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CRITICAL REVIEW

Research status of insufficient sidewalls penetration in narrow gap TIG welding of thick metal plates

Honglei Zhao[1,2] · Siyu Zhang[1,2] · Xianglong Yu[1,2] · Yiwen Li[1,2] · Junyan Miao[1,2] · Chenhe Chang[2,3] · Yunlong Chang[1,2]

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Abstract

Due to its high-quality weld seam and excellent arc stability, narrow gap Tungsten Inert Gas (TIG) welding has become a critical technology for welding thick metal plates. However, this technology has the problem of insufficient sidewalls penetration, which has a significant impact on the performance of the components. This study provides a comprehensive overview of three optimization methods, including mechanical improvement, field control, and composite welding. It critically analyzes the principles and research status of each method. The advantages and disadvantages of these methods have been summarized. In Outlook, application scenarios for auxiliary processes have been presented. Further, there is a prospect for the development of an ultra-long arc narrow gap TIG welding process.

Keywords Narrow gap TIG welding · Sidewalls penetration · Thick metal plates · High-efficiency welding · External physical field

1 Introduction

As the welding structure becomes larger and more complex, more researchers pay attention to the design and optimization of welding process for thick metal plates [1]. In certain significant domains, such as nuclear power engineering [2, 3], shipbuilding [4, 5], pressure vessels [6, 7], and military industry [8, 9], the welding structure typically consists of thick plates (ranging from 20 to 60 mm) or even ultra-thick plates (exceeding 60 mm) [10]. This presents a great challenge to conventional welding techniques, necessitating the development of more efficient welding technologies.

As a common thick plate welding process, narrow gap welding has always been an engaging research topic. The Battelle Welding Research Institute in the United States introduced this process in 1963. A U-shaped or I-shaped groove with a small gap is typically used, which reduces the amount of welding filler material by 50%—80% compared to the traditional V-shaped or X-shaped groove with a large gap [11]. It has the advantages of high welding efficiency, less filling materials, and good joint performance [12]. Various narrow gap welding processes have been developed, including narrow gap TIG welding (NG-TIG), narrow gap gas metal arc welding (NG-GMAW), and narrow gap submerged arc welding (NG-SAW). Among them, narrow gap TIG welding is frequently used for the welding of critical components. This method incorporates the benefits of traditional TIG welding, including good weld quality, low heat input, high arc stability, a wide range of applicable materials, and suitability for all-position welding [13–16].

During the development of narrow gap TIG welding, researchers found that there was insufficient sidewalls penetration [17–19]. Mainly due to the non-uniform distribution of arc heat. TIG arc is generally bell-shaped, and the energy is mainly concentrated in the bottom area of the arc, which leads to insufficient penetration of the sidewalls. It seriously endangers the performance of welded joints and limits the application of this process. Therefore, how to realize the uniform distribution of arc heat between the sidewalls and the bottom of the groove in high-efficiency welding has become

✉ Yunlong Chang
zhl08302021@126.com

[1] School of Material Science and Engineering, Shenyang University of Technology, No. 111, Shenliao West Road, Economic & Technological Development Zone, Shenyang 110870, P. R. China

[2] Shenyang Collaborative Innovation Center Project for Multiple Energy Fields Composite Processing of Special Materials, Shenyang 110027, China

[3] Liaoning Xinyuan Special Welding Technology Co., Ltd, Shenyang 110011, China

an urgent problem in the development of narrow gap TIG welding. For many years, researchers have been committed to optimizing this technology, and this study has summarized some representative achievements.

2 Narrow gap TIG welding process research progress

This study categorizes different optimization methods into three distinct groups: mechanical improvement, field control and composite welding.

2.1 Mechanical improvement

Through mechanical design and transformation, arc energy is transferred from the bottom of the groove to the sidewalls. The method mainly includes oscillating tungsten electrode process, ceramic sheet constraint process, and double tungsten electrode welding process.

2.1.1 Oscillating tungsten electrode process

A set of narrow gap TIG welding systems has been designed and developed by Hitachi Group of Japan, as shown in Fig. 1 [20]. Using a tungsten electrode with a curved front end is easier to form an arc with sidewalls. Moreover, the rotating motor can realize the mechanical rotation of the tungsten electrode so that the tip of the electrode periodically points to the sidewalls.

Oscillating tungsten electrode can periodically bring arc heat to the sidewalls, resulting in a more uniform distribution of heat. According to the actual needs of the groove shape and welding process parameters, the amplitude and frequency of tungsten electrode oscillation can be adjusted [21]. This process is suitable for the welding of thick titanium alloys, as it exhibits a stable welding process, good sidewalls penetration and high weld seam strength [22]. But as a non-standard part, the bent tungsten electrode is difficult to manufacture, and this system is very expensive.

Feng et al. [23] have redesigned the structure of the conventional narrow gap TIG welding torch. Install the tungsten electrode inclined and mechanically drive it to rotate, as shown in Fig. 2. This method effectively achieves the formation of high-quality weld seams while maintaining low equipment costs. But the oscillating angle of tungsten electrode necessitates a wider groove gap, thereby resulting in increased workload and decreased welding efficiency.

Yan [24] has developed a non-axisymmetric rotating tungsten electrode. As shown in Fig. 3, grinding the tip of the tungsten electrode into a non-axisymmetric shape and mechanically driving the electrode to rotate. This process is extensively used in the welding of medium-thick plate stainless steel [25] and alloy steel [26]. Compared with the above two processes of oscillating tungsten electrode, this process offers a simpler equipment setup and lower cost. But the welding consistency of this process is poor, potentially attributed to the burning loss of tungsten electrode at high temperatures, leading to alterations in the tip angle of the electrode.

Oscillating tungsten electrode process realizes arc oscillation by mechanically rotating tungsten electrode. The arc periodically brings its heat to the sidewalls, which effectively improves the insufficient sidewalls penetration, resulting in a weld seam that exhibits excellent formation and welding quality [27–31]. However, the welding efficiency is low due to the low frequency of mechanical oscillation.

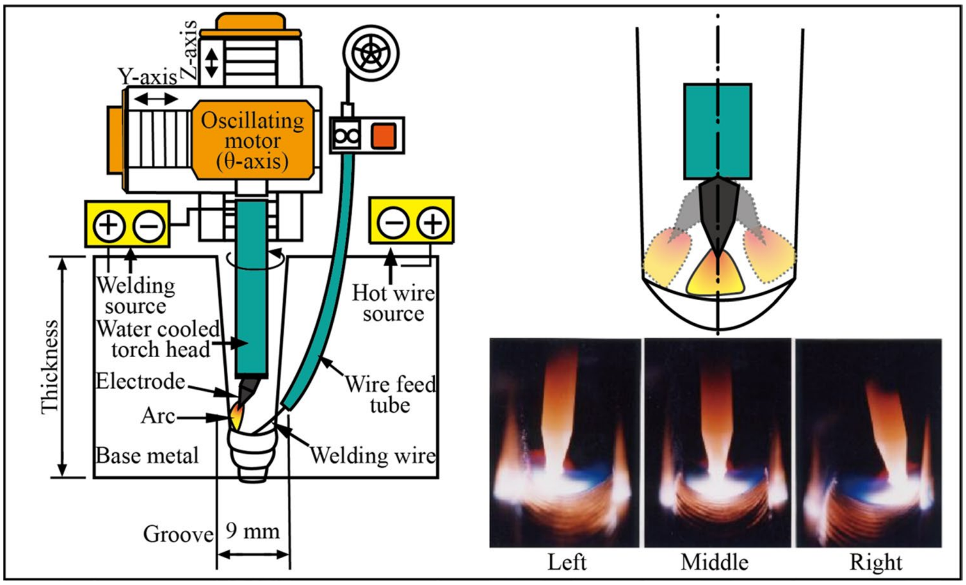


Fig. 1 Narrow gap TIG welding system designed by Hitachi Group and welding arc shape [11]

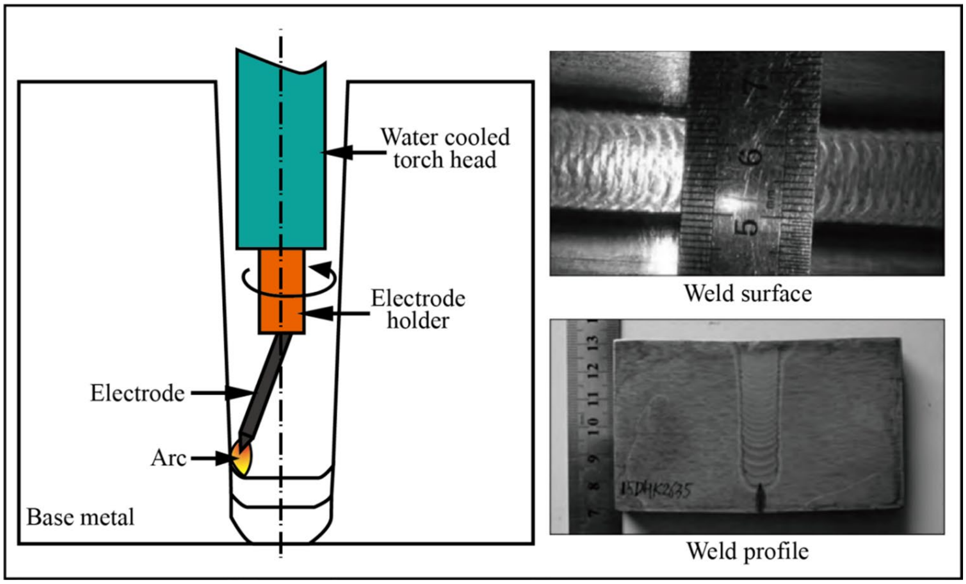


Fig. 2 Schematic diagram of inclined tungsten electrode narrow gap TIG welding and physical drawing of weld seam formation [23]

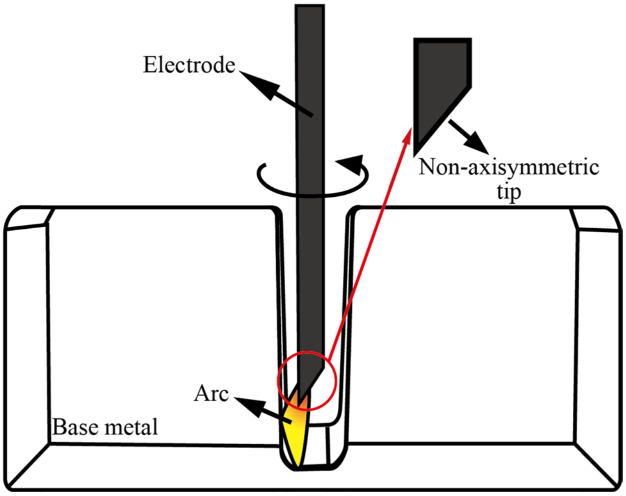


Fig. 3 Schematic diagram of non-axisymmetric rotating tungsten electrode narrow gap TIG welding [24]

The application of this process in high-efficiency welding of thick plates is constrained.

2.1.2 Ceramic sheet constraint process

Since the 1990s in Japan, a research group has made significant advancements in narrow gap welding, leading to the development of ultra-narrow gap welding (UNGW) with a groove gap below 5 mm. This technological innovation has resulted in a substantial improvement in welding efficiency [32]. However, in ultra-narrow gap welding, the arc is easy to burn to the sidewalls along the shortest path [33–37], resulting in incomplete fusion of the groove bottom and sidewalls [33–37].

Zhu et al. [38] have proposed a rotating ceramic sheet constraint process. As shown in Fig. 4, a pair of rotating circular ceramic sheets are respectively close to both sidewalls, effectively confining the arc. The insulating function of the ceramic sheet can prevent the arc from climbing along the sidewalls. The high-speed rotation of ceramic sheets generates a cold airflow, resulting in a large temperature gradient surrounding the arc, thereby creating a thermal contraction effect on the arc. The rotating speed of the ceramic sheet can be adjusted, which can improve the shape and heating characteristics of the arc [39]. But due to the extremely small groove spacing of ultra-narrow gap, the diameter of tungsten electrode must be limited to below 2.5 mm. The current carrying capacity of tungsten electrodes is low, resulting in reduced welding efficiency.

Researchers have developed a sheet tungsten electrode, characterized by its flat rectangular shape and a thickness of approximately 1.3 mm. When the length of the rectangle reaches 6 mm, the sheet tungsten electrode exhibits a current carrying capacity that is comparable to that of a cylindrical tungsten electrode with a diameter of 3.2 mm [40]. Further, researchers have improved the original rotating ceramic sheet into a fixed ceramic sheet, as shown in Fig. 5. This process realizes ultra-narrow gap welding with a groove gap of 4 mm, and the penetration depth is doubled compared with the rotating ceramic sheet constraint process [41]. But the equipment for this process is complex, the sheet tungsten electrode is difficult to manufacture, and the ceramic sheet is easy to burn loss at high temperatures.

Through the solid wall constraint of ceramic sheets, the ceramic sheet constraint process limits the arc to the bottom corner of the narrow gap sidewalls. Therefore, insufficient fusion between the bottom plate and the sidewalls can be

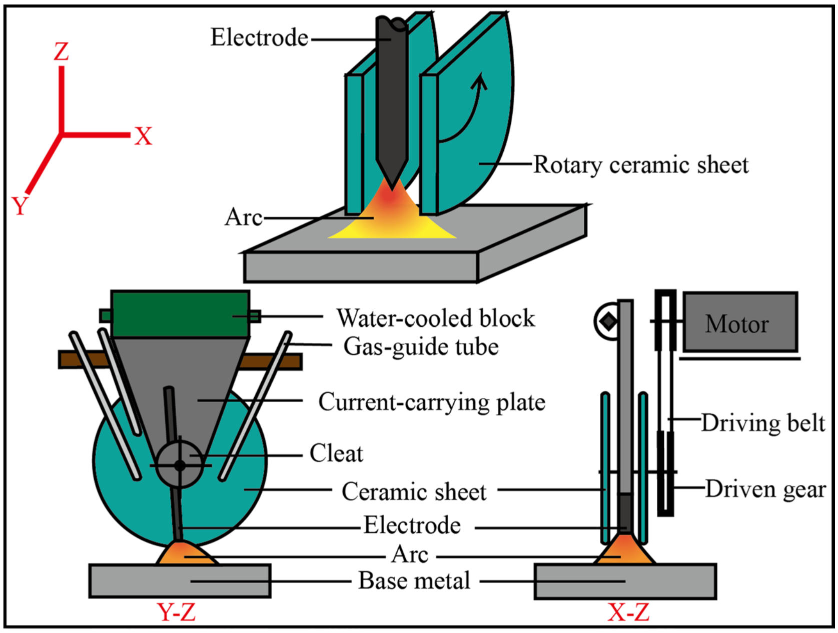


Fig. 4 Schematic diagram of the rotating ceramic sheet constraint process [38]

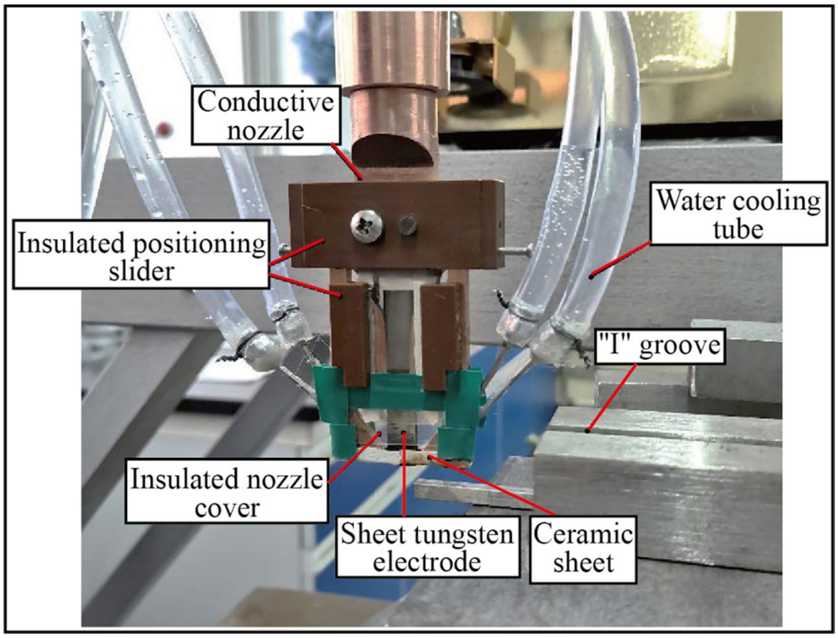


Fig. 5 Physical drawing of sheet tungsten electrode welding torch [40]

improved. However, the complexity of the device and the instability of the process make its application prospects poor.

2.1.3 Double tungsten electrode narrow gap TIG welding process

At the beginning of the twenty-first century, Yamada et al. [42] proposed a double tungsten electrode narrow gap TIG welding process. Two tungsten electrodes are installed on the welding torch and connected with two separate power sources respectively, as shown in Fig. 6. Tungsten electrodes on both sides can increase the heating range of arc and the heat input of sidewalls.

Different welding current matching forms on two tungsten electrodes can significantly impact welding efficiency and the formation of weld seams [43]. When two power sources provide two pulse square wave currents with opposite phases, the welding efficiency is doubled and the arc power is halved compared to using a single tungsten electrode [44]. Wu et al. [45–47] have developed a novel high-frequency compound double tungsten electrode TIG power supply. This power supply is capable of simultaneously

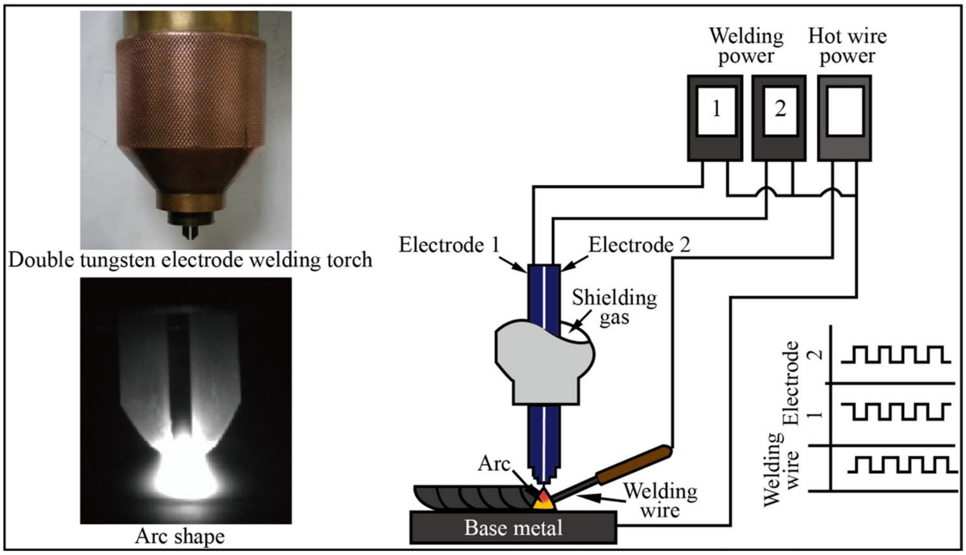


Fig. 6 Double tungsten electrode narrow gap TIG welding system and arc shape [50, 51]

generating high-frequency square wave current and variable polarity square wave pulse current. The arc shape is a symmetrical triangle, and the weld seam is well-formed.

This process has the advantages of high welding efficiency, good welding quality, low arc pressure, and good weld formation [48–50]. It has a good application prospect in high-efficiency narrow gap welding of thick plates, such as titanium alloy [51] and 9%Ni steel [52]. However, the utilization of dual welding power sources results in elevated equipment expenses. Moreover, the welding torch exhibits inadequate cooling capabilities and is unable to sustain prolonged operation.

2.2 External field control

Through the action of external field, the welding conditions are changed, which indirectly improves the welding quality of narrow gap TIG. The external field mainly includes magnetic field, thermal field, flow field, and electric field.

2.2.1 Magnetic controlled narrow gap TIG welding process

Magnetic controlled narrow gap TIG welding has been proposed by Barton Welding Research Institute of Ukraine, which has realized a non-contact oscillating arc. Figure 7 shows a narrow gap TIG welding system with an external transverse magnetic field [53]. A coil is made by winding a copper wire on a silicon steel sheet. When an alternating current is applied to the coil, it generates an alternating magnetic field. The arc will periodically oscillate towards the sidewalls due to the Lorentz force exerted by the magnetic field.

The intensity and frequency of the external magnetic field can be adjusted, which affects the arc. Wang et al. [54] have found that properly increasing the magnetic field intensity can improve the uniformity of arc pressure distribution at both the groove bottom and sidewalls. Sun et al. [55] have comparatively analyzed the magnetic field effect of a single magnetic pole and a double magnetic pole on the narrow gap TIG welding arc area and found that the magnetic field intensity of the double magnetic pole increased by 81.8%. Figure 8 shows a schematic diagram of double magnetic pole TIG welding. The effect of magnetic field parameters on the arc shape of narrow gap TIG welding is shown in Fig. 9. The decrease of magnetic field frequency and the increase of magnetic field intensity can significantly increase the heat input to the sidewalls.

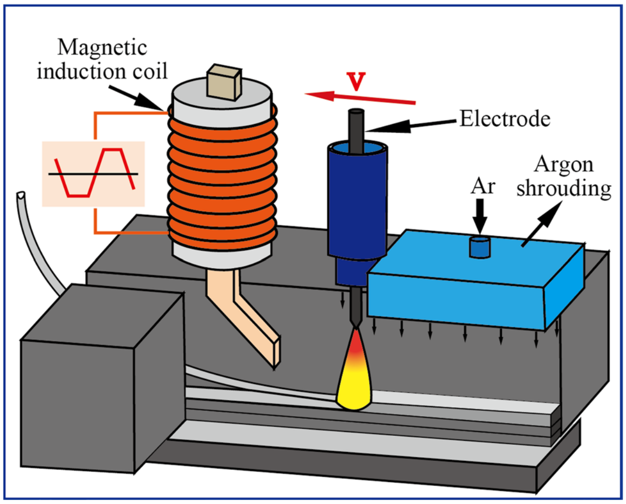


Fig. 7 Narrow gap TIG welding system with an external transverse magnetic field [53]

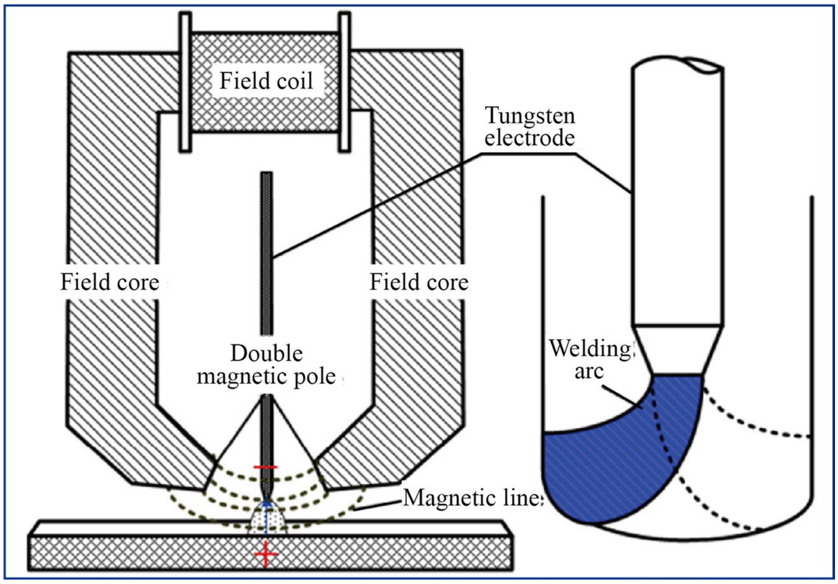


Fig. 8 Schematic diagram of double magnetic pole TIG welding [54]

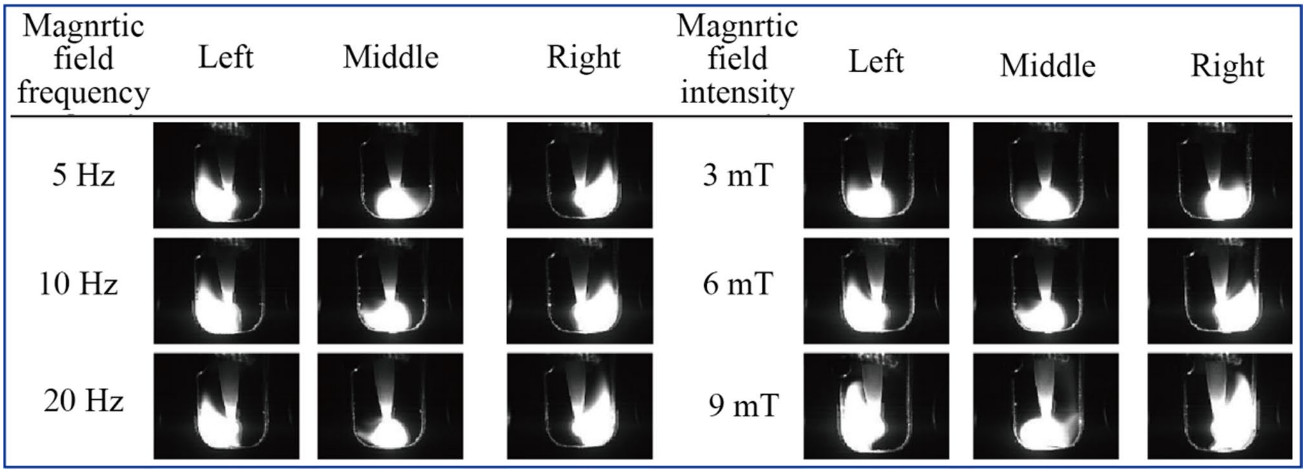


Fig. 9 Effect of magnetic field parameters on the arc shape of narrow gap TIG welding [55]

The magnetic field also provides an electromagnetic stirring effect promoting the flow of molten pool. As a result, a refined microstructure could be obtained, leading to an improvement in the mechanical properties of the weld seam [56]. Jian et al. [57] studied the flow direction of a molten pool. Numerical simulations show that the magnetic field can cause molten metal to flow from bottom of the groove to the sidewalls. Therefore, a counterclockwise flow cycle is obtained, which ensures uniform heat distribution, as shown in Fig. 10.

Magnetic controlled narrow gap TIG welding can obtain excellent welded joints, which is of great significance for thick plates with high welding quality requirements [58–60]. However, for complex components, it is difficult to apply the magnetic field because of the large volume of the magnetic field generator device.

2.2.2 Narrow gap hot wire TIG welding process

Narrow gap hot wire TIG welding process is to preheat the wire with a heating device. The wire can reach the preset temperature before being sent into the molten pool, as shown in Fig. 11.

A common hot wire system is to form a series closed loop between wire and hot wire power supply. The wire is preheated by resistance heating. This method is simple in operation and low in cost. However, there is a current loop between wire and workpiece, which can produce a magnetic field. Arc is easy to be influenced by Lorentz force of magnetic field, resulting in magnetic bias blowing, which affects arc stability. Moreover, the resistance heating efficiency is low for wires such as aluminum alloy with low resistivity.

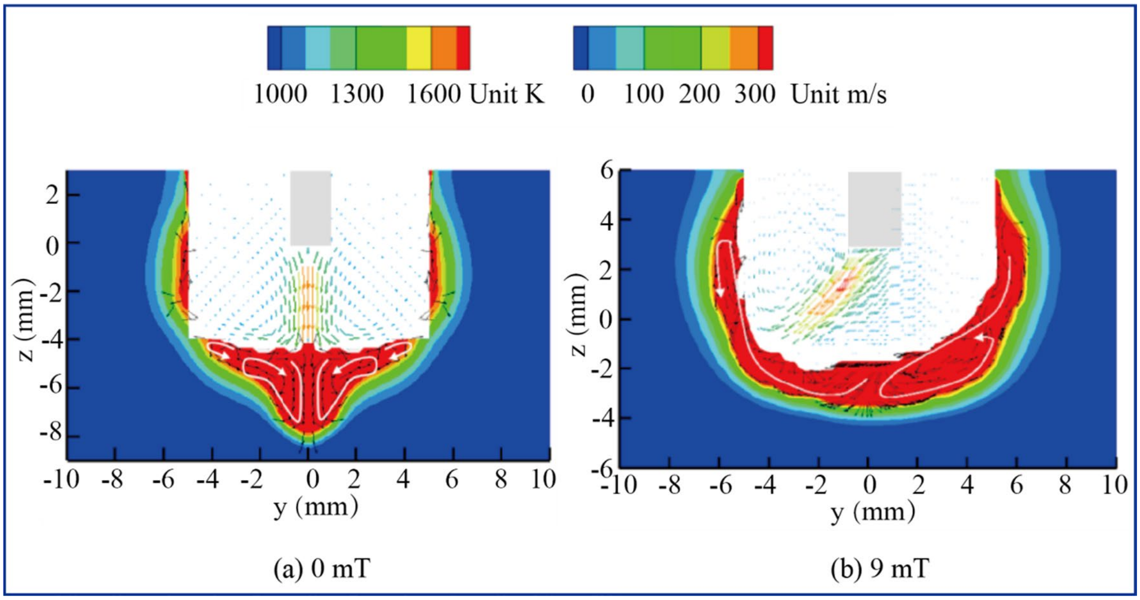
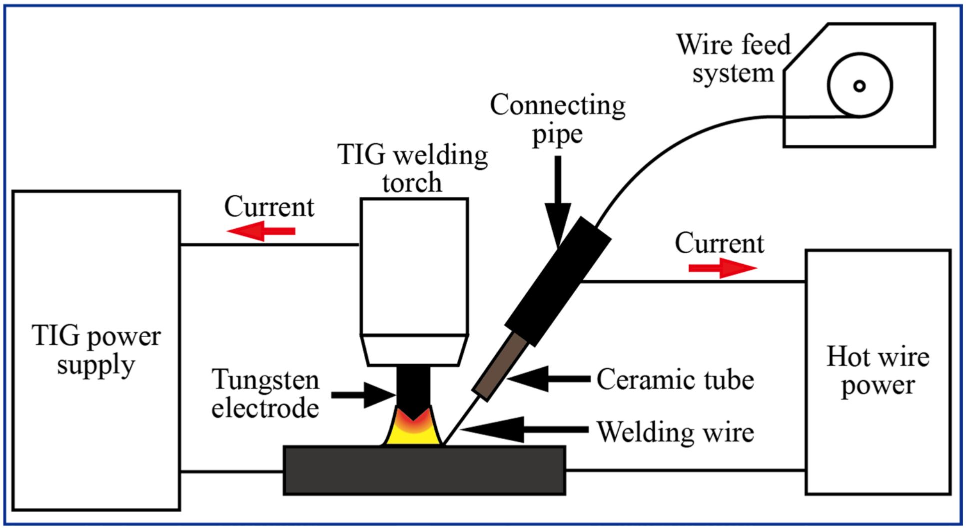


Fig. 10 The effect of magnetic field on the direction of molten pool flow [57]

Fig. 11 Schematic diagram of narrow gap hot wire TIG welding process [62]



Fan et al. [61] developed a high-frequency induction hot wire system, as shown in Fig. 12. A hollow coil consisting of 21 turns is wound around the wire-feeding tube. When a high-frequency alternating current is applied to the coil, it induces a high-density eddy current near the surface of the wire, thus heating the wire. This method eliminates the magnetic field interference caused by bypass current and is suitable for wires of various metals.

Compared to conventional narrow gap TIG welding, the narrow gap hot wire TIG welding has been shown to significantly enhance welding efficiency, with improvements of 3–5 times reported [62]. Therefore, the reduction in production cost and the shortening of the production cycle have been achieved [63], leading to the realization of high-efficiency welding. By reducing heat input and superheat of molten pool, the flow of molten pool could be improved. This process has great advantages in sidewalls penetration and crack resistance [64, 65], and has a broad application prospect in high-efficiency welding of thick plates [66].

Compared with resistance heating, high-frequency induction heating has great advantages. However, there are few studies on temperature control. When the wire feeding speed or wire material changes, the wire heating system needs to change synchronously to heat the wire to the preset temperature.

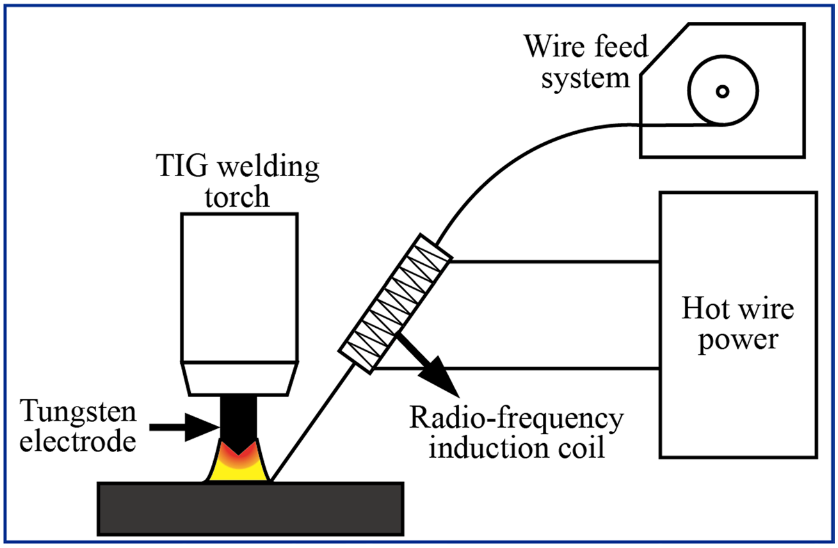


Fig. 12 Schematic diagram of high-frequency induction hot wire system [61]

2.2.3 Welding protective atmosphere

Argon gas is commonly used as a protective atmosphere in narrow gap TIG welding, which leads to poor weld seam penetration, low deposition rate, and low welding efficiency. Research shows [67] that a mixed protective atmosphere can effectively improve welding efficiency and realize high-speed welding. Further, the flow of the molten pool and the depth-width ratio of the molten pool can be improved.

In the 1970s and 1980s, Bad'yanov and Heiple et al. [68] studied the influence of a mixed protective atmosphere on weld seam penetration. They found that adding a certain amount of fluoride gas or sulfide gas into argon gas can increase the weld seam penetration. The application of this method is limited because fluoride and sulfide are both toxic gases. Later, researchers found that the introduction of oxygen, carbon dioxide, or diatomic gas can also increase weld seam penetration [69]. Therefore, the method of mixed protective atmosphere has been more widely developed. The mixed protective atmosphere mainly has the following forms (based on argon): adding He, N_2, H_2, O_2, or CO_2 to form binary mixed gas; adding O_2+CO_2, CO_2+H_2, or $He+CO_2$ to form ternary mixed gas; adding $He+CO_2+O_2$ to form quaternary mixed gas [70]. Lu et al. [71] studied the influence of O_2 and CO_2 in binary mixed gases of $Ar+O_2$ and $Ar+CO_2$ on the morphology of molten pool. As shown in Fig. 13, proper oxygen content can increase weld seam penetration and improve welding efficiency.

The introduction of oxidizing gas can result in the burning of tungsten electrode during welding [72]. Therefore, researchers have developed a double protective atmosphere method, as shown in Fig. 14. In this method, an inert gas is used as the inner gas, serving the purpose of safeguarding the tungsten electrode against oxidation. The gas containing trace activity is used as the outer gas, and the active elements in it can enter the molten pool after being separated by arc to improve the flow of the molten pool.

Double protective atmosphere has been shown to effectively improve the insufficient penetration of sidewalls. Asai et al. [73] used the mixed gas consisting of argon and hydrogen as the inner gas, while the outer gas was composed of 50% argon and 50% helium. They found that the current density at the bottom corner of the sidewalls increased, and the sidewalls penetration improved. Further, the double protective atmosphere has been found to improve effect of weld seam formation, microstructure, and properties. Lu et al. [74] used the double protective atmosphere consisting of inner argon and outer CO_2 to obtain the weld seam with a large depth-width ratio. Zheng et al. [75] used the double protective atmosphere consisting of inner argon and outer nitrogen to obtain equiaxed crystals. They found that the microstructure at the center of the weld seam was refined. The addition of nitrogen improves the hardness and impact toughness of weld seam and heat-affected zone. However, welding protective atmosphere method wastes a lot of protective gas and is not economical.

2.2.4 Pulse current narrow gap TIG welding

Pulse current welding means that the welding current changes periodically from a low base current to a high peak current. DC or AC pulse current can be realized by adding a pulse on the basis of the original current waveform inside the welding power supply [76]. Rectangular wave is a common welding current waveform. When a pulse is applied to it, we can get a waveform as shown in Fig. 15. Main parameters shown in the figure include peak current (I_p), base current (I_b), peak current time (t_p), and base current time (t_b). Pulse current plays a significant role in shaping the welding arc and controlling the flow of the molten pool [77, 78].

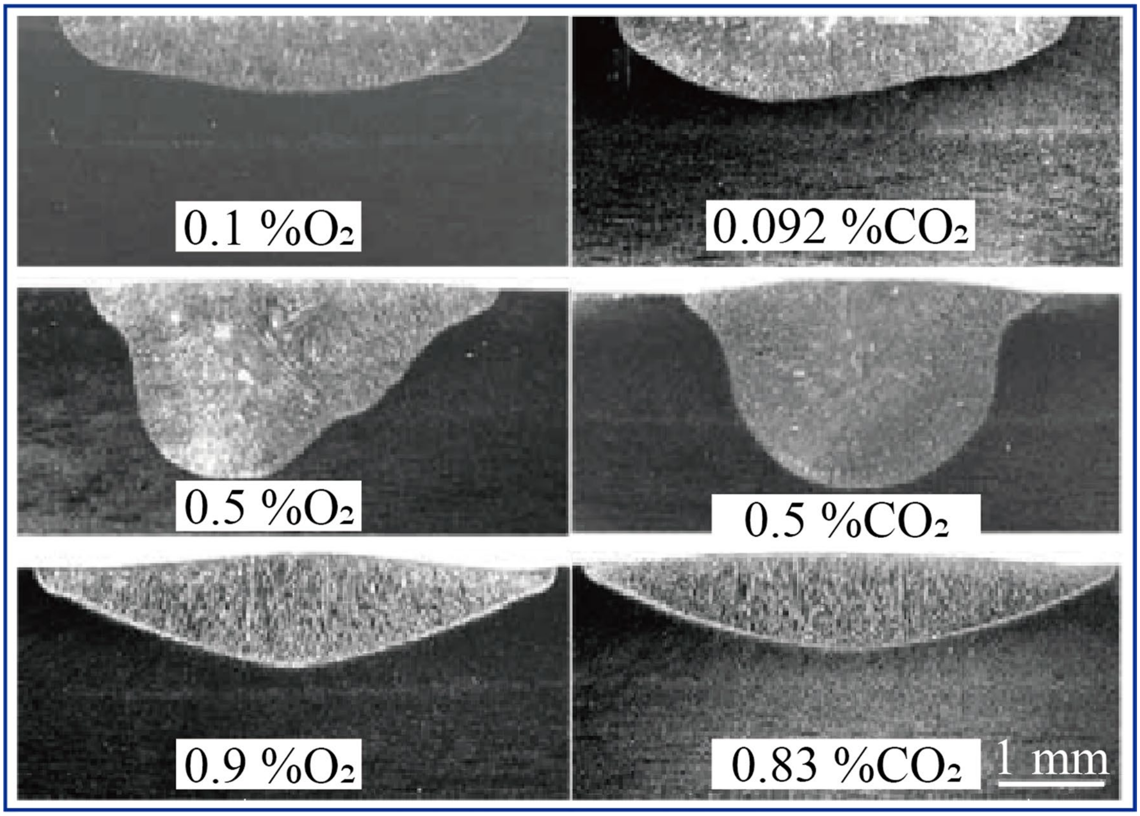


Fig. 13 Molten pool morphology with different O_2 and CO_2 additions [71]

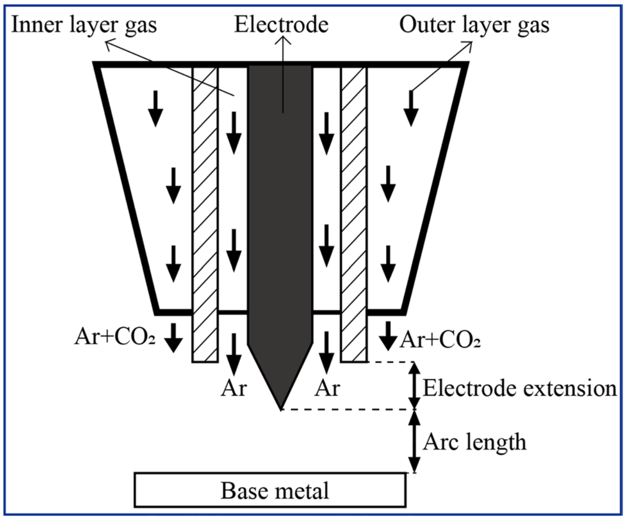


Fig. 14 Schematic diagram of the double protective gas TIG welding process [74]

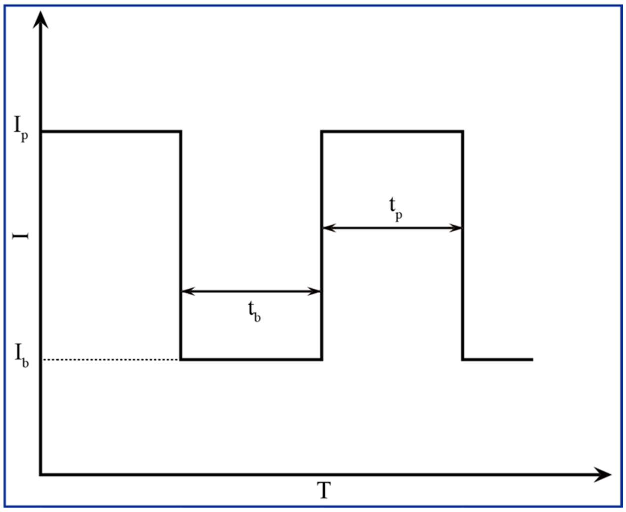


Fig. 15 Schematic diagram of pulse rectangular waveform [76]

According to the pulse frequency, pulse current can be categorized into low frequency (less than 100 Hz), medium frequency (100–1000 Hz), and high-frequency (more than 1000 Hz). Korhonen et al. [79] studied the influence of high-frequency pulse current on the arc shape of narrow gap welding, as shown in Fig. 16. They found that the arc will be periodically distributed at the bottom corner of the groove sidewalls, and the bottom corner will fuse well. Therefore, the pulse current can change the arc width.

Xu et al. [80] measured the maximum arc width at a pulse frequency of 2 Hz-15,000 Hz and obtained its natural

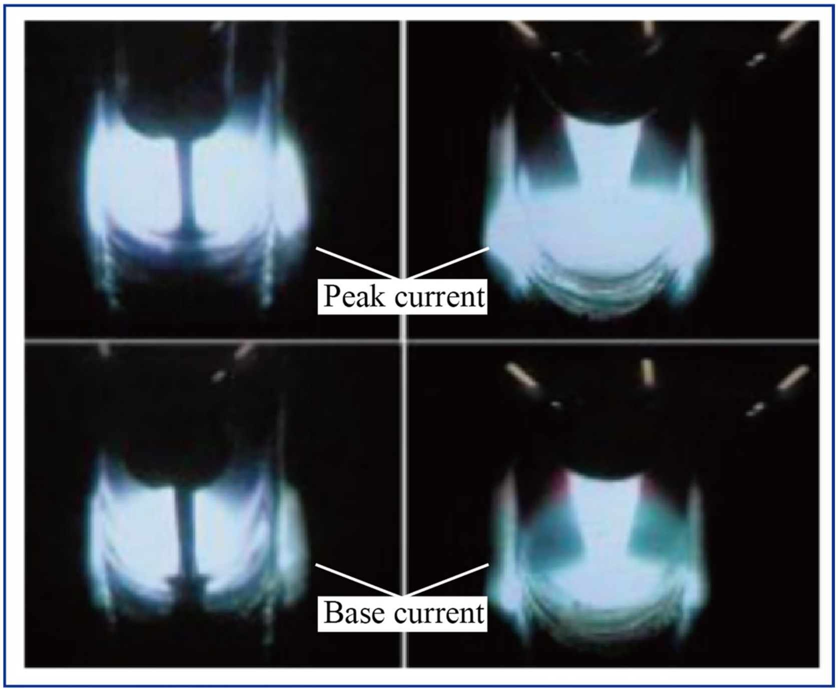


Fig. 16 Arc shape under pulse current [79]

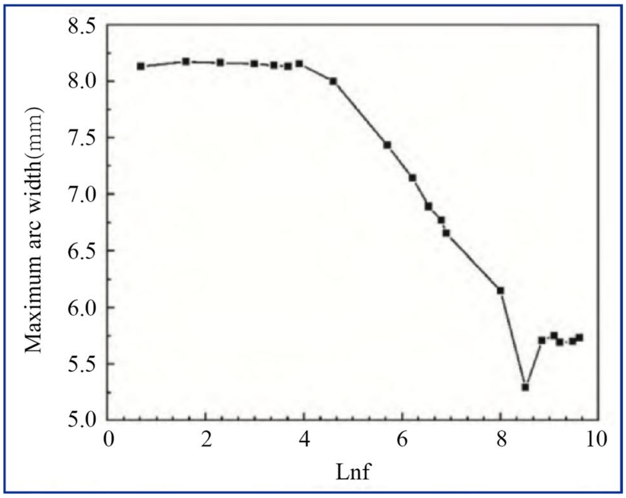


Fig. 17 Relationship between maximum arc width and pulse current frequency [80]

logarithmic relationship curve with the pulse current frequency. As shown in Fig. 17, with the increase of pulse current frequency, the maximum arc width decreases.

Research shows that pulse current will produce radial pulsating electromagnetic contraction force [81]. With the increase of pulse frequency, the electromagnetic contraction force, arc stiffness, and arc stability are enhanced [82]. High-frequency pulse current can improve the flow of molten pool, form a middle concave weld seam [83, 84], and improve the insufficient penetration of sidewalls. However, when the difference between the pulse base current and the peak current is large, it is easy to form middle convex weld seam and increase the probability of insufficient sidewalls penetration.

2.3 Composite welding

In order to realize the complementary advantages of different heat sources and reduce costs, the narrow gap welding method with composite heat sources has appeared in recent years. Commonly used are narrow gap laser-TIG composite welding process and narrow gap TIG-MIG composite welding process.

2.3.1 Narrow gap laser-TIG composite welding process

Narrow gap laser-TIG composite welding process is an extension of the conventional narrow gap TIG welding. In this process, a laser source is added to provide additional heat to the sidewalls of the narrow gap groove, as shown in Fig. 18 [85]. This process combines the advantages of laser welding and TIG arc welding. Laser welding has the advantages of high welding speed, high energy density, excellent penetration, and strong anti-interference ability. TIG arc welding has the advantages of good groove gap adaptability, low assembly accuracy, and high metal deposition rate [86]. The interaction between a laser and a TIG arc results in a synergistic effect that exceeds the sum of their individual contributions [87].

Laser defocusing significantly impacts the fusion of groove sidewalls. In general, the larger the defocus, the

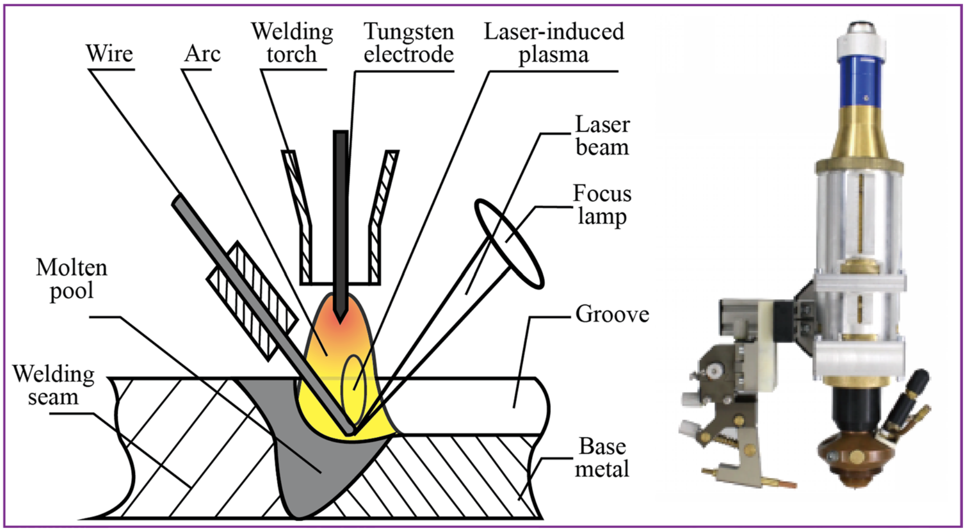


Fig. 18 Schematic diagram and physical drawing of the narrow gap laser -TIG composite welding process [85, 87]

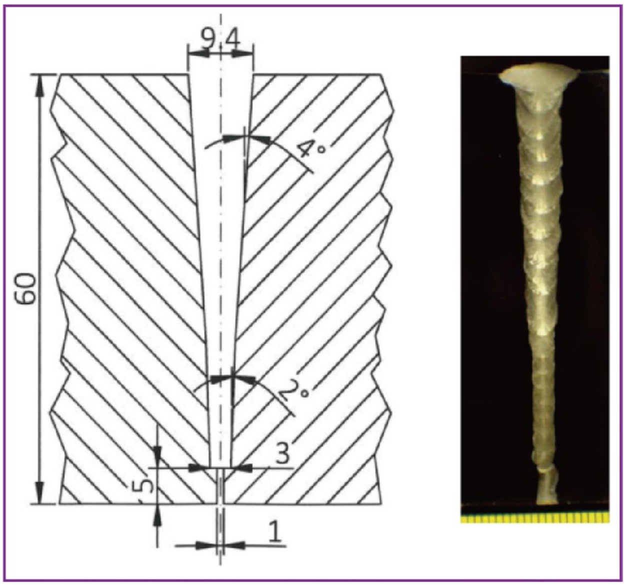


Fig. 19 Narrow gap weld seam formation by combining positive defocusing laser with TIG arc [88]

larger the laser spot diameter. Therefore, the increase in laser heating area is beneficial to the fusion of groove sidewalls. Subsequent arc can further increase heat input and improve fusion efficiency. Karhu et al. [88] found that excellent weld seam formation can only be achieved by combining positive defocusing laser with a TIG arc, as shown in Fig. 19.

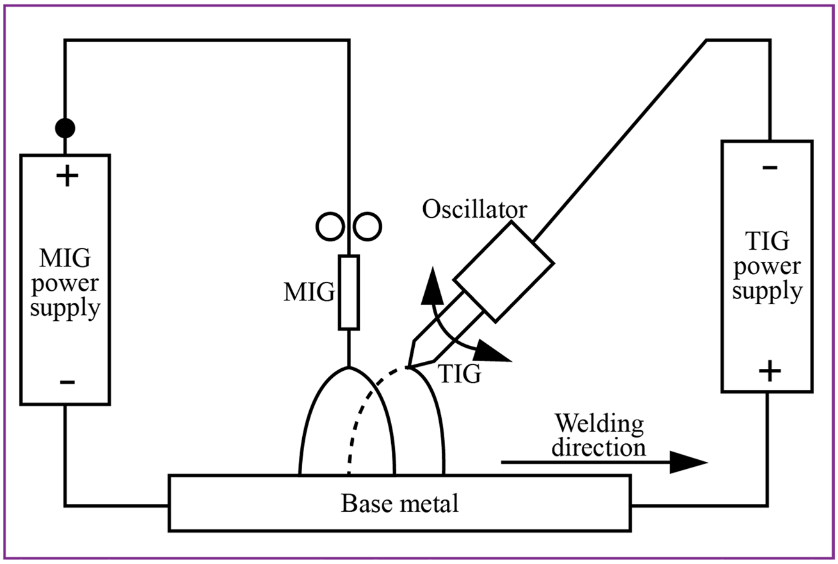
Because of the high requirements of laser assembly and low gap tolerance, the laser cannot completely reach the bottom of the groove simply by adjusting the defocus. Researchers have proposed a mechanical oscillating laser welding process, which can realize the welding of medium-thick plates. The welding quality is not good because of the low oscillating precision and the oscillating frequency being less than 50 Hz. Yamazaki et al. [89] have developed a scanning galvanometer laser welding process, which realized the oscillating laser with a higher frequency (0–2 kHz) and a more complicated trajectory. The principle is to use the deflection of the mirror. Chen [90] and Ma [91] combined scanning galvanometer laser with narrow gap TIG welding. They found that an oscillating laser can promote the flow of a molten pool. The direct heating of the laser and the flow of the molten pool can enhance the wetting effect of sidewalls and increase the sidewalls penetration. Scanning galvanometer laser narrow gap TIG welding has great advantages for welding complex thick plates. But the equipment cost is too high.

2.3.2 Narrow gap TIG-MIG composite welding process

Narrow gap TIG-MIG composite welding process combines the advantages of TIG and MIG, which is a high-quality and high-efficiency welding method [92]. The interaction between TIG and MIG arcs forms a unique composite heat source. Research shows that [93–97], when the distance between two electrodes is less than 8.5 mm, two molten pools can be well combined into one molten pool. TIG arc can stabilize the arc of MIG, and MIG arc can improve the arc starting ability of TIG. When MIG welding torch is placed behind TIG welding torch, it is beneficial to the stability of arc and can improve the stability of welding process. But there is still insufficient sidewalls penetration in this process.

He [98] proposed a narrow gap oscillating TIG-MIG composite welding process. A mechanical oscillating TIG heat source is adopted, as shown in Fig. 20, which can provide more heat for sidewalls fusion. Further, the composite heat source can effectively increase the arc spread and weld seam width.

Fig. 20 Narrow gap oscillating TIG-MIG composite welding process [98]



Huang et al. [99, 100] found that when the oscillating frequency increases to a certain extent, the TIG weld seam widens, and the subsequent MIG wire enters the molten pool and spreads out. Therefore, this process can improve the molten pool width [101], weld seam formation, and weld seam quality, as shown in Fig. 21.

However, the shortcomings of this process are that it adopts mechanical oscillating TIG with a low oscillating frequency. Moreover, the oscillation of TIG welding torch requires a wider groove gap, resulting in inefficiency. As for complex thick metal plates, the application of this device is limited because of its large volume.

3 Summary and outlook

As one of the key technologies for welding thick metal plates, narrow gap TIG plays an extremely important role in the development of manufacturing technology. In order to improve insufficient sidewalls penetration, new methods based on narrow gap TIG are constantly emerging, as shown in Fig. 22. Thickness of plates that can be welded by various methods is shown in Fig. 23.

Both oscillating tungsten electrode process and oscillating TIG-MIG composite welding process use a mechanical oscillating heat source to periodically transfer arc heat to

Fig. 21 Weld seam formation at different oscillating frequencies [98, 101]

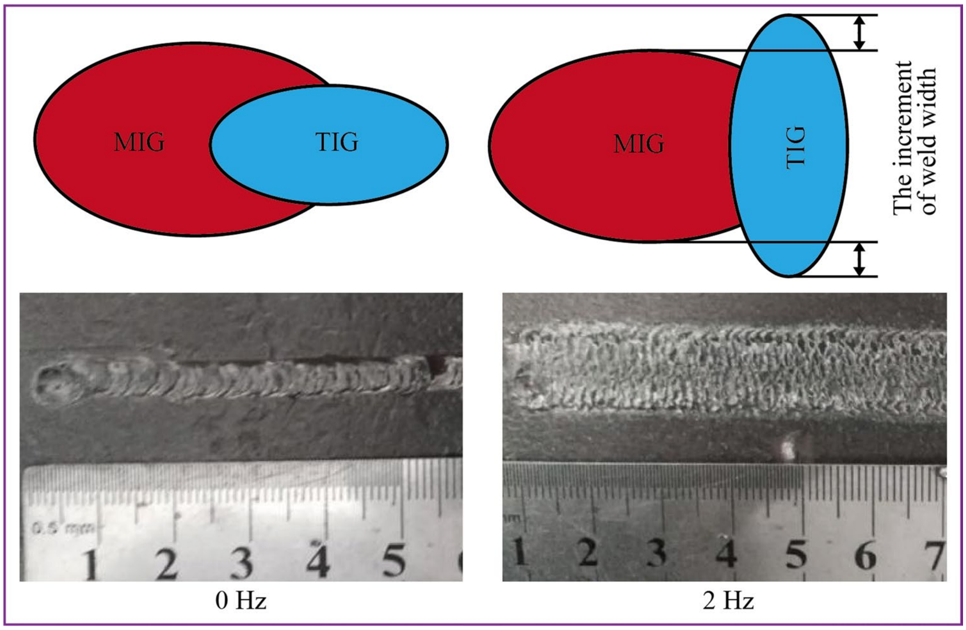
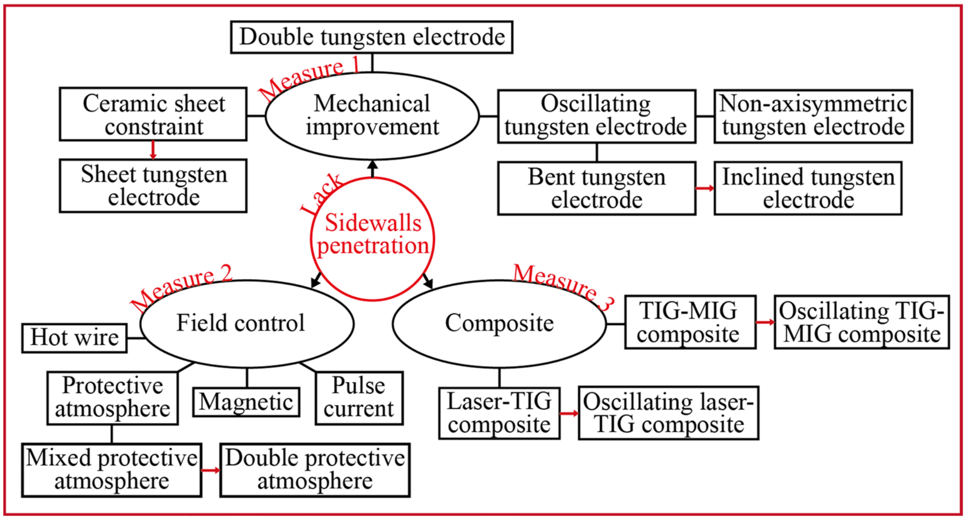


Fig. 22 Narrow gap TIG welding technology development



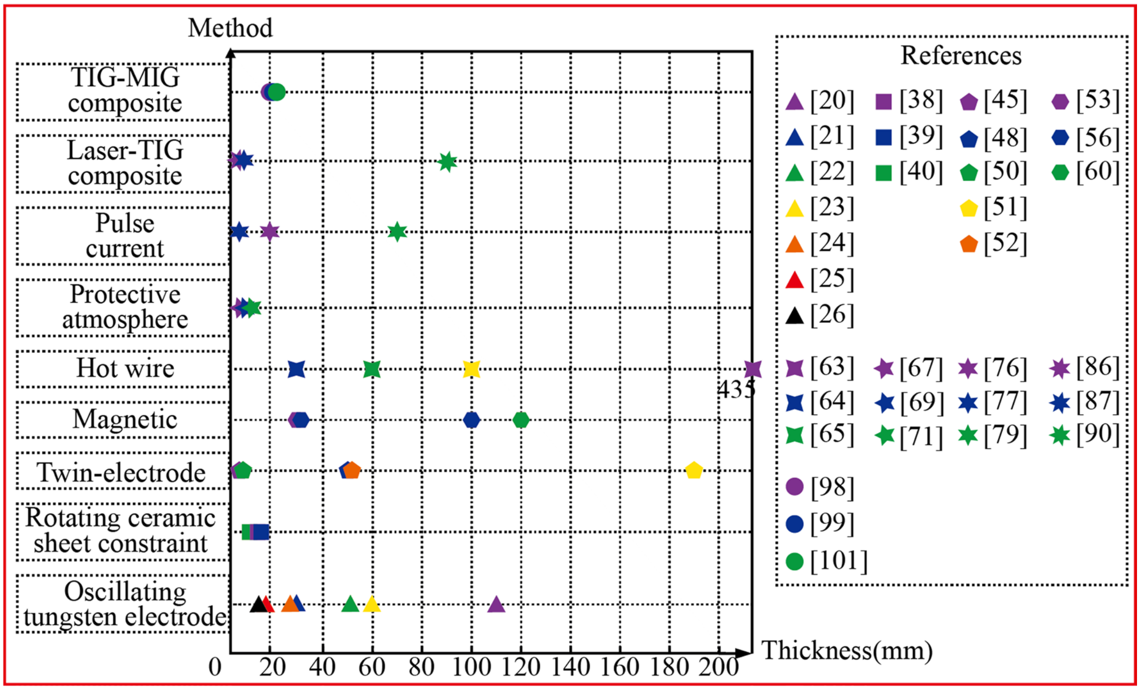


Fig. 23 Plate thicknesses that can be welded by various methods

the sidewalls, but the efficiency is low. Magnetic control, pulse current, and scanning galvanometer laser realize a higher frequency and larger amplitude of heat source oscillation, which are more suitable for high-efficiency welding. Ceramic sheet constraint process limits the arc to the bottom corner of the sidewalls, but the ceramic sheet is easily burned at high temperatures, resulting in poor application prospects. Double tungsten electrode forms a symmetrical triangle arc, which expands the arc range. Hot wire method can improve the temperature distribution of molten pool and increase efficiency by preheating wire. Welding protective atmosphere method improves the flow of molten pool by introducing diatomic gas and oxygen, but it wastes a lot of protective gas and is not economical. The shortcomings of all processes are summarized in Table 1.

Magnetic control, hot wire, and pulse current are also commonly used for auxiliary welding. For example, a hot wire system can be added to the oscillating tungsten electrode process. Further, auxiliary welding processes A-TIG (Activating TIG welding), TIP-TIG, and U-TIG (Ultrasonic TIG welding) also have great application prospects in narrow gap TIG welding. Using the idea of

Table 1 Shortcomings of all processes

Optimization methods	Process categories		Shortcomings
Mechanical improvement	Oscillating tungsten electrode	Bent tungsten electrode	Difficult operation High cost
		Inclined tungsten electrode	Inefficiency
		Non-axisymmetric tungsten electrode	Poor welding consistency
	Ceramic sheet constraint	Rotating ceramic sheet	Inefficiency
		Sheet tungsten electrode	Difficult operation Ceramic sheet is easy to burn
	Double tungsten electrode		High cost Poor cooling effect of welding torch
External field control	Magnetic		Large device size
	Hot wire	Resistance heating	Magnetic bias blowing Not suitable for wire with low resistivity
		High-frequency induction hot wire	Heating temperature of wires with different materials or different wire feeding speeds is difficult to control
	Protective atmosphere	Mixed protective atmosphere	Tungsten electrode burns easily
		Double protective atmosphere	Uneconomical
	Pulse current		Pulse base current and peak current should not differ too much
Composite welding	Laser -TIG composite	Non-oscillating laser -TIG composite	Poor quality Inefficiency
		Oscillating laser -TIG composite	Low mechanical oscillation efficiency Scanning galvanometer laser has high cost
	TIG-MIG composite	Non-oscillating TIG-MIG composite	Poor quality
		Oscillating TIG-MIG composite	Low mechanical oscillation efficiency Large device size

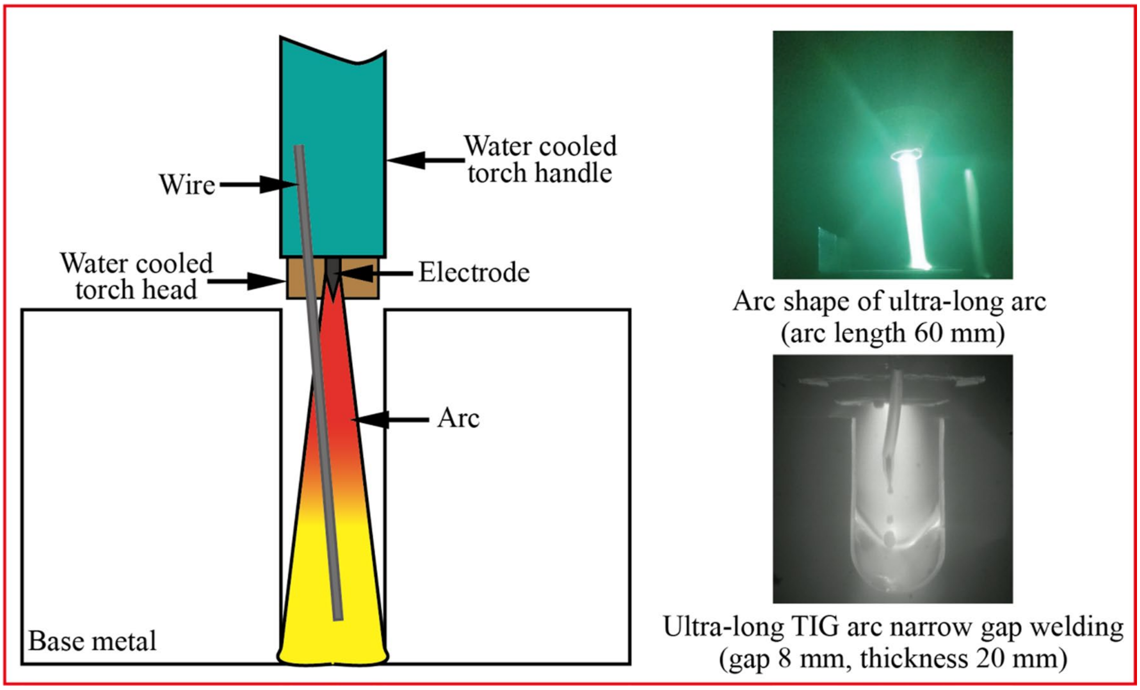


Fig. 24 Ultra-long arc narrow gap welding and arc shape

A-TIG to coat metal halide on the sidewalls as an activator in advance may improve the energy density. Using the idea of TIP-TIG to vibrate wire feeding at a frequency of thousands of times per minute may improve the flow of the molten pool. Using the idea of U-TIG to apply an ultrasonic field to the arc may make it oscillate.

When welding thick plates, it is necessary to put the whole welding torch into the groove gap, which leads to wide groove gap, large welding wire filling, and low efficiency. A novel idea would be to introduce an ultra-long TIG arc directly into the groove bottom, which could further reduce the gap and improve the welding efficiency. Moreover, the ultra-long arc has good coverage on the bottom of the groove, which can effectively improve insufficient penetration of sidewalls. The insulating effect of protective gas between TIG arc and sidewalls and the constraint effect of laminar plasma on TIG arc could prevent arc deviation, thus forming a stable arc, as shown in Fig. 24.

In a word, narrow gap welding has broad prospects. The emergence of various new methods and processes has promoted the progress of industry and the development of human civilization.

Author's contributions Honglei Zhao: Conceptualization, Methodology, Writing-original draft. Siyu Zhang: Collecting documents, Writing-original draft. Xianglong Yu: Conceptualization, Collecting documents, Writing-original draft. Yiwen Li: Collecting documents, Supervision. Junyan Miao: Collecting documents, Supervision. Chenhe Chang: Writing-review & editing, Resources. Yunlong Chang: Project administration, Supervision. All co-authors participated in the writing or guidance of the paper and played an important role.

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Data availability All data in this manuscript is original and does not involve any copyright issues.

Declarations

Ethical approval We comply with the COPE guidelines and make the following commitments. All the data and experimental contents involved in this manuscript are original. It does not involve publishing in any form or language elsewhere. The quoted words of other people are marked in the text by reference.

Consent to participate All co-authors are aware of the writing and publication of this article and agree to publish it.

Consent to publish All co-authors agree to publish this article.

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