

Article

Swing Arc Behavior and Thick-Wire Droplet Transfer Characteristics in Narrow-Gap GMAW Using Pre-Embedded Cold Wire

Zhengyu Zhu ¹, Yuqing Jiang ², Shubin Liu ³, Yong Xiao ¹, Songyi Wu ¹, Jiayou Wang ^{3,*} and Yunli Lei ^{1,*}

¹ Guangxi Engineering Research Center for Robotic Welding, Guangxi Technological College of Machinery and Electricity, No. 101, East University Road, Nanning 530007, China; zhuzhengyu@gxcme.edu.cn (Z.Z.); xiaoyong@gxcme.edu.cn (Y.X.); wusongyi@gxcme.edu.cn (S.W.)

² School of Intelligent Manufacturing, Shazhou Professional Institute of Technology, No. 1 Fuxin Road, Suzhou 215600, China; jyuqing@szit.edu.cn

³ School of Materials Science and Engineering, Jiangsu University of Science and Technology, 666 Changhui Road, Zhenjiang 212100, China; shubin_l18@just.edu.cn

* Correspondence: jywang@just.edu.cn (J.W.); lyl@gxcme.edu.cn (Y.L.)

Abstract

To improve the stability and controllability of narrow-gap welding (NGW) and systematically elucidate the mechanism by which pre-embedded cold wire modulates arc behavior and metal transfer, this study investigated the arc characteristics and metal transfer behaviors in thick-wire narrow-gap gas metal arc welding (GMAW) with a swing arc and pre-embedded cold wire. Two types of thick wires, single-strand welding wire (SWW) and cable-type welding wire (CWW), were compared under different numbers of pre-embedded cold-wire layers ($n = 0, 1, 2$). The results indicate that during arc swinging, the average arc spreading angle at the sidewalls is consistently smaller than that at the groove center for both wire types. For SWW, the sidewall arc spreading angle decreased by 13.1% and 18.4% with $n = 0$ and $n = 2$, respectively, compared with the groove center; for CWW, the reductions were 24.6% and 20.2%. Moreover, pre-embedded cold wire significantly increased the arc spreading angle (by up to 15.8% for SWW at the groove center) and induced deflection of arc cathode spots toward the cold wire, thereby improving heat distribution on the sidewalls and promoting sidewall penetration. In terms of droplet transfer, SWW exhibited stable spray transfer at the sidewalls and globular spray transfer at the groove center, while CWW showed rotating spray transfer at the sidewalls and a unique hanging droplet transfer mode at the groove center. The average droplet diameter of CWW at the groove center is 17% larger than that of SWW. Pre-embedded cold wire also significantly improved arc stability for both wire types, as indicated by a more concentrated voltage–current distribution, with CWW showing superior stability in the absence of cold wire, whereas no clear regularity was observed in its effect on droplet transfer. The findings suggest that pre-embedded cold wire is beneficial for applications requiring reliable sidewall fusion, as it improves heat distribution while maintaining droplet transfer stability. Further optimization of cold-wire layer number and positioning is recommended for enhanced weld quality.

Keywords: swing arc; thick-wire; arc behavior; droplet transfer; narrow-gap GMAW; pre-embedded cold wire



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1. Introduction

Narrow-gap arc welding is one of the earliest narrow-gap welding technologies, among which narrow-gap gas metal arc welding (GMAW) is the most widely used in medium-thick and thick plates due to its high welding efficiency, sound weld quality, and suitability for automation and intelligent control [1–3]. To improve groove sidewall penetration, narrow-gap GMAW processes with rotating [4–7], oscillating [8,9], or swinging [10,11] arcs controlled by mechanical or electromagnetic methods have been developed, enabling precise arc trajectory and good sidewall penetration.

In addition, to further improve the efficiency of narrow-gap GMAW, methods of introducing cold wire and increasing wire melting rate have been proposed. An ultra-narrow-gap GMAW method with cold wire addition was proposed [12,13], where the addition of cold wire significantly improves welding efficiency and enhances arc stability. Nevertheless, it compromises weld penetration, with a risk of incomplete penetration defects. A narrow-gap GMAW method with an additional wire swinging along with the main wire was proposed [14], where the additional wire attracts and stabilizes the swing arc by digital synchronous control, greatly increasing its melting rate by up to 120% and reducing welding time by 54%.

Nevertheless, the above methods mainly focus on wires of conventional diameters (<1.6 mm). For thick-plate welding, using a thick wire (≥ 1.6 mm) in GMAW is more attractive due to its higher deposition rate [15,16]. Several attempts have been made to apply thick-wire GMAW in narrow-gap configurations, achieving improved deposition efficiency [17,18]. A cable-type welding wire (CWW) of thick diameter was applied in narrow-gap GMAW [17]. And this process leverages the unique arc self-rotation and high-resistance heating effects [17,19] of CWW to significantly improve the sidewall penetration and welding efficiency of narrow-gap welds. A thick-wire swing arc narrow-gap GMAW method and process with pre-embedded cold wire was investigated [18], using two kinds of thick wire for welding: CWW and single-strand welding wire (SWW). Furthermore, cold wire is pre-embedded in the groove before welding, which significantly improves narrow-gap GMAW efficiency while ensuring sufficient weld penetration, and reveals how welding efficiency and weld formation vary with the number of pre-embedded cold wires.

Compared with conventional wires (<1.6 mm), thick wires (≥ 1.6 mm) exhibit distinct differences in droplet transfer behavior and arc characteristics. For conventional wires, stable spray or globular transfer modes are typically observed under normal welding conditions [12,13]. For thick wire (e.g., $\phi 1.6$ mm), globular transfer is also commonly observed, but only under high-current conditions, and the arc stability is highly dependent on the welding parameters [16]. Moreover, for CWW, the multi-strand structure induces a self-rotation effect of the molten droplet, leading to rotating spray transfer at the sidewalls [17,19]. These differences between conventional and thick wires are attributed to the stronger electromagnetic forces and higher current densities generated in thick wires. However, systematic comparative studies between conventional and thick wires in narrow-gap welding remain limited, especially regarding the influence of pre-embedded cold wire on arc behavior and droplet transfer mechanisms.

Previous studies on thick-wire narrow-gap GMAW have mainly focused on welding efficiency and macro-scale weld formation, with limited attention to the arc physics and metal transfer behavior under the influence of pre-embedded cold wire. In particular, the mechanisms by which pre-embedded cold wire affects arc stability, arc morphology, and droplet transfer dynamics in thick-wire swing arc welding remain unclear. A summary of previous studies and the research gap addressed in this work is presented in Table 1.

Table 1. Summary of previous studies on thick-wire narrow-gap GMAW and the research gap addressed in this work.

Reference	Process Features	Key Focus	Contribution of This Study
[1–3]	Review of NGW technologies	Overview of narrow-gap welding processes	Not focused on thick wire or cold wire
[4–7]	Conventional wire, rotating arc	Sidewall penetration	Conventional wire, no cold wire
[8,9]	Conventional wire, oscillating arc	Sidewall penetration	Conventional wire, no cold wire
[10,11]	Conventional wire, swing arc	Sidewall penetration	Conventional wire, no cold wire
[12,13]	Conventional wire + cold wire (feeding)	Efficiency improvement	No arc behavior or droplet transfer analysis
[14]	Conventional wire + cold wire (swaying)	Melting rate increase	Not for thick wire
[15,16]	Thick wire, no cold wire	High deposition rate	No cold wire
[17,19]	CWW (2.4 mm), no cold wire	Arc coupling, rotation, and sidewall penetration mechanisms	No cold wire
[18]	SWW & CWW + pre-embedded cold wire	Weld formation and efficiency	Regulatory mechanisms of arc behavior and droplet transfer not systematically studied Systematically clarifies the regulatory mechanism of pre-embedded cold wire on arc behavior, droplet transfer, and arc stability
This study	SWW & CWW + pre-embedded cold wire	Arc behavior, droplet transfer, stability mechanisms	

2. Materials and Methods

2.1. Welding System

Schematic diagram of the experimental system for cold wire-assisted thick-wire narrow-gap GMAW with swing arc is illustrated in Figure 1. The system mainly consists of three modules: the welding system, the electrical signal acquisition system, and the dynamic observation system for welding processes. The welding system, equipped with a welding supply (MZ-1250, Aotai, Jinan, China), is configured for swing arc narrow-gap GMAW using a thick wire with pre-embedded cold wire assistance. The electrical signal acquisition system comprises Hall current sensors (LF1005-S, LEM, Geneva, Switzerland), high-voltage differential probes (P5200, Tektronix, Beaverton, OR, USA), and an oscilloscope (DSO6034A, Agilent, Santa Clara, CA, USA). The dynamic observation system for welding processes is composed of a high-speed camera (Revealer 5F01, FuHuang AglieDevice, Hefei, China) cooperating with a laser light source (FC-W-808-30W, Changchun New Industries Optoelectronics Technology, Changchun, China), which is employed to characterize the arc morphology and droplet transfer behavior during the welding process.

The welding power source features a constant-current characteristic with a maximum output current of 1250 A. In thick-wire GMAW, the welding power source maintains a basically constant welding current by means of variable-speed wire feeding, thereby sustaining the stability of the welding process when the arc length changes, caused by arc swing. A self-developed thick wire swing arc welding torch was adopted, which drives the welding wire to perform periodic swing through a bent conductive rod, making the arc swing within the narrow-gap groove to achieve sidewall penetration. The arc swing mechanism and the definition of arc swing parameters are described in previous research [19].

Welding current and arc voltage were acquired in real time via a Hall current sensor and a high-voltage differential probe, respectively, with the waveforms recorded by an os-

cilloscope. This system enables synchronous capture of the dynamic variations in electrical parameters during welding, thereby providing reliable data support for the analysis of arc behavior and process stability. A high-speed imaging system consisting of a high-speed camera and a laser light source was employed to photograph the welding arc profile and metal transfer process. During imaging, exposure times of 25 μs and 3 μs were set for the arc and molten droplet, respectively, and the other detailed imaging parameters are listed in Table 2. Two camera viewing angles were used: a transverse view and a transverse view along the welding direction.

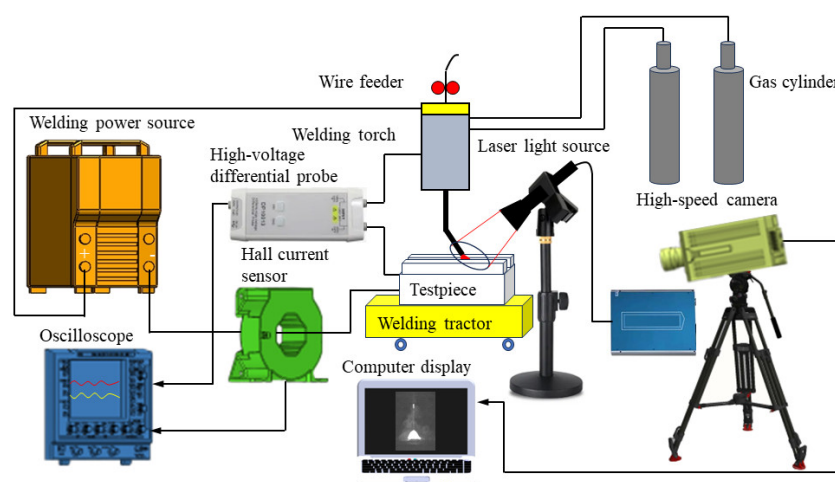


Figure 1. Schematic diagram of cold wire-assisted thick-wire narrow-gap GMAW with swing arc experimental system.

Table 2. Experimental parameters of the arc high-speed camera shooting.

Parameters	Values
Camera depression angle	$\sim 35^\circ$
Frame rate	4000 fps
Aperture	$F/0.8$
Exposure time	25 μs /3 μs
Neutral density (ND) filter	ND-400, Variable ND PRO
Narrow-band filter	970 $\pm$ 10 nm
Camera-to-arc distance	~ 100 mm

The arc morphology (characterized by the arc spreading angle) and the metal transfer behavior (characterized by the droplet diameter and liquid column diameter) were quantitatively analyzed using image processing software (Adobe Photoshop CS5, Adobe Inc., San Jose, CA, USA). For the arc spreading angle, at least 50 frames were randomly selected from the high-speed videos for each experimental condition. Two tangent lines were drawn along the left and right contours of the arc on each frame, and the angle between them was defined as the arc spreading angle. The mean and standard deviation were then calculated from all selected frames. For the droplet diameter, at least 50 droplets were randomly selected from the high-speed images for each condition. Since the droplets were approximately spherical, each droplet image was fitted as an equivalent circle, and the diameter of that circle was taken as the droplet diameter. For the liquid column diameter, at least 50 liquid columns were randomly selected from the high-speed images for each condition, and the diameter was measured at the stable section of the liquid column. All diameters were measured using the same calibrated image analysis software, and the mean diameters and standard deviations were then calculated.

2.2. Experimental Materials and Parameters

The test specimens were fabricated by butt-welding three Q235 steel plates, with a cross-sectional schematic illustrated in Figure 2. A narrow-gap I-shaped groove was adopted, featuring a groove width of 12 mm, while both the base plate thickness and groove depth were set to 20 mm. Two types of thick welding wires were employed in the experiments: one was SWW with a diameter of 1.6 mm (CHW-50C6, ATLANTIC, Zigong, China); the other was a cored wire (CWW, Suzhou Yinli Welding Industry Technology Co., Ltd., Suzhou, China), stranded from seven fine wires with a diameter of 0.8 mm each, resulting in an overall CWW diameter of 2.4 mm [17]. Cold filler wires used for pre-embedded were straight wires with a diameter of 1.6 mm (JQ.TG50, Tianjin Golden Bridge Welding Materials Group Co., Ltd., Tianjin, China), with seven wires embedded per layer. The number of pre-embedded cold-wire layers, denoted as n , was set to 0, 1, and 2. For each experimental condition, a single welding bead was deposited to facilitate the observation of arc morphology and droplet transfer behavior. Preliminary experimental investigations revealed that pre-embedding an excessive number of cold-wire layers may lead to incomplete fusion at both sides of the weld root. Accordingly, the number of pre-embedded layers was limited to a maximum of 2 in this study, enabling a systematic investigation into the effects of pre-embedded cold wire on arc behavior, droplet transfer, and weld penetration. The arc energy parameters and swing parameters adopted in the experiments are listed in Table 3 (the welding current and arc voltage in the table are measured average values, hereinafter the same). A shielding gas mixture consisting of 80% Ar + 20% CO₂ was used at a flow rate of 50 L/min.

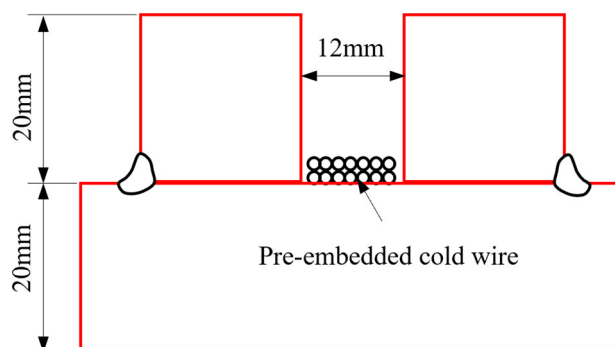


Figure 2. Cross-sectional diagram of thick-wire swing arc GMAW testpiece.

Table 3. Energy parameters and swing parameters of the arc.

Wire Type /Diameter (mm)	Cold-Wire Layer n	Welding Current (I_a , A)	Arc Voltage (U_a , V)	Welding Speed (V_W , mm/min)	Arc Swing Frequency (f , Hz)	Sidewall Dwell Time (t_s , ms)	Reserve Gap (g , mm)
SWW/1.6	0, 1, 2	390	32.0	230	3.6	50	2.5
CWW/2.4	0, 1, 2	460	31.7	260	3.6	50	2.7

3. Results and Discussion

3.1. Characteristics of Swing Arc in Thick-Wire Narrow-Gap GMAW

3.1.1. Arc Morphology and Behavior of Thick Wires

Typical arc morphologies at different positions, during swinging within the narrow-gap groove, are presented in Figure 3. To ensure consistent comparison, the arc images on the left and right sidewalls in the figure were all captured during the middle period of arc dwell time on each respective side. It is observed that the arc exhibits an obvious deflection tendency toward the sidewall during dwell time, regardless of whether SWW or CWW are

employed. This phenomenon can be explained by the “minimum voltage principle” [20]: the arc tends to spontaneously maintain the minimum arc length (i.e., the minimum arc voltage) to sustain stability. When the arc approaches the sidewall, the distance between the arc and the sidewall becomes smaller than that between the arc and the bottom of the molten pool, which drives the cathode spots to shift toward the sidewall and causes the arc profile to bend toward it. This self-regulating characteristic is crucial for ensuring that arc heat acts effectively on the sidewalls and achieves reliable sidewall fusion. It also verifies the suitability of the thick-wire swinging arc process for narrow-gap welding.

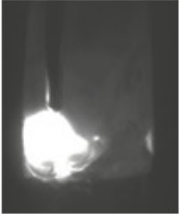
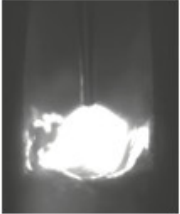
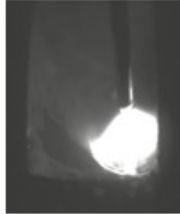
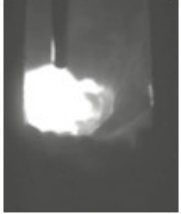
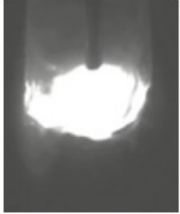
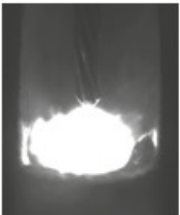
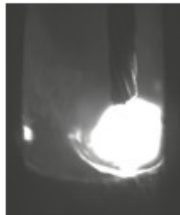
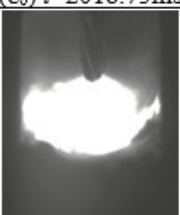
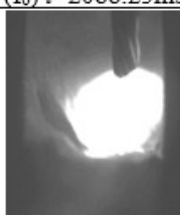
Main wire type	Cold wire layers	Arc at left	Arc at the center	Arc at right
SWW	$n=0$	 (a0) $t=2013\text{ms}$	 (b0) $t=2082.5\text{ms}$	 (c0) $t=2152\text{ms}$
	$n=2$	 (a1) $t=1855.5\text{ms}$	 (b1) $t=1925\text{ms}$	 (c1) $t=1994.5\text{ms}$
CWW	$n=0$	 (d0) $t=1949.25\text{ms}$	 (e0) $t=2018.75\text{ms}$	 (f0) $t=2088.25\text{ms}$
	$n=2$	 (d1) $t=1918.25\text{ms}$	 (e1) $t=1987.75\text{ms}$	 (f1) $t=2057.25\text{ms}$

Figure 3. Swing arc images in thick-wire narrow-gap GMAW, transverse view. Reprinted with permission from Ref [19]. Copyright 2026 Springer Nature.

3.1.2. Comparison of Arc Spreading Angles

To further quantify the arc morphology, statistical results of the average arc spreading angles at different positions in Figure 3 are listed in Table 4. Figure 4 serves as a representative example to illustrate the arc deflection phenomenon toward the pre-embedded cold wire. The measurement procedure is illustrated in Figure 5. The average spreading angle at the sidewalls was calculated as the mean of measurements taken during the middle dwell period on both sidewalls. When the arc swings close to the sidewalls, the cathode spots shift toward the sidewalls in accordance with the minimum voltage principle. This arc deflection shortens the effective arc length, which, under the constant-current power supply

characteristic, gives rise to an instantaneous increase in welding current and strengthens the electromagnetic constriction effect of the arc, resulting in a more concentrated arc profile and a reduced spreading angle. Correspondingly, the average spreading angles of both wire types at the sidewalls are smaller than those at the groove center. Specifically, for SWW under the conditions of no cold wire and two pre-embedded cold-wire layers, the sidewall arc spreading angles decreased by 13.1% and 18.4%, respectively, compared with those at the groove center; for CWW, the reductions are 24.6% and 20.2%, respectively.

Table 4. Comparison of average arc spreading angles of different thick-wire wires.

Wire Type /Diameter (mm)	Cold-Wire Layer n	Average Arc Spreading Angle at the Sidewalls ($^{\circ}$)	Average Arc Spreading Angle at the Groove Center ($^{\circ}$)
SWW/1.6	0	105.4 ± 8.3	121.3 ± 9.6
	2	114.7 ± 8.9	140.5 ± 11.2
CWW/2.4	0	95.8 ± 7.6	127.1 ± 9.3
	2	108.4 ± 8.5	135.9 ± 10.1

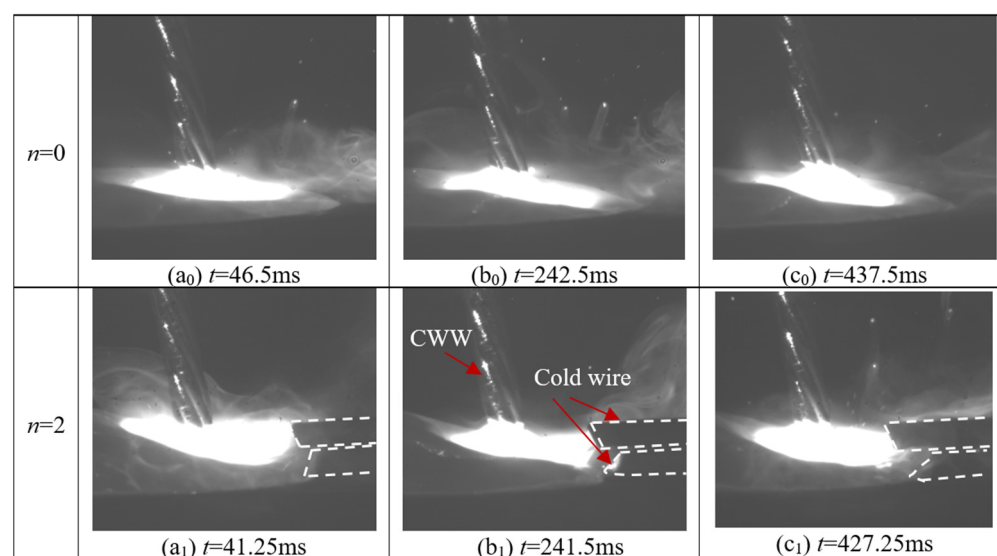


Figure 4. The arc is offset towards the pre-embedded cold wire side (CWW, $n = 2$, average arc current: 460 A, average arc voltage: 31.7 V, welding speed: 260 mm/min, arc swing frequency: 0 Hz, transverse view along welding direction).

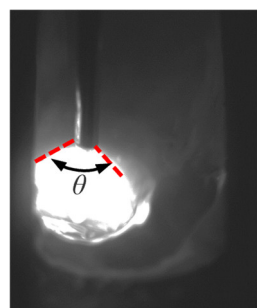


Figure 5. Schematic illustration of the measurement method for the arc spreading angle. The red dashed lines outline the arc contour, and the angle (θ) represents the arc spreading angle (SWW, $n = 0$, arc swing frequency: 0 Hz, $t = 1098.5$ ms).

Similarly, based on the minimum voltage principle, the arc cathode spots tend to shift toward the pre-embedded cold wire exposed at the molten pool as the arc seeks the shortest

path, as illustrated in Figure 4. Such a deflection leads to a distinct increase in the arc spreading angle after pre-embedding the cold wire. For SWW with two pre-embedded cold-wire layers, the arc spreading angles increase by 8.8% and 15.8% at the sidewalls and groove center, respectively. This deflection behavior weakens the direct penetration capability of the arc into the molten pool and reduces the constraint effect of the molten pool on the arc, which is beneficial to controlling the bottom profile of the weld and preventing the formation of finger-shaped penetration.

Compared with SWW, CWW exhibits a more pronounced arc constriction characteristic at the sidewalls. Its average arc spreading angle is reduced by 9.1% and 5.5% under the conditions of no cold wire and two pre-embedded cold-wire layers, respectively. This is mainly attributed to the stronger electromagnetic force generated by the multi-strand structure of the cabled wire, which induces a more intensive arc constriction effect [17]. As a result, the arc of CWW tends to assume a beam-like morphology during dwell at the sidewalls, thereby yielding a smaller arc spreading angle.

Nevertheless, at the groove center, the high welding current and deposition rate of CWW produce an elevated molten pool profile, which weakens the arc penetration capability and consequently increases the arc spreading angle to a level comparable to that of SWW. Under the combined influence of these two mechanisms, CWW presents a significantly larger variation range of arc spreading angle throughout the arc swinging cycle, demonstrating a more sensitive dynamic response to the welding position.

In accordance with the previous weld formation results [18], during thick-wire swinging arc narrow-gap GMAW, the heat absorption effect of pre-embedded cold wire exerts a minor influence on sidewall penetration, which is closely related to the aforementioned increase in arc spreading angle. Although the pre-embedded cold wire absorbs part of the welding heat and may reduce the total heat input available for sidewall melting, the deflection of cathode spots toward the cold wire simultaneously leads to an enlarged arc spreading angle. A larger arc spreading angle indicates a wider and more dispersed coverage of arc heat flux on the sidewall region. Such a heat distribution compensation effect counteracts the adverse impact induced by cold wire heat absorption to a certain extent, thereby ensuring continuous and effective heating of the sidewalls by the arc.

Therefore, in the thick-wire swinging arc GMAW process, the adaptive adjustment of arc behavior (i.e., the increase in arc spreading angle) constitutes the key reason why sufficient sidewall penetration can still be maintained even under high-layer pre-embedded cold wire conditions.

The heat distribution compensation effect proposed in this study is based on qualitative observations of arc morphology and sidewall penetration. Quantitative evaluation of the compensation magnitude requires further investigation, and the present study does not provide direct calorimetric measurements to support the exact compensation ratio. This remains a limitation of the current work.

3.1.3. Stability of Thick-Wire Swing Arc

To quantitatively evaluate arc stability during welding, arc stability was characterized in this study by analyzing the distribution concentration of characteristic points in the arc voltage–current (U – I) domain.

Arc U – I plots for SWW and CWW under different numbers of pre-embedded cold-wire layers are presented in Figure 6(a₁–a₃, b₁–b₃), respectively. The area of the envelope region S_p enclosing the scattered data points was quantitatively calculated using image processing methods, as indicated by the dashed region in Figure 6(a₁). This area directly reflects the fluctuation range and distribution concentration of arc voltage and current. A

comparison of S_p under different thick wires and pre-embedded cold wire conditions is shown in Figure 6c.

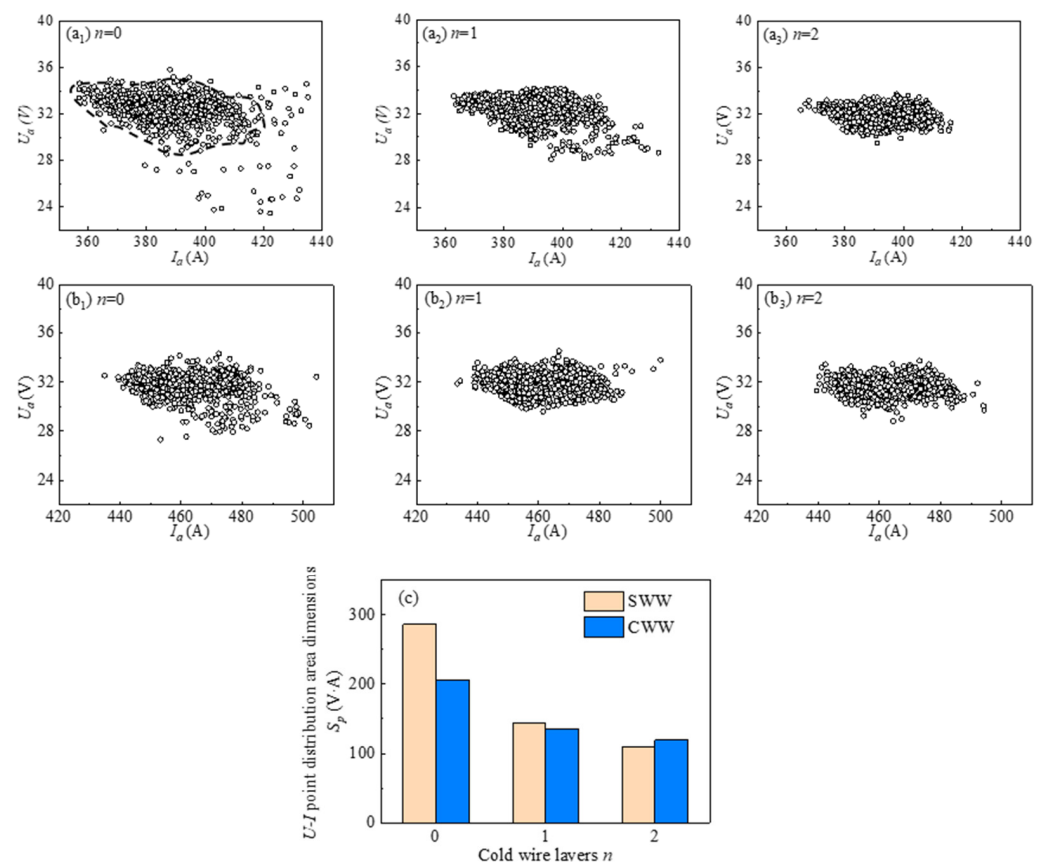


Figure 6. Arc U - I diagrams of GMAW with different numbers of pre-embedded wire layers: (a₁–a₃) SWW; (b₁–b₃) CWW; (c) S_p comparison.

It can be observed from Figure 6c that S_p exhibits a decreasing trend with an increase in the number of pre-embedded cold-wire layers for both SWW and CWW. This indicates that the introduction of pre-embedded cold wire leads to a more concentrated voltage–current distribution and consequently more stable arc behavior for both wire types.

Meanwhile, in the absence of pre-embedded cold wire, S_p of CWW is noticeably smaller than that of SWW, implying a more stable arc for CWW under this condition. When the number of pre-embedded cold-wire layers is ≥ 1 , S_p values of the two wire types are relatively close, suggesting comparable arc stability between SWW and CWW.

3.2. Droplet Transfer Characteristics of Thick Wires

3.2.1. Droplet Transfer Behavior of Thick Wires

Images of droplet transfer during thick-wire narrow-gap GMAW at different positions within the narrow-gap groove are presented in Figure 6. Images corresponding to the left and right sides were captured at the midpoint of the arc dwell period on the left and right sidewalls, respectively. The outer contour of the welding wire is delineated by white dashed lines, while the groove edges are marked by red dashed lines.

In general, when the arc dwells at the sidewalls during swinging, the droplets are small in size and exhibit a high transfer frequency. In contrast, at the groove center, relatively large droplets and a low transfer frequency are observed.

For SWW, stable spray transfer dominates the droplet transfer behavior when the arc dwells at the sidewalls, as shown in Figure 7(a₀,a₁,c₀,c₁). At the groove center, the transfer mode is primarily globular spray transfer, as illustrated in Figure 7(b₀,b₁).

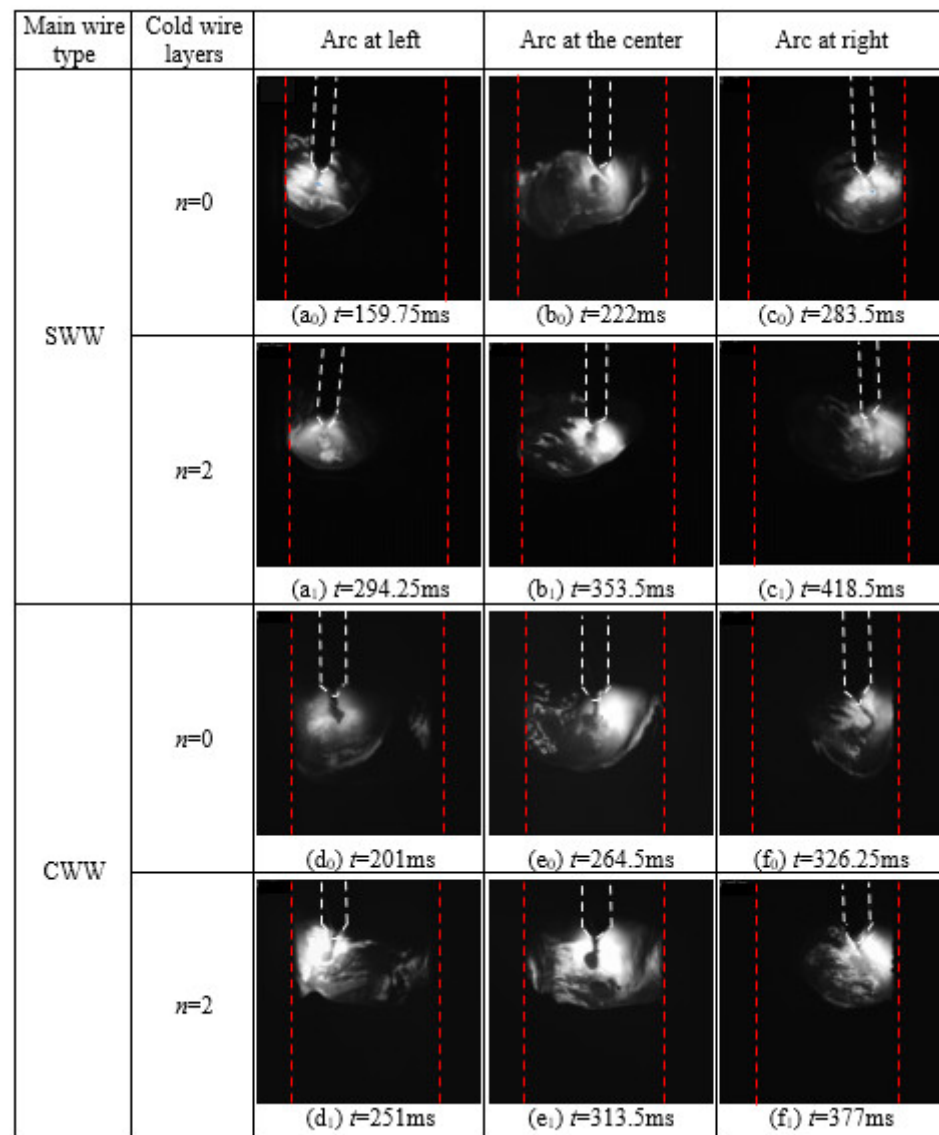


Figure 7. High-speed images of droplet transfer in thick-wire narrow-gap GMAW.

For CWW, rotating spray transfer prevails at the sidewalls (Figure 7(d₀,d₁,f₀,f₁)), whereas hanging droplet transfer is the main mode at the groove center (Figure 7(e₀,e₁)). The underlying mechanisms are described below.

As shown in Figure 8, during the droplet transfer process of CWW, the individual strands first melt into fine sub-droplets, which subsequently converge toward the wire center and eventually coalesce into a large droplet [21]. Owing to the finite time required for this coalescence, the droplet continues to grow at the wire tip until it reaches a critical size. During the detachment stage, the droplet is progressively elongated into a liquid column under the combined effects of arc force and gravity, with its front end appearing as if an incompletely detached droplet is suspended there. It finally separates from the wire tip, completing the so-called “hanging droplet transfer” mode.

On the other hand, the occurrence of rotation in the droplet transfer of CWW is attributed to the self-rotation effect induced by the movement of arc anode spots on the cabled wire. The droplets at the wire tip are subjected to a rotational force exerted by the self-rotating arc [21], leading to rotating spray transfer. This rotating spray transfer imposes a centrifugal effect on the droplets, which facilitates their detachment from the wire tip and thereby increases the droplet transfer frequency.

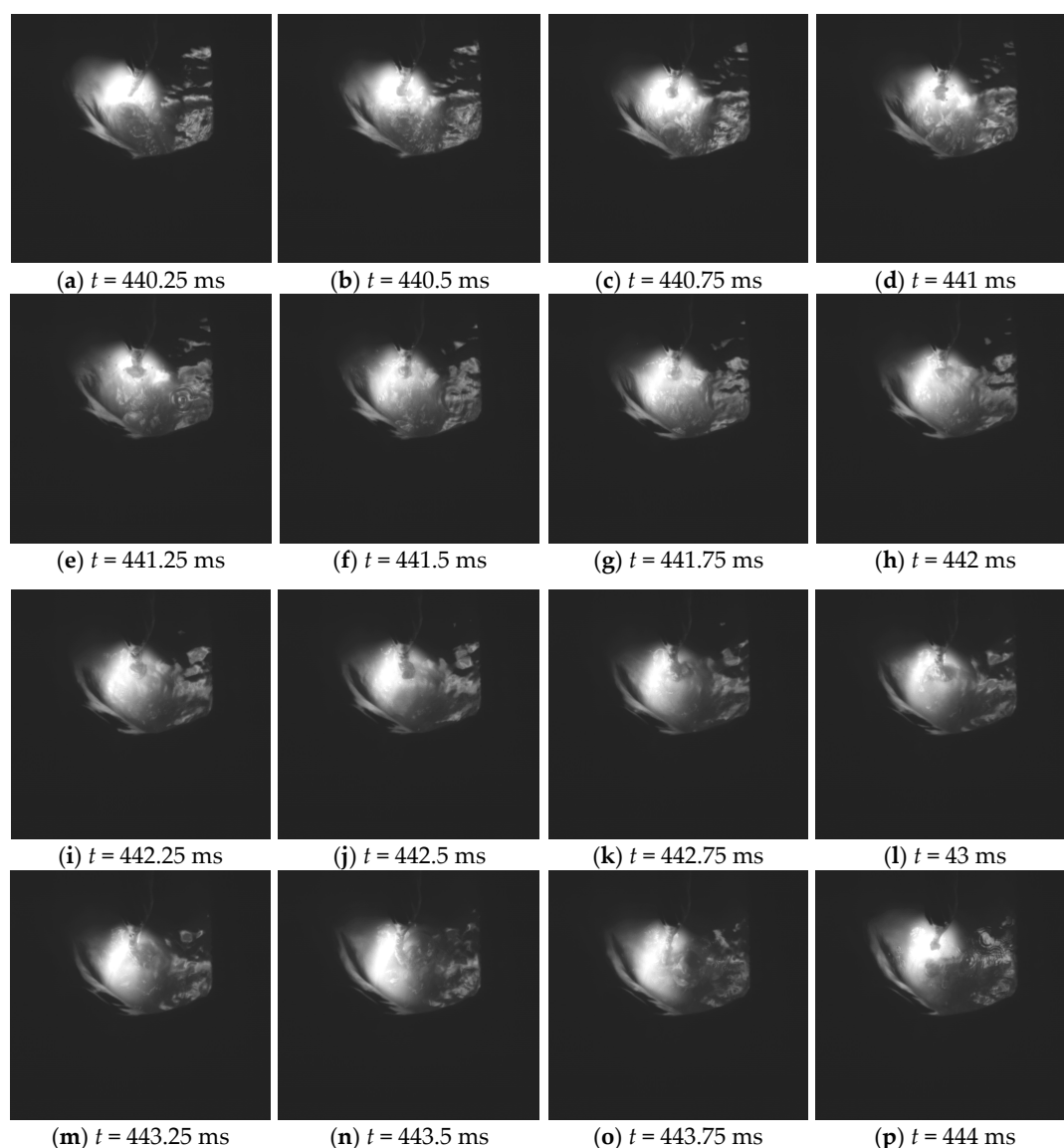


Figure 8. Typical sequence of hanging droplet transfer for CWW at the groove center (CWW, $n = 2$, arc swing frequency: 3.6 Hz). The images show the complete process from droplet formation to detachment: (a,b) droplet begins to hang at the wire tip; (c–k) droplet gradually grows; (l,m) droplet reaches maximum size; (n–p) droplet detaches.

3.2.2. Comparative Analysis of Droplet Diameter

Table 5 summarizes the experimentally measured droplet diameters for different thick wires during the arc swinging process. The droplet diameter and liquid column diameter were measured following a procedure similar to that for the arc spreading angle. At least 50 droplets or 50 liquid columns were randomly selected separately from the high-speed images for each condition. The diameters were measured using the same calibrated image analysis software, and the mean diameters were calculated. All data are presented as mean values, with standard deviations indicating the measurement variability. As can be seen from the table, under the conditions of no cold and two pre-embedded cold-wire layers, the average droplet diameter of SWW at the sidewalls is reduced by 30% and 19.6%, respectively, compared with that at the groove center. For CWW, the average droplet diameter at the sidewalls is decreased by 9.2% and 20.2%, respectively, relative to that at the groove center.

Table 5. Comparison of droplet size of different thick wires during arc swing process.

Wire Type /Diameter (mm)	Cold-Wire Layer <i>n</i>	Average Liquid Column Diameter During Sidewall Dwell (mm)	Average Droplet Diameter at the Groove Center (mm)
SWW/1.6	0	0.28 ± 0.03	1.12 ± 0.09
	2	0.43 ± 0.04	1.07 ± 0.10
CWW/2.4	0	0.47 ± 0.07	1.31 ± 0.12
	2	0.51 ± 0.06	1.24 ± 0.13

This phenomenon can be similarly explained as follows: when the arc deflects toward the sidewalls, the arc length is shortened, resulting in a higher welding current than that at the groove center, which in turn reduces the droplet size.

In addition, for the same type of thick-wire, no clear regularity was observed in the effect of pre-embedded cold wire on the average droplet diameter, as the welding current and arc voltage remained essentially unchanged.

Furthermore, under the same number of pre-embedded cold-wire layers and identical groove position, both the average liquid column diameter and average droplet diameter of CWW are larger than those of SWW. Without pre-embedded cold, the average liquid column diameter of CWW during sidewall dwell is 41.7% larger than that of SWW, and its average droplet diameter at the groove center is 17% larger. With two pre-embedded cold-wire layers, the average liquid column diameter of CWW at the sidewalls is 15.1% larger, and the average droplet diameter at the groove center is 15.9% larger, compared with SWW. This is mainly attributed to the difference in wire diameter between CWW and SWW used in this study. The diameter of CWW is 2.4 mm, which is considerably larger than the 1.6 mm diameter of SWW.

3.2.3. Small-Scale Explosive Spattering

In addition, experimental observations reveal that CWW is prone to droplet explosion during the formation of hanging droplet transfer, generating a large amount of small-scale spatter with diameters ranging from 0.1 to 0.3 mm. The typical evolution process is illustrated in Figure 9, where the number of pre-embedded cold-wire layer is set to two. To investigate the formation mechanism of such explosive spattering, a dynamic model describing the formation process of explosive spatter for CWW is established, as shown in Figure 10.

Since the droplets first melt from the individual strands of CWW and then fall toward the molten pool [21], and given the independent and spatially separated positions of the individual strands, the falling trajectories of these droplets are inherently divergent, as illustrated in Figure 10a. Meanwhile, owing to the extremely high arc current density of each strand, the electromagnetic contraction force acting on the droplets is significantly enhanced. This strong force causes the detached droplets to accelerate and fall rapidly downward from the wire tips.

As a result, these fast-moving droplets with inconsistent trajectories inevitably collide with each other frequently during their descent (Figure 10b). Such intense droplet collisions continuously entrap ambient gas into the interior of the droplets [22,23], gradually increasing the internal gas pressure. Once the internal gas pressure reaches a critical threshold, the combined effect of collision force and high internal pressure triggers a violent explosion of the individual strand droplets. This process ultimately produces numerous fine-sized welding spatter, as presented in Figure 10c,d.

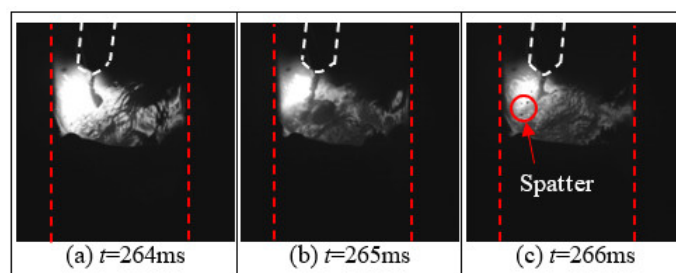


Figure 9. Process of the spatter explosion images of CWW.

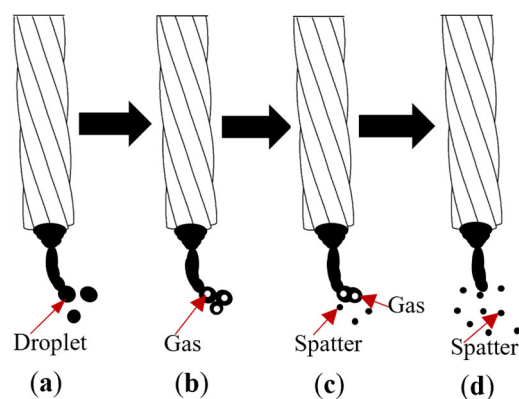


Figure 10. Dynamic model of formation process for droplet explosion spatter of CWW: (a) divergent falling; (b) collision and gas entrapment; (c,d) explosion and fine spatter.

The droplet transfer behavior observed in this study can be placed in the context of previous thick-wire GMAW investigations. For CWW, the ‘hanging droplet transfer’ mode at the groove center and the rotating spray transfer at the sidewalls are consistent with the arc rotation and droplet coalescence mechanisms reported by Chen et al. [9], who found that the arc in CWW migrates from the wire end to the droplet necking region, and the rotating arc exerts a strong stirring effect on the molten pool, promoting heat transfer to the sidewalls. Similarly, Yang et al. [21] demonstrated that the self-rotation effect of CWW results from the electromagnetic forces generated by currents running through individual strands, which is in good agreement with the self-rotating behavior observed in the present CWW experiments. Furthermore, unlike the findings in cold-wire GMAW where the addition of cold wire significantly modifies droplet transfer mode [24], the pre-embedded cold wire in this study exhibits no clear regularity in affecting droplet diameter, suggesting that its regulatory role is primarily on arc behavior through cathode spot deflection and arc spreading angle modification, rather than on metal transfer dynamics.

4. Conclusions

This study systematically investigated the influence mechanisms of pre-embedded cold wire narrow-gap gas metal arc welding (GMAW) with swing arc on arc behavior, droplet transfer, and welding stability. The main conclusions can be summarized as follows:

- (1) Pre-embedded cold wire increases the arc spreading angle by deflecting cathode spots toward the cold wire. For SWW at the groove center, the arc spreading angle increased by up to 15.8%, while sidewall angles decreased by 13.1% and 18.4% with $n = 0$ and $n = 2$, respectively, compared with the groove center. This heat distribution compensation effect offsets the heat absorption of the cold wire, ensuring reliable sidewall penetration.
- (2) CWW exhibits a unique “hanging droplet transfer” transfer mode at the groove center, where the finite convergence time of sub-droplets leads to droplet elongation into

a liquid column with an incompletely detached droplet at its front end. This mode generates numerous small spatters (0.1–0.3 mm) due to droplet explosion caused by droplet collision and gas entrapment.

- (3) Pre-embedded cold wire significantly improves arc stability for both wire types, as indicated by more concentrated voltage–current distributions, with CWW showing superior stability in the absence of cold wire. However, no clear regularity was observed in its effect on droplet transfer, indicating that its regulatory role is primarily on arc behavior rather than metal transfer.
- (4) From a practical perspective, pre-embedded cold wire offers a viable approach to improving sidewall penetration in thick-plate narrow-gap welding, with only a minor effect on overall penetration depth. The findings also suggest that CWW provides better arc stability in the absence of cold wire, while SWW exhibits more stable droplet transfer at the sidewalls, providing guidance for wire selection under different welding conditions.

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