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ORIGINAL ARTICLE

Research on the “jump sidewall” behavior and its signal characteristics in narrow gap P-MAG welding

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Abstract Arc “jump sidewall” phenomenon is observed during P-MAG welding in narrow gap conditions. The mechanism and formation conditions are analyzed, and the phenomenon is found to be the arc channel re-establishment process, which results from large changes in the welding current. The arc channel position is the result of the balance between the electric field force and the magnetic field force. The current characteristics of P-MAG welding in a narrow groove provide adequate conditions for a “jump sidewall” phenomenon. The influences of a narrow gap groove on droplet transfer and arc signal of P-MAG power supply with modified I-I external characteristics are discussed. The research results lay a foundation for arc sensor-based welding seam tracking technology in narrow gap P-MAG welding.

Keywords P-MAG welding · Arc behavior · Seam tracking · Arc signal · Narrow gap

1 Introduction

Narrow gap welding (NGW) technology can reduce the amount of filler metal, reduce costs, and improve welding efficiency while reducing the welding heat input and thermal deformation. These technical and economic advantages make NGW the preferred technology for thick plates. To ensure narrow groove sidewall fusion, either welding torch swing or rotation technologies are typically used in the welding process. Xu et al. [1–3] studied the influence of swing angle, speed, and dwell time on the weld seam for both flat and vertical welding processes; they also established all-position narrow gap MAG welding statistical models. Zhen et al. [4] designed a specially shaped strip electrode that automates the welding arc swing. With this improvement, they studied the effects of gap width, arc voltage, and wire feed rate on the arc behavior. Kang et al. [5] designed an electromagnetic generator to automate a MAG arc swing for horizontal NGW. Guo et al. [6] studied droplet transfer characteristics and its impact on the behavior of the molten pool in narrow gap transverse position welding. By using the support vector machine method, Li et al. [7] developed a narrow gap MAG welding prediction model that can be used to control sidewall penetration. Zhao et al. [8] developed a new device to rotate the torch at high speed and studied its effects on droplet transfer and weld shape.

The above research was mainly focused on arc behavior and droplet transfer in particular their influence on sidewall fusion and weld formation. Vision sensors were normally used for NGW seam tracking, and due to the narrow gap groove’s negative effect on arc stability, arc sensors were only used on the gas tungsten arc welding (GTAW) method. For example, Guo et al. [9] developed a vision sensor system used in seam tracking MAG welding, Huang et al. [10] developed a 3D and 2D visual information fusion vision sensor tracking system for laser welding, and Xu et al. [11] designed an arc sensor for robotic GTAW process height tracking. In recent years—as welding power sources have continuously improved and the arc and droplet transition have become more stable—it has become possible to apply arc sensors to narrow groove welding seam tracking. The famous American pipeline engineering company, CRC-EVANS, has successfully developed a narrow groove welding robot with an arc sensor for seam tracking that has been used in gas pipeline construction [12]. At present, in order to improve the accuracy of arc sensors in narrow groove welding, scholars are

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Fig. 1 Experimental platform

Table 1 Welding parameters

Parameters	Value
Swing amplitude/mm	4
Swing frequency/Hz	1.5
Welding speed/mm s^{-1}	5
Welding wire diameter/mm	1
Wire feeding speed/m min^{-1}	6
Shielding gas	80%Ar + 20%CO_2
Base metal	Q235

revisiting arc sensing characteristics in narrow gap welding. Kim et al. [13] has studied the arc shape and the current characteristics of P-MAG welding at 45° and 60° groove angles. In addition, the variation of arc characteristics in response to smaller groove angle was discussed. Li et al. [14, 15] studied the welding deviation extraction algorithm for a rotating arc sensor based on rough sets and a support vector machine method for narrow gap MAG welding. Moon et al. [16, 17] designed a dual torch automatic welding system for narrow gap grooves. Through analysis of the arc signal sensitivity on torch height variation between the I-I mode and the modified I-I mode in pulse MIG welding, they selected the former as the driving torch and obtained its arc signal to track the weld center. The latter was selected as the following torch, mainly to ensure welding quality.

This paper analyzes the arc behavior and signal characteristics of P-MAG welding using external features of the modified I-I mode for narrow groove scenarios. We also lay a foundation for arc sensing-based welding seam tracking technology in narrow gap P-MAG welding.

2 Experimental conditions

The experimental platform used in this research is shown in Fig. 1. Using this apparatus, we can control the gun's swing amplitude, swing speed, height, and welding speed with a PLC. In addition, we can obtain synchronized arc voltage, current, and image information. The welding power source is a Fronius TPS3200 operated in P-MAG welding mode; the wire feeding speed is fixed, and other parameters are automatically matched. The power source is a modified I-I model. When the arc length changes—determined by monitoring the voltage change—the pulse frequency and welding current are modified in order to rapidly recover the arc length and ensure arc and droplet transfer stability. The groove form used in the experiment is shown in Fig. 2, and the welding parameters are given in Table 1.

3 Arc "jump sidewall" behavior and analysis

In the experiment simulating narrow groove P-MAG welding of a pipeline segment, we found that under certain welding conditions, the welding arc jumped between the sidewall and the bottom of the weld at a regular pulse frequency. As shown in Fig. 3b, during the base current period (i.e., 1 to 3 ms), the welding current is approximately 40 A; this current can only maintain the arc for burning and heating the wire. In the case where the gun is swung to one of the sidewalls, the arc channel is built between the wire tip and the sidewall. Note that the arc

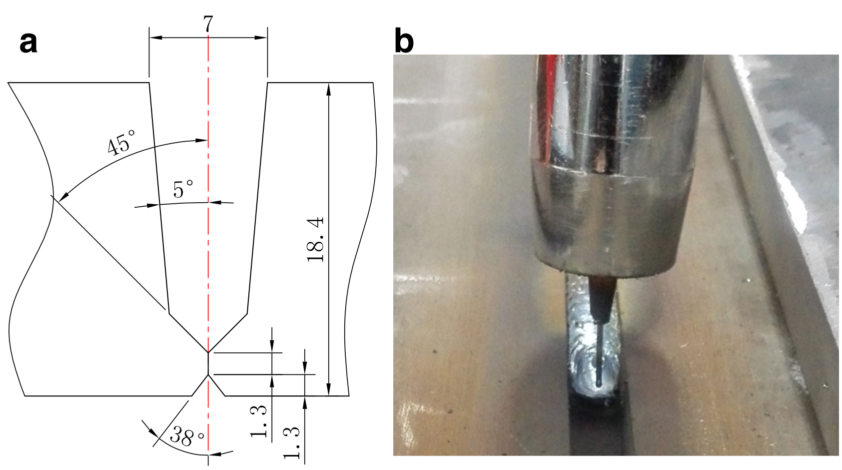

Fig. 2 Groove form used in the experiment: **a** - Groove schematic, **b** - Actual groove

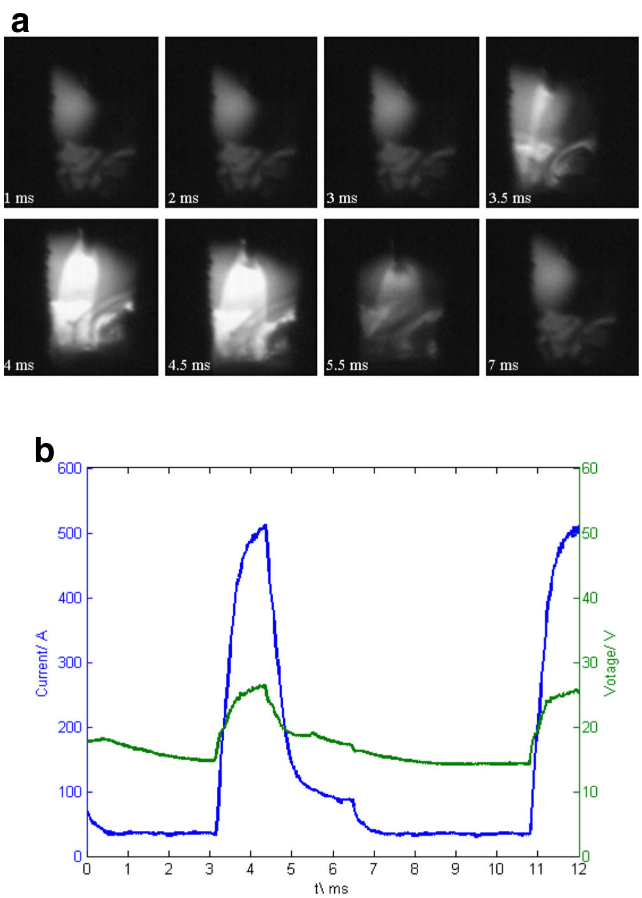

Fig. 3 P-MAG arc shape and current/voltage changes: **a** - Arc shape observed with high speed photography, **b** - Current and voltage values in a pulse period

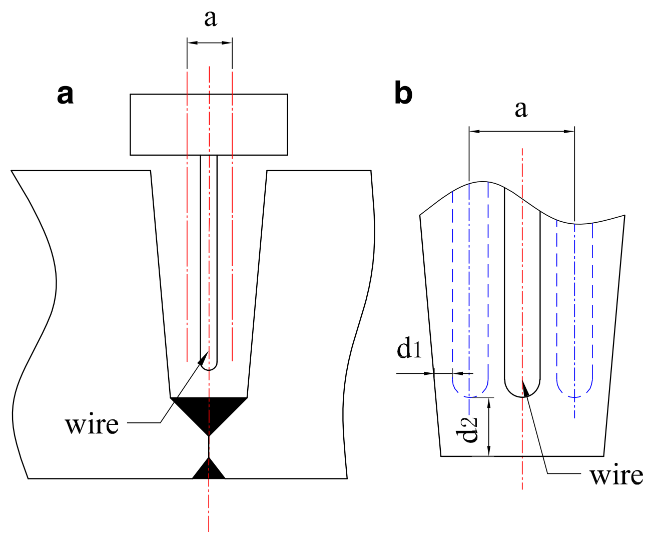

Fig. 4 Welding gun swing in narrow gap groove: **a** - Swing amplitude of the gun, **b** - Swing amplitude detail (d1< d2)

axis is perpendicular to the wire axis. After 3 ms, the current rapidly increases to more than 500 A, the arc stiffness increases significantly, the arc channel moves down the sidewall to the weld pool surface, and the arc axis roughly aligns along the wire axis. Next, the current quickly drops to about 100 A and droplet transfer occurs between 5 and 6 ms. Before the droplet transfer—due to the continuous wire feed—the wire tip is near the surface of the weld pool. Thus, the arc channel is still located between the bottom of the droplet and the surface of the molten pool. When the transition completes, there is an increase in the distance between the wire tip and the weld pool surface. At the same time, the current quickly reduces to the base value and the arc jumps back to the sidewall. Through high speed photography, the welding arc crawling phenomenon can be directly observed. Note that the arc alternates between the sidewall and the surface of the molten pool; we call this the “jump sidewall” behavior.

This arc “jump wall” behavior is present in pulse MAG/MIG welding under certain groove conditions.

First, the narrow groove characteristics create the basic conditions for building an arc channel perpendicular to the wire axis. As shown in Fig. 4, the narrow groove sidewall is almost parallel to the welding wire and the distance from the wire tip to the sidewall is far less than it is to the bottom of the groove. Thus, the electric field strength between the wire tip and the side wall is maximized ($E = U/d$, where E is the electric field strength, U is the electric potential, and d is the distance). If the other conditions are fixed, an arc will form between the wire tip and the side wall. In addition, when the arc passes through—the shortest path between the electrode and the base metal—minimum energy consumption is ensured (i.e., IEd is minimized, where I is the current, E is the electric field strength, and d is distance), which satisfies the minimum voltage principle.

The current profile for P-MAG—a small base current is small and large peak current—satisfies the necessary conditions for the occurrence of the “jump sidewall” phenomenon. As shown in Fig. 5, the arc plasma is affected not only by the electric field, but also by its magnetic field. When the welding current enters the pulse period, the arc size contracts and the arc stiffness increased. This drives the well-developed arc along the axis of the wire. At this time, although the voltage and the electric field intensity are increased, the magnitude of the current change results in the magnetic force playing the dominant role in building the arc channel.

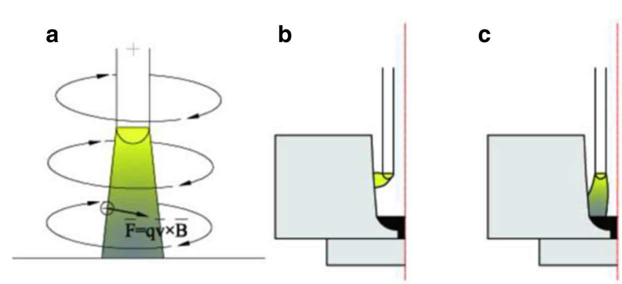

Fig. 5 Narrow gap P-MAG arc shape analysis: **a** - Lorenz force, **b** - Base current arc shape, **c** - Peak current arc shape

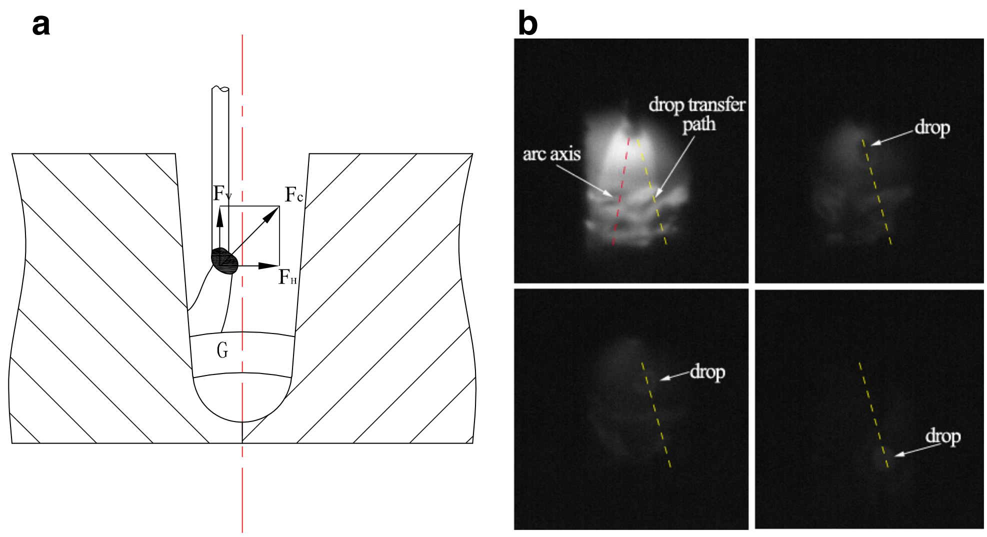

Fig. 6 Welding arc effects on droplet transfer: **a** - Droplet pressure, **b** - Droplet transition path

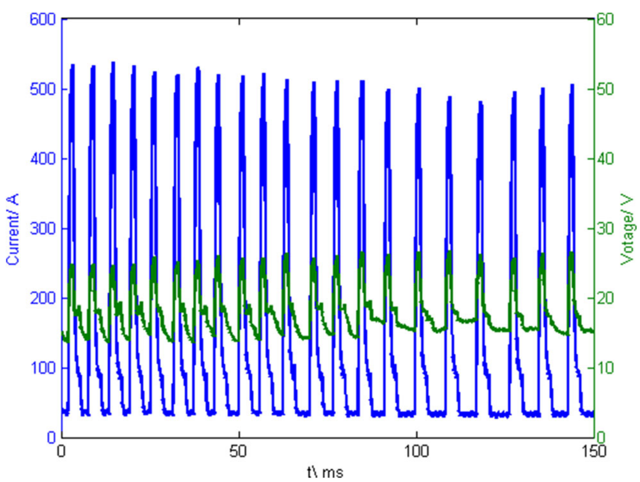

Fig. 7 P-MAG welding current and voltage profiles (sampling time 150 ms)

However, even in the pulse period, the arc will continue to tilt towards the sidewall when the torch swings to the sidewall position. In comparison to the base period, the inclination of the arc is largely due to the presence of the sidewall which results in an asymmetric magnetic field intensity around the arc. The arc is pushed to the sidewall by the force of the magnetic field, not by the electric field.

4 Effect of arc behavior on droplet transfer and arc signal in narrow gap pulse MAG welding

4.1 Effects on droplet transfer

As shown in Fig. 6, when the torch swings to the sidewall position, the droplet pressure is no longer aligned along the welding wire axis. There is a component perpendicular to the axis of the wire, which results in droplet transition that is no longer aligned to the wire axis. The change to the droplet transition path not only affects the temperature field distribution on the base metal, but also affects the weld formation.

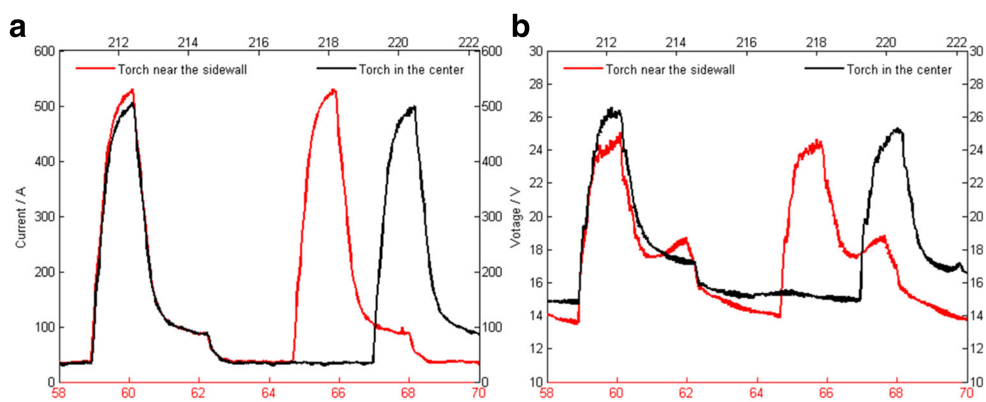

Fig. 8 Peak value comparison between sidewall and the central position in narrow gap P-MAG welding: **a** - Comparison of current peak values (sampling time 12 ms), **b** - Comparison of voltage peak values (sampling time 12 ms)

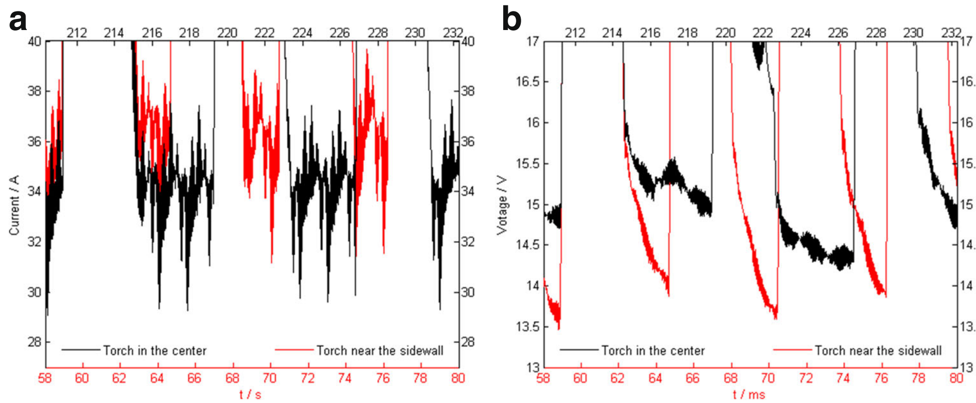

Fig. 9 Base value comparison between sidewall and the central position in narrow gap P-MAG welding: **a** - Comparison of current base values (sampling time 22 ms), **b** - Comparison of voltage base values (sampling time 22 ms)

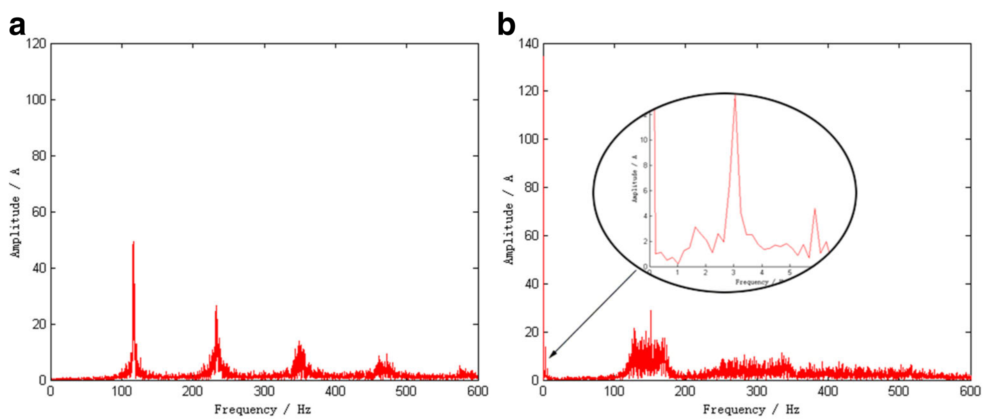

Fig. 10 Effect of narrow gap side wall on P-MAG welding frequency characteristics: **a**- Amplitude spectrum of current signal in plate surfacing P-MAG welding, **b** - Amplitude spectrum of current signal in narrow gap P-MAG welding

4.2 Effects on arc signal

As shown in Fig. 7, the arc voltage and current signal change when the torch swings and the "jump sidewall" phenomenon occurs. Twelve millisecond of data taken from both the sidewall position, and center position are compared to determine the differences between the peak current and peak voltage. Additionally, twenty-two millisecond of data from the sidewall position and center position are used to compare the base current and base voltage. The results are shown in Figs. 8 and 9, respectively. It is evident from the graph that when the torch swings to the sidewall, both the peak current and the base current increase while the peak voltage and base voltage decrease. In addition, the base period becomes shorter, the peak time is constant, and thus the pulse frequency is increased. This difference is more obvious when the torch is closer to the sidewall.

In order to investigate the influence of the groove sidewall on the pulse frequency, the P-MAG plate surfacing and narrow gap welding frequency spectrums were compared, as shown in Fig. 10. The plate surfacing amplitude spectrum is

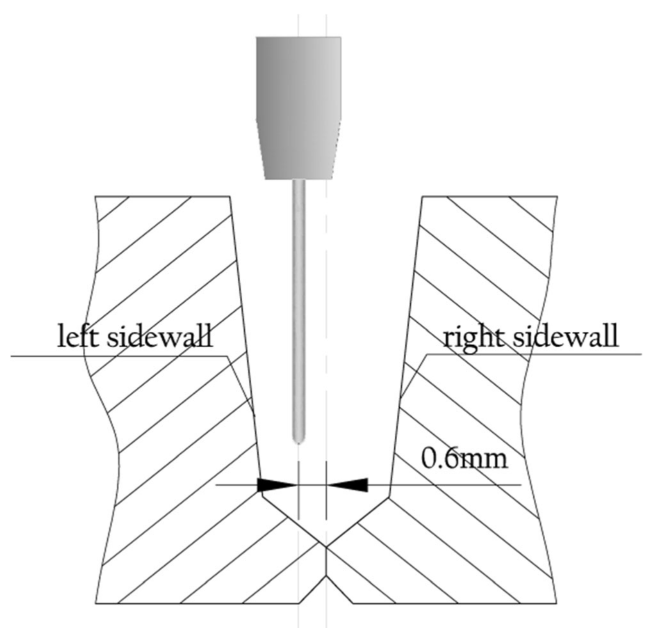

Fig. 11 The torch position in the experiment

nearly a rectangular wave. The current amplitude peak values are at 0, 1, 2, and 3 times the pulse frequency. For narrow gap conditions, the current amplitude spectrum is distributed primarily between 100–200 Hz. This is largely due in part to groove pulse frequency dependence on proximity to the sidewall. The amplitude spectrum distribution is related to both the size of groove and the swing amplitude. If the groove is larger and the swing amplitude is smaller, the amplitude spectrum distribution is closer to the plate surfacing amplitude spectrum. If the groove is smaller and the swing is larger, the spectrum tends to a higher frequency distribution. In the narrow groove spectrum, there is amplitude distribution near the 3 Hz position; this is two times swing frequency and represents the welding torch swing frequency. However, there is no corresponding peak in the plate surfacing distribution. This illustrates that the gun swing characteristics can be surmised from the spectrum information alone when the arc is influenced by the groove sidewall.

The change to the voltage, current, and pulse frequency is closely related to the welding power source control principle. For the P-MAG welding power source with modified I-I external features, the voltage change is roughly proportional to the arc length, while the pulse frequency and current are adjusted according to the voltage variation. This control strategy simultaneously ensures both the arc length and droplet transfer stability. As mentioned earlier, magnetic blow occurs during

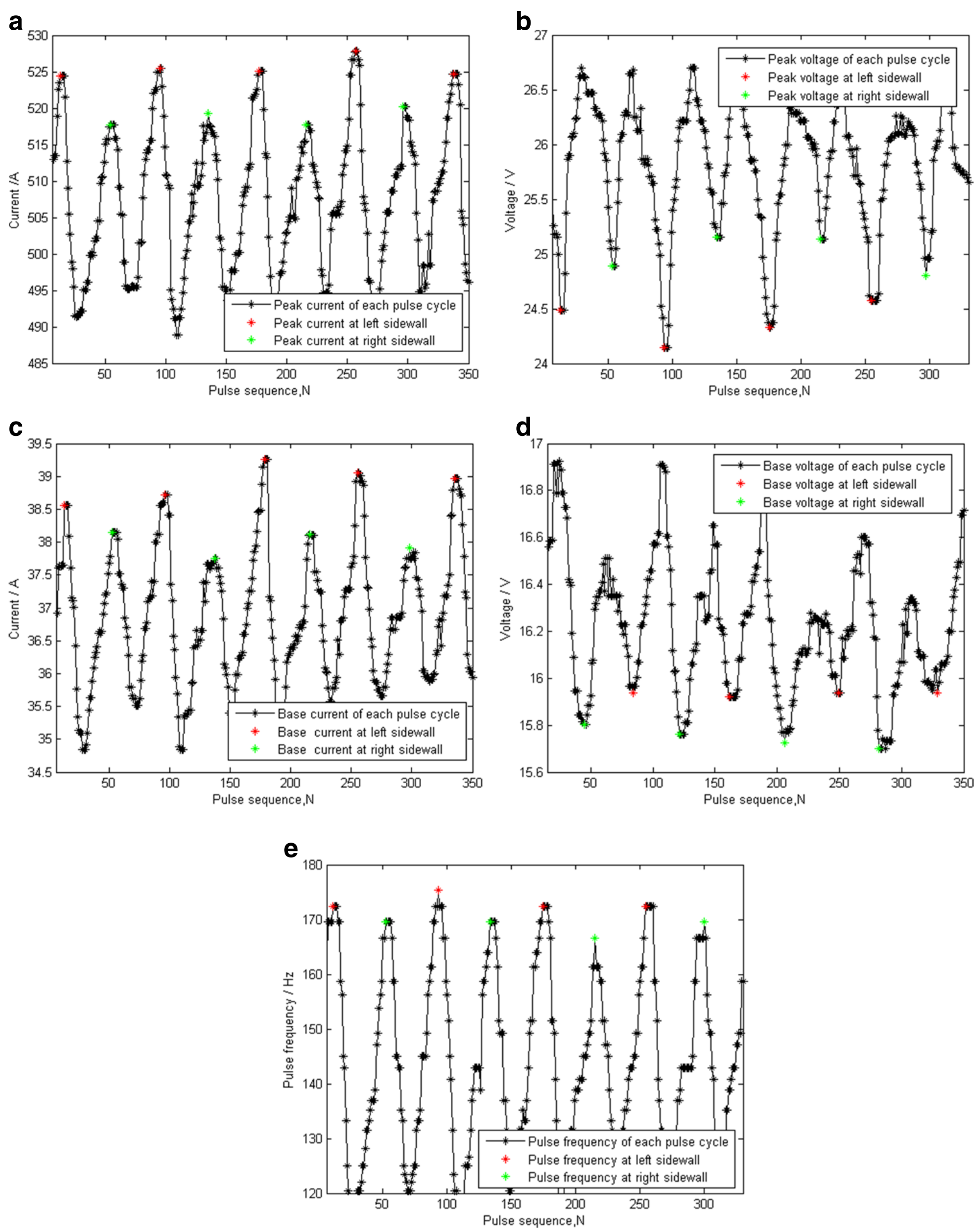

Fig. 12 Characteristic parameters for a 0.6 mm welding torch deviation from the center seam: **a** - peak current, **b** - peak voltage, **c** - base current, **d** - base voltage, **e** - Pulse frequency

the peak period near the sidewall. This leads to a shorter arc length and a lower peak voltage. In comparison, the base voltage decrease is due to the reduced distance to the sidewall during the torch swing. The change in peak current, base current, and pulse frequency is the adaptive adjustment of the welding power control system in response to voltage change. Therefore, the base value and the peak value of the voltage directly reflect the arc length change. Furthermore, the change to the current base, current peak, and pulse frequency lag behind the voltage change by one to two pulse periods, which reflects the arc length change indirectly.

In regard to the arc sensor-based seam tracking technology, when a P-MAG welding power supply with a modified I-I mode is used for narrow gap, the arc parameters (e.g., peak current, peak voltage, base current, base voltage, or pulse frequency) reflect the distance from the torch to the sidewall to an extent. As shown in Fig. 11, the torch deviated from the gap center by 0.6 mm and the current and voltage were collected at a sampling frequency of 40 kHz. The maximum current and voltage during each peak cycle are shown in Fig. 12a, b, respectively. The red dots represent the peak current and peak voltage (i.e., when the torch swings to the left sidewall of the gap), and green dots represent the values at the right sidewall. In the case where the torch deviated from the center by 0.6 mm to left, the peak current at the left sidewall is about 10A higher than that at the right sidewall, while the peak voltage at the left sidewall is about 0.5 V lower than that at the right sidewall. Figure 12c, d shows the base current and base voltage variation, which show changes similar to the peak values. Figure 12e shows the pulse frequency variation. We found that when the torch swung from the left sidewall to the center and then to the right sidewall, the pulse frequency dropped from more than 170 to 120 Hz and then rise again to about 170 Hz. The frequency changes are much greater than the current and voltage changes. On the whole, the arc parameters (i.e., peak current, peak voltage, base current, base voltage, and pulse frequency) reflect the welding torch deviation setting.

5 Conclusion

(1). The arc "jump sidewall" phenomenon in narrow gap P-MAG welding is a result of the arc channel reestablishment process. The arc channel position is the result of the balance between the electric field force and the magnetic field force. During the base current period, the electric field force plays a leading role, and in the peak current period, the magnetic field force plays a leading role. The sidewall condition of the narrow groove (which is almost parallel to the wire) and the large change in the P-MAG welding current create adequate conditions for the "jump sidewall" phenomenon.

(2). The P-MAG welding arc behavior influences droplet transfer and the arc signal. Experiments were performed with a Fronius TPS3200, which is with a modified I-I model used in P-MAG welding mode. We found that when the torch swings near the sidewall, the droplet path no longer follows along the wire axis. In addition, when compared to the torch in the gap center, the current—including peak and base current—increases; both the peak and base voltage decrease. The pulse frequency is higher at the sidewall than it is at the gap center. In addition, the spectrum exhibited more amplitude in the high frequency region. These features can be used in P-MAG welding seam tracking technology; a deviation of 0.6 mm can be easily detected in an experiment. These research results lay a foundation for arc sensor-based welding seam tracking for narrow gap P-MAG welding.

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Compliance with ethical standards This article does not involve any human participants and animals.

Conflict of interest The authors declare that they have no conflict of interest.

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