate at the lower part of the track. This bulging is intensified in upward deposition as gravity works against the molten pool, leading to instability and inconsistent bead profiles, especially for short circuit.

The aforementioned effect is further illustrated in **Figure 9**, which presents the deposition height consistency. 3D confocal microscopy was used to measure the surface topography of deposited beads to improve understanding of track integrity. This method is non-destructive and provides high-resolution images, making it great for quality control and improving manufacturing processes. By taking a series of vertical images and reducing out-of-focus light, a clear 3D model of the deposited track is created, allowing for precise measurements of height and volume, which are important for assessing the quality and consistency of the deposition process. As evident from the figures, pulse mode results in more uniform tracks. Two indices are used to quantify the track integrity of the deposited beads against gravity based on the confocal microscopy results. To evaluate the track consistency, average high deviation (h_A) and root mean square of track high (h_{RMS}) are defined as [25]:

$$h_A = \frac{\sum_N |Z - Z_m|}{N} \tag{1}$$

$$h_{RMS} = \sqrt{\frac{\sum_N (Z - Z_m)^2}{N}} \tag{2}$$

where, *N* denotes the total number of height values measured along the track length, *Z* is the height of deposited bead at the mid plan in the width direction and Z_m is the mean values of heights. Based on those formulas, the deviation of the track height from the mean height which represents the deposition consistency can be extracted. Higher values shows the track inconsistency and lower values verify the track quality during deposition. Quantitative analysis based on root mean square height deviation and average height deviation confirms that pulsed transfer produces lower deviation values compared to short-circuit transfer. As shown in **Figure 9 (c)** and **(d)**, the blue column represents the short-circuit mode which has poor track integrity due to the lack of molten pool stability against gravity. However, the green column for the pulse mode deposition shows the better deposition quality due to molten pool stability and droplet control against gravity. This highlights the effectiveness of the pulsed technique in mitigating gravity-induced irregularities and improving overall deposition quality.

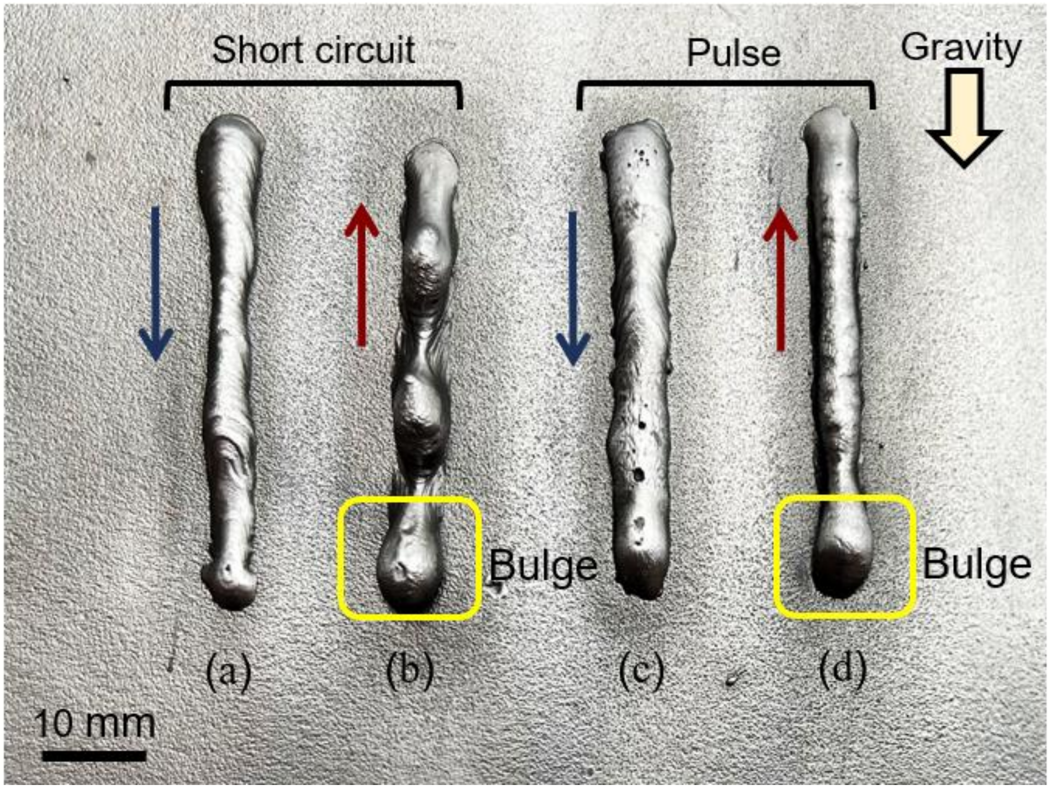

Figure 8: The experimental cases for pulse and short-circuit metal transfer modes with a 60-degree angle are illustrated. The blue line indicates the downward direction, and the red line represents the upward direction.

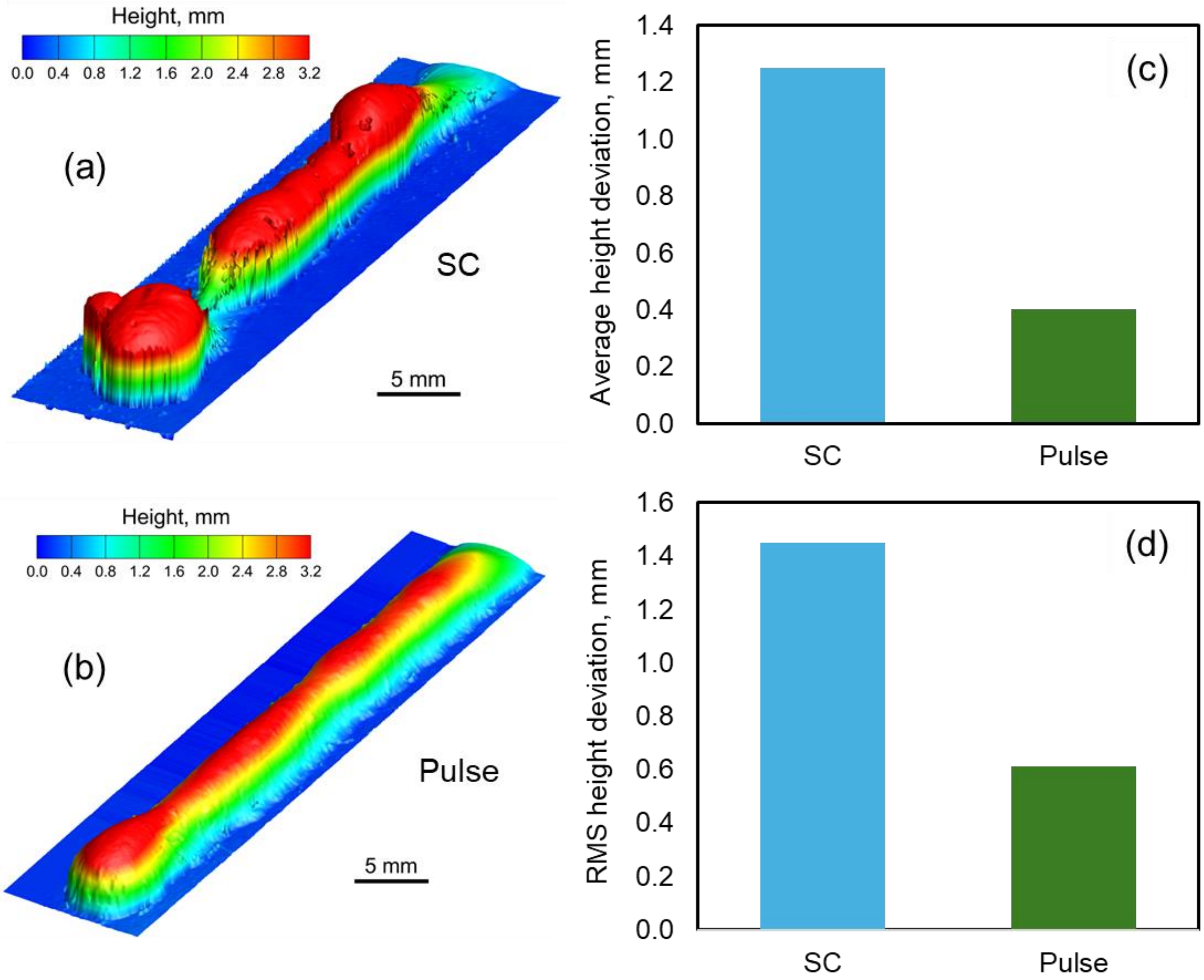

Figure 9: 3D topography using confocal microscopy of tracks made against gravity at 90-degree angle using (a) short-circuit and (b) pulse modes. (c) Average and (d) RMS height deviation.

Table 1 summarizes important observations on the effects of gravity for both upward and downward scanning with different deposition angles for pulse and short circuit metal transfer. The deposition behavior of pulse and short-circuit metal transfer modes was evaluated across three different deposition angles: 30°, 60°, and 90°, in both upward (against gravity) and downward (along gravity) directions. For upward deposition, short-circuit transfer exhibited severe bulging and humping as the angle increased, especially at 60° and 90°, due to arc instability and gravitational resistance. In contrast, pulse mode provided better control, maintaining track consistency at all angles, with only minor bulging observed at the initiation point due to a lack of support. In downward deposition, both modes benefited from gravitational assistance; however, short-circuit still showed instability at higher angles due to excessive droplet accumulation and humping, whereas pulse mode produced consistently uniform tracks. These observations demonstrate that pulse transfer offers superior control over droplet behavior and bead geometry across varying deposition angles and gravitational conditions. Based on these aforementioned observations and understanding, wire arc deposition on curved surfaces is performed. Deposition on a curved surface presents a dynamic combination of changing deposition angles and scanning directions, incorporating both upward and downward movements, as discussed below.

Figure 10 (a) represents a continuous transition through the angular orientations along a curved surface. The first segment of the curve involves upward deposition, where gravity opposes the metal transfer, while the second segment involves downward deposition, where gravity assists the process. In short-circuit mode, this curved deposition path leads to prominent defects, such as bulging, humping in the upward region in the first part of the track, where arc instability and gravitational resistance are most significant. In contrast, pulse mode maintains greater stability throughout the curved path by delivering one droplet per pulse, preserving arc continuity, and minimizing heat input during the deposition on the curved surface. As a result, the tracks deposited using pulse mode are smoother and more consistent, demonstrating its superiority for complex geometries involving continuously varying angles and gravitational influences. **Figure 10 (b) and (c)** show the side and front views of the two deposition techniques.

Table 1: Summary of important observations on the gravity effects for both upward and downward scanning with different deposition angles for both pulse and short-circuit metal transfer.

Scanning direction	**Metal transfer mode**	**Deposition angle with the horizontal plane**			**Scientific explanation**
		30°	60°	90°	
Upward (against gravity)	Short circuit	Bulging happens at the first part	Bulging and humping observed	Bulging and deposition inconsistency occurred	Frequent arc extinction and large, unstable droplets resulting in bulging and humping.
	Pulse	Consistency is observed except for the first part	Bulge happens at the bottom part, but still consistent	Deposition is still consistent except for the first bulge	The stable arc and small, precisely controlled droplets reduce gravitational disturbance
Downward (along gravity)	Short circuit	Continuous track	Uneven deposition happened	Bulging and humping observed	Unstable arc reignition still leads to uneven bead shape and molten pool disruption.
	Pulse	Continuous track	Continuous track	Still consistent except the bottom part	A stable arc and controlled heat input assist uniform droplet deposition.

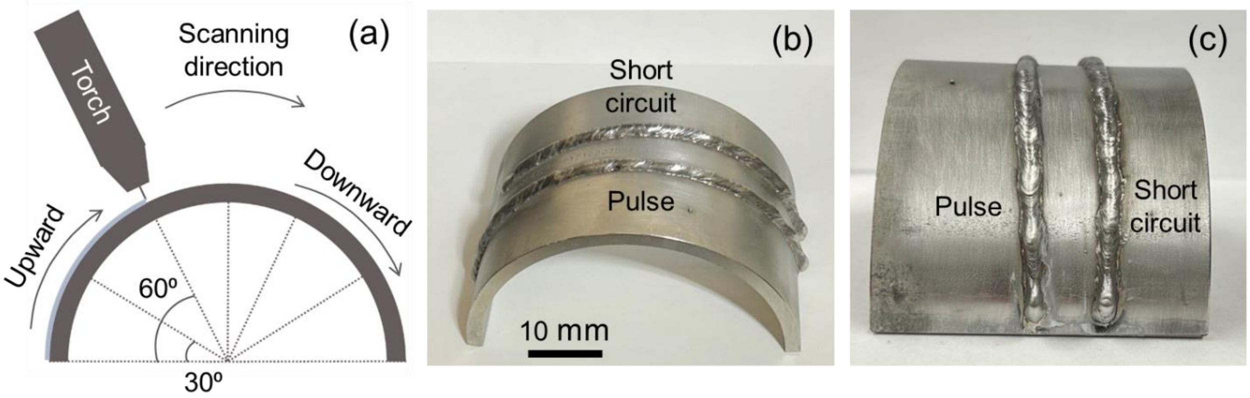

Figure 10: (a) Schematic of curved deposition with upward and downward scanning direction. (b) Side view and (c) front view show that pulse mode achieves more consistent and smoother tracks than short-circuit mode.

Summary & Conclusions

This research investigates the effects of gravity on metal deposition for curved surfaces and non-horizontal planes with different angles using upward and downward scanning directions and different metal transfer modes. Key findings from this investigation are outlined below.

(1) The scanning directions, such as upward (against gravity) or downward (along gravity) introduce key differences in deposition behavior. In the upward scanning, gravity is against the molten pool, generally leading to bulge formation and potentially larger bead profiles shaped at the first part of the track. Conversely, downward scanning can allow for better control over the shape of the bead and is effective in minimizing humping and bulging.
(2) The track integrity for both upward and downward scanning degrades with the increase in the deposition angle with the horizontal plane. For example, tracks made at 90º angle exhibit more discontinuity than those made at 30º angle. This is because the molten pool becomes unstable due to the gravity effects at higher deposition angles.
(3) Metal deposition using a pulsed arc metal transfer results in better tracks than that using a short circuit metal transfer. Pulse mode uses a periodic peak current, which helps a droplet of molten metal detach from the electrode and transfer to the molten pool with precise control, resulting in a more uniform track. In contrast, less uniform tracks are formed in short-circuit transfer due to physical contact between the electrode and the molten pool.
(4) Deposition on curved surfaces is a unique combination of both upward and downward scanning at various deposition angles. The first and second halves of the convex curve surface need upward and downward scanning, respectively. However, unlike the non-horizontal planes, the deposition angle over the curved surface varies smoothly, resulting in uniform tracks.

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