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RESEARCH STATUS AND PROSPECTS FOR TIG-MIG HYBRID-ARC-WELDING TECHNOLOGY

RAZISKAVA STANJA IN PERSPEKTIVE TEHNOLOGIJE TIG-MIG HIBRIDNEGA OBLOČNEGA VARJENJA

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TIG-MIG hybrid welding integrates the merits of tungsten insert-gas welding (TIG) and metal inert-gas welding (MIG), and achieves a new material-joining process with high quality, high efficiency and low cost. However, TIG-MIG hybrid welding also had some shortcomings, such as a complex process, unstable arc, large heat input, limiting its application. To further improve and promote TIG-MIG hybrid welding, numerous universities and research institutes have put forward a series of improvement programs that achieve relatively good results. In this study TIG-MIG hybrid welding is discussed in three aspects: the welding-process improvement, welding-parameters optimization and numerical simulation of the welding process. It was found that the stability of the hybrid arc welding process and the quality of the weld bead can be improved by improving the current polarity, wire type and arc swing. The TIG current, the distance between the wire and tungsten, and the heat input had an important impact on the weld quality and the formation of defects. A numerical simulation of the welding process analyzed the effects of torch angle, the distance between the wire and tungsten, the welding speed and the temperature fields on the arc morphology, molten-pool behavior, and droplet transfer. According to the above analysis, it summarized the current research status of TIG-MIG hybrid welding, and then proposed future research directions based on the existing shortcomings and deficiencies.

Keywords: tungsten insert-gas welding; metal inert-gas welding; welding parameters; numerical simulation

TIG-MIG hibridno varjenje združuje prednosti električnega varjenja z volframovo fiksno elektrodo v zaščitnem plinu (TIG) in obločnega varjenje s kontinuirano dodajalno kovinsko elektrodo v zaščitnem plinu (MIG). Zaščitni plin je v prvem primeru običajno Ar v drugem pa mešanica Ar in CO_2. S tem hibridnim dokaj stroškovno ugodnim postopkom se doseže nov način visoko kvalitetnega in učinkovitega vezanja različnih materialov. Vendar pa ima hibridno TIG-MIG varjenje tudi nekaj slabosti. To je kompliciran postopek z dokaj nestabilnim oblokom in velikim vnosom toplotne energije, ki omejuje njegovo splošno uporabo. Številne univerze in raziskovalni inštituti so zato, da bi nadalje izboljšali in promovirali TIG-MIG hibridno varjenje, začeli s številnimi raziskovalno-razvojnimi programi in projekti, ki so dali relativnodobre rezultate.V tem članku avtorji opisujejo in razpravljajo o TIG-MIG hibridnem varjenju s treh vidikov: izboljšav procesa varjenja, optimizacije parametrov varjenja in numeričnih simulacij procesa varjenja. Avtorji ugotavljajo, da je možno stabilnost procesa hibridnega obločnega varjenja in kvaliteto raztaljene kovine oziroma »posteljice« izboljšati z izboljšanjem polarnosti električnega toka, vrsto žice in nihanjem obloka. Električni TIG tok, razdalja med kovinsko žico in volframovo žico ter količina vnesene toplotne energije imajo pomemben vpliv na kvaliteto zvara in nastanek napak v zvaru. Z numerično simulacijo procesa varjenja so avtorji analizirali vpliv kota med MIG in TIG gorilnikoma, razdalje med žico in volframovo elektrodo, vpliv hitrosti varjenja in temperaturnega polja na morfologijo obloka, obnašanja »bazenčka« in prenosa kapljic raztaljenih kovin. V skladu z njihovo analizo opisano v tem članku avtorji povzemajo, da trenutno stanje raziskovanja TIG-MIG hibridnega varjenja in predlagane smeri bodočih rešitev temeljijo na obstoječih slabostih in znanih težavah tega postopka.

Ključne besede: obločno varjenje kovin in zlitin z volframovo elektrodo v zaščitnem plinu,parametri varjenja, numerične simulacije

1 INTRODUCTION

With the extensive application of metal materials, welding technology has played an important role in fields such as aerospace, mechanical manufacturing, construction engineering, energy, and power.[1] Currently, low-carbon manufacturing demands welding technology that is both environmentally friendly and cost effective. Traditional single-heat-source arc-welding processes struggle to balance high-performance welded joints and a high welding efficiency.[2]

Hybrid-heat-source welding was a process that combines two or more heat sources to obtain the advantages of each. As shown in **Figure 1**, common methods of hybrid-heat-source welding included laser-friction hybrid heat source,[3] laser-arc hybrid heat source,[4,5] ultrasonic-plasma hybrid heat source, and multi-arc hybrid heat source.[6] As early as the 1970s, scholars proposed the hybrid welding process of laser coupling with other heat sources, but it failed to become popular due to its high cost, low energy-utilization efficiency, and poor adaptability.[7] Traditional TIG welding has the advantages of simple equipment, low cost, and high quality. However, its welding efficiency is relatively low because the tungsten electrode did not melt. Traditional MIG welding used wire as the electrode, which improved the welding efficiency, but it was prone to splattering due to unstable cathode spots.[8] To integrate the advantages of TIG and MIG welding processes, scholars proposed

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TIG-MIG hybrid welding. It coupled the TIG torch and MIG torch together through the fixture to utilize the hybrid arc for melting the base material and the wire, formed a molten pool, and achieved material joining under the shield of inert gas. TIG-MIG hybrid welding improved the weld quality and efficiency, presenting unparalleled advantages compared to single-heat-source welding. However, in practical applications, it still faced drawbacks such as complex welding parameters, unstable arc, and high heat input.[9] To further promote TIG-MIG hybrid welding, numerous experiments and improvements have been conducted by universities and research institutions. This paper provides an overview of the research conducted by scholars to address the aforementioned issues, including welding-process improvements, optimization of the welding parameters, and a numerical simulation of the welding process. Additionally, it discussed and outlined the hot issues and future research directions in TIG-MIG hybrid welding.

2 WELDING-PROCESS IMPROVEMENT

Numerous scholars had conducted research to further improve the welding quality and adaptability by investigating the hybrid-arc morphology and bead formation from the perspectives of current polarity, welding-wire type, and arc oscillation.

Gao[10] used alternating current TIG and direct current MIG to form the TIG-MIG hybrid arc and conducted welding experiments on low-carbon steel. It found that DC MIG ensured the reliability of arc ignition when the TIG arc polarity was converted. The polarity change of the TIG arc caused the two arcs to attract and repel periodically. When the two arcs repelled each other, the molten metal at the wire tip transferred to the rear of the molten pool, which helped the molten metal reflux, thus suppressing the formation of the humping bead. Zhang et al.[11] and Li[12] proposed the TIG-MIG alternating double-arc welding process to solve the problems of excessive heat input and an insufficient amount of filler metal in traditional MIG. As shown in **Figure 2a** and **2b**, an auxiliary arc was used to heat the base metal in the base value stage of the main arc pulse to change the shape of the heat source and improve the weld quality. In the peak stage of the main arc pulse, an auxiliary arc was used to heat the welding wire to increase the deposition efficiency. Tang et al.[13,14] studied the effect of electrode polarity on the arc-ignition performance of the TIG-MIG hybrid welding. As shown in **Figure 2c** and **2d**, MIG could realize non-contact ignition by using a direct current electrode positive (DCEP). The polarity connection of the TIG and the distance between the wire and tungsten only affected the difficulty of non-contact ignition. Wang et al.[15] studied the influence of polarity matching and the distance between the wire and tungsten on the TIG-MIG hybrid welding process for 5A06 aluminium alloy. As shown in **Figure 2e** and **2f**, the two arcs could be completely coupled when the polarity of the TIG arc and the MIG arc were the same. The two arcs repelled each other and the coupling was difficult when the polarity was opposite. With an increase of the distance between the wire and tungsten, the two arcs gradually changed from coupling to mutual influence, until independence.

Liang et al.[16] proposed a TIG-CMT hybrid-welding process to solve the problem that Cold Metal Transfer

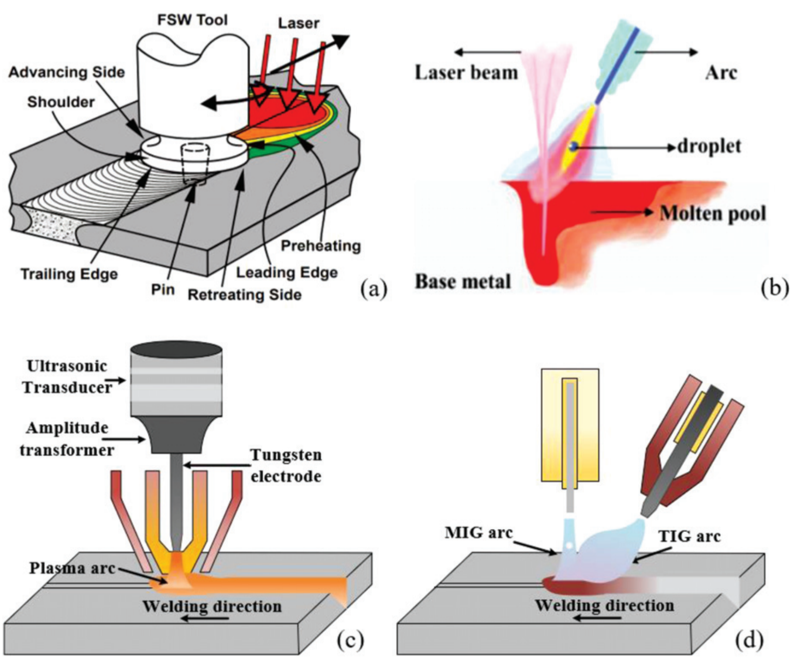

Figure 1: a) Laser-assisted friction-stir-welding schematic[3], b) laser-arc hybrid-heat-source-welding schematic[5], c) ultrasound-plasma hybrid-heat-source-welding schematic and d) TIG-MIG hybrid-welding schematic

(CMT) could not be applied to thick plates, as shown in **Figure 2g** to **2i**. The TIG arc was added to increase the heat input on the workpiece to improve the penetration. Jiang et al.[17] proposed a welding method for bypass hybrid variable polarity plasma arc, which offered a unique advantage for adjusting the heat input of the wire and the base metal freely. Similarly, to improve the stability of the keyhole welding, Guo et al.[18] and Liu et al.[19] proposed a hybrid-plasma-free arc-welding method based on a plasma arc welding torch. The added free arc acted in an assistant role to adjust the arc heat output without affecting the arc pressure peak. Dong[20] and Zhang et al.[21] studied the droplet transfer of TIG-MIG hybrid welding by using a cable-type wire. As shown in **Figure 2j** to **2m**, the TIG arc force and the mechanical rotation force of the cable-type wire changed the droplet shape, reduced the droplet diameter, and improved the stability of the droplet transfer.

Zhu et al.[22] proposed a two-electrode TIG-MIG indirect arc-welding method. As shown in **Figure 3a**, the two tungsten electrodes were connected to the negative electrode of the two TIG power supplies, and the welding wire was connected to the positive electrode of the two TIG power supplies. The effect of wire feeding rate and current on the process stability was studied. The results showed that there was an optimal wire feeding rate for a certain welding current, which made the arc more concentrated and the coupling degree higher. With the increase of the welding current, the arc length increased gradually. When the current exceeded the critical current, the electromagnetic force and arc pressure acting on the droplet increased obviously, which was manifested as a projected transfer, and the process stability was excellent.

Huang et al.[23] proposed a swing TIG-MIG hybrid welding method to solve the problem of poor side-wall fusion. As shown in **Figure 3b** and **3c**, swing TIG-MIG hybrid welding could increase the width of the TIG molten pool, effectively increase the spread of the weld, and prevent the undercut defect. With the increase of the swing frequency, the weld boundary becomes smoother. Huang et al.[24] developed a rotary pendulum TIG-MIG

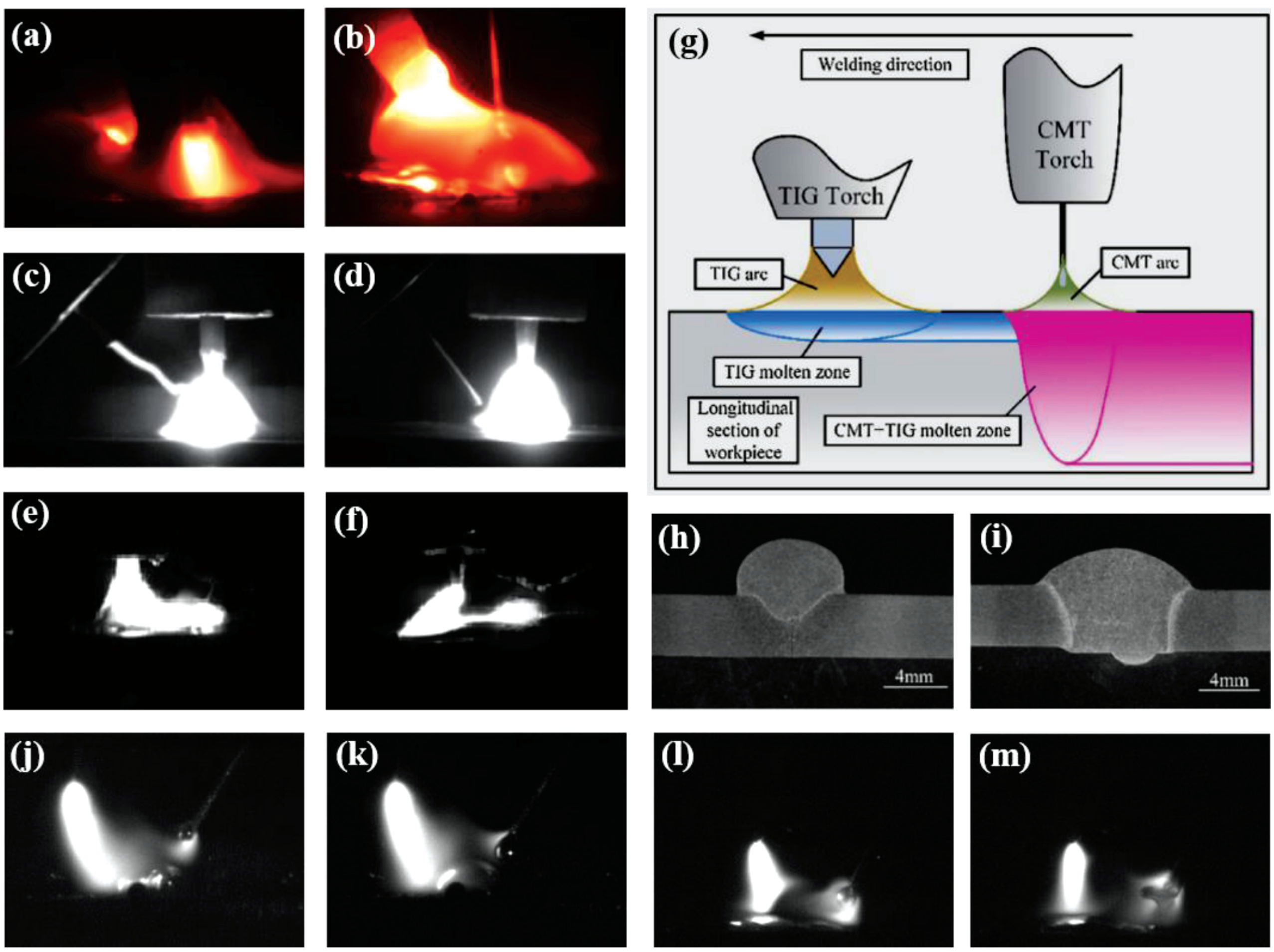

Figure 2: a) Arc shape at the base value of the main arc, b) arc shape at the peak value of the main arc[12], c) MIG DC reverse non-contact arc-initiation moment, d) MIG DC positive arc image[13], e) TIG positive hybrid-arc morphology, f) TIG reverse-hybrid-arc morphology[15], g) Schematic diagram of melt-through formation during TIG-CMT welding, h) macrostructure of DC-CMT joint, i) TIG-CMT joint macrostructure15[16], j) 0-ms single-filament MIG droplet transfer, k) 10.5-ms single-filament MIG droplet transfer, l) 0 ms cable-type welding-wire droplet transfer and m) 10.5-ms cable-type welding-wire droplet transfer[20]

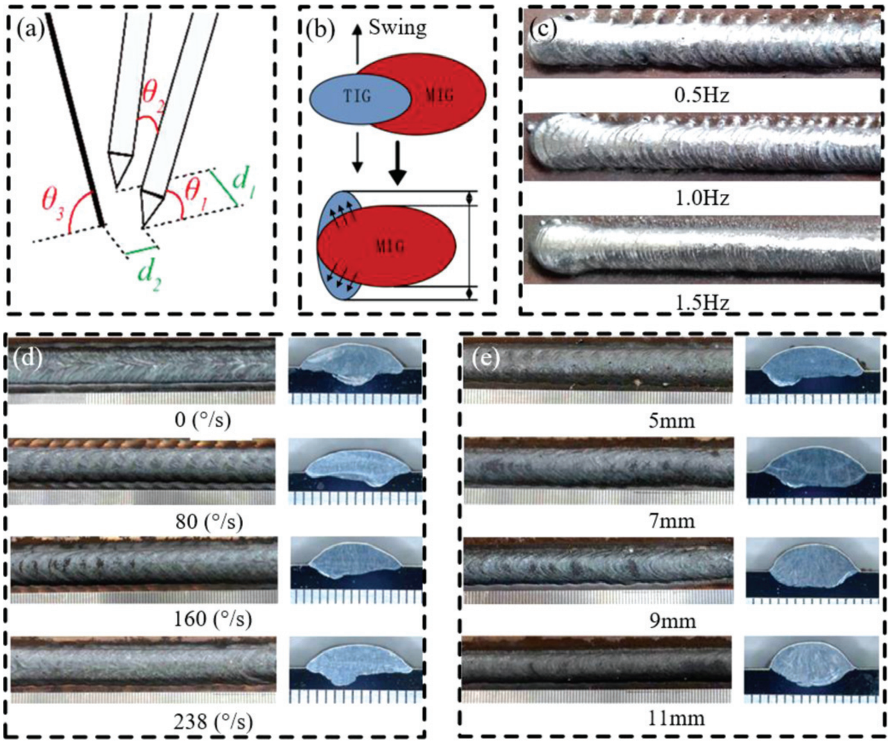

Figure 3: a) Schematic diagram of the relative positions of tungsten electrode and wire[22], b) Schematic diagram of oscillating TIG-MIG hybrid molten pool, c) comparison of weld bead at different oscillation frequencies[23], d) shape and cross-section of weld bead at different oscillation speeds and e) at different distance between wire and tungsten[24]

hybrid welding torch. It explored the influence of the combination of transverse swinging TIG arc and MIG arc on the bead formation. When the rotating pendulum speed increased, the weld width decreased, the weld penetration and residual height slightly increased, the ripple spacing on the weld surface decreased, and the weld surface gradually became smooth, as shown in **Figure 3d**. The weld penetration gradually changed from asymmetry to symmetry with the increase of the distance between the wire and tungsten, and the weld surface gradually became smooth from rough, as shown in **Figure 3e**.

According to the above analysis, the improvement of the TIG-MIG hybrid welding process gave satisfactory results. Changing the electrode polarity could improve the stability of arc, suppress the formation of humping defects, and increase the deposition efficiency. Changing the type of welding wire and the relative position of the electrode promoted the droplet transfer and improved the weld quality. The mechanical swing of the TIG welding torch integrated the advantages of manual arc welding, which significantly increased the spread of the molten metal, widened the molten pool and improved the weld morphology and welding quality. The above hybrid-heat-source welding processes were improved for specific materials and special working conditions. The scope of the application urgently needed to be expanded. A large number of experiments should be carried out for the TIG-MIG hybrid welding process to develop a new hybrid heat source welding process with strong adaptability and high welding efficiency.

3 WELDING-PARAMETER OPTIMIZATION

Unreasonable parameter selection or excessive fluctuation in the welding process would have a great impact on welding quality, such as: weld size out-of-tolerance, cracks, spatter, undercut, and humping.[25] To suppress the welding defects and improve weld quality, researchers studied arc shape, droplet transfer, molten-pool behavior and bead formation from the aspects of shielding-gas composition, welding current, voltage waveform and heat input.

Tang et al.[13,14] studied the influence of shielding-gas types on the arc-ignition performance of TIG-MIG hybrid welding. In **Figure 4a** to **4c**, the reason for achieving non-contact ignition was that the outer electrons of the TIG arc moved towards the wire tip and collided with the shielding gas to partially ionize it. This led to a significant increase in the conductivity of the gap, causing it to breakdown at low voltage. It was easier to realize non-contact ignition in a pure Ar atmosphere than in an active atmosphere. Li[26] used Ar + N_2 double-layer shielding gas for narrow-gap TIG-MIG hybrid welding of dissimilar steel. As shown in **Figure 4d** and **4e**, the welding arc existed in the form of dual arc coupling under the protection of inner Ar and outer N_2, the arc shrank significantly, changed from fasciculate to cone, which could reduce the droplet size and increase the transfer frequency.

Kaneemar et al.[27] studied the influence of torch angle on the TIG-MIG hybrid welding, as shown in **Figure 4f**.

When the angle of the TIG torch was 90° and the MIG torch was 45°, the repulsive force between the two arcs caused the MIG arc to shift from the wire axis by a small angle, and the concentration of hybrid arc was higher, resulting in wider spreading and better surface finish, as shown in **Figure 4g** to **4i**. Chen et al.[28] carried out a low-current TIG arc-assisted MIG high-speed welding process. It analysed the influence of various parameters on bead formation from the aspects of heat and mass transfer. The auxiliary TIG arc increased the MIG arc length and reduced the arc pressure, as illustrated in **Figure 4j** to **4l**. It reduced the tendency of molten metal to gather behind the arc, and promoted the filling of the weld toe, thereby suppressing the undercut defect. When TIG arc was leading, MIG arc was stable and there were no obvious spatters. When the TIG arc was trailing, the current-voltage waveform of the hybrid arc fluctuates irregularly, and a small amount of spatter was produced, leading to poor weld quality.

Kaneemar et al.[29] used a symmetrical hybrid welding torch to study the influence of TIG current on the bead formation when the MIG current was fixed at 270 A. As shown in **Figure 5a** to **5c**, the MIG arc was stable, and the weld was well formed, when the TIG current was larger than the MIG current. The weld penetration increased with the TIG current. As shown in **Figure 5d** and **5e**, the MIG arc was unstable, and there was a large amount of splashing, when the TIG current was smaller than the MIG current. The weld penetration was independent of the TIG current. The experimental results were compared with those obtained by traditional MIG welding. The mechanical properties of the joint were equivalent, and the welding efficiency was increased by more than twice. Zong et al.[30] studied the influence of the electrode's relative position on arc stability and bead formation in TIG-MIG hybrid welding. As shown in **Figure 5f** and **5g**, the width of weld narrows to suppress the occurrence of undercut defects, when TIG arc was leading. Even if the TIG current was as low as 50 A, the

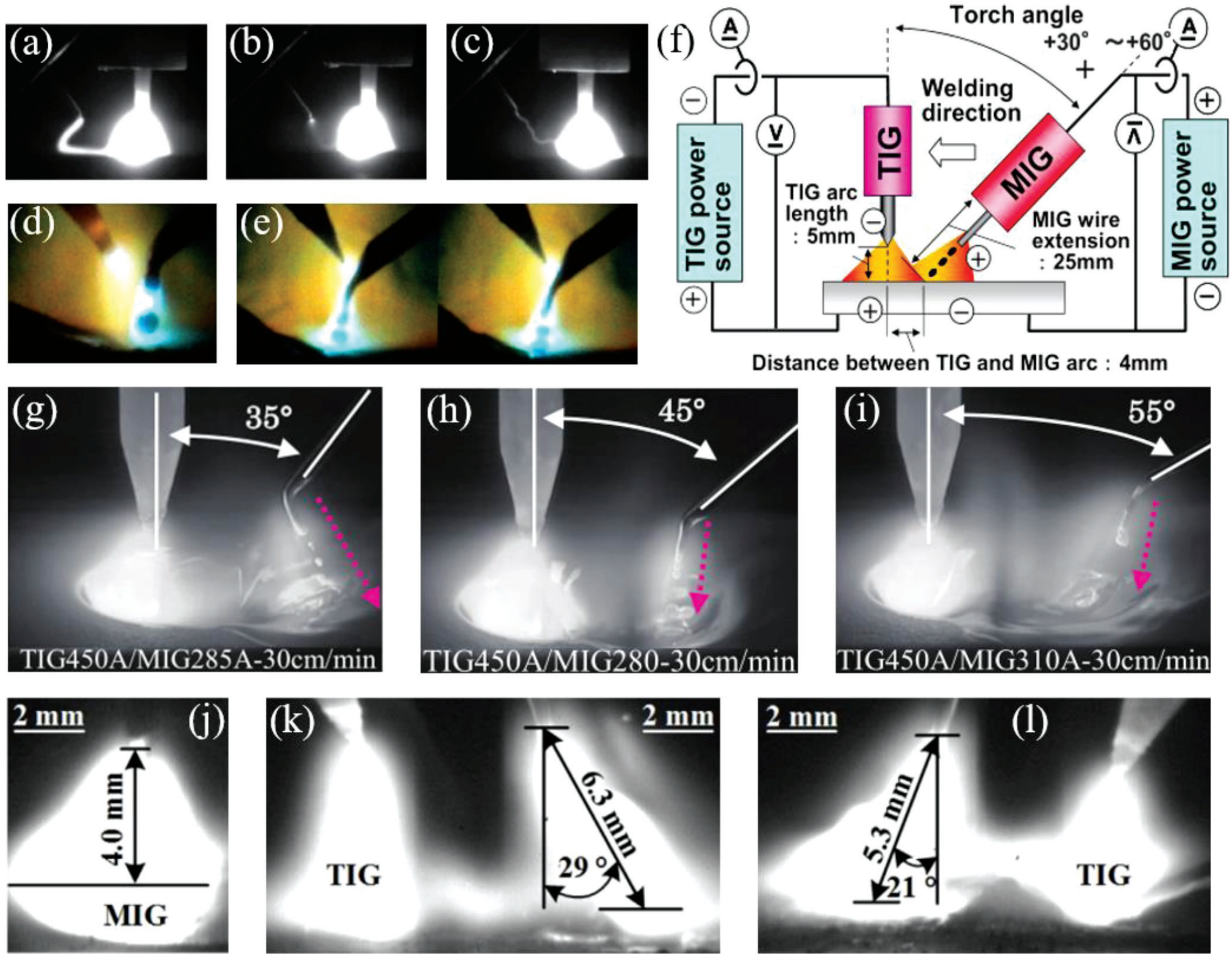

Figure 4: Effect of shielding gas on non-contact arc initiation: a) Ar, b) Ar + 1% O_2, c) Ar + 15% O_2[14]; Effect of shielding gas on arc morphology and droplet transfer d) Ar, e) Ar + N_2[26]; f) Schematic diagram of the hybrid welding experiment; Effect of torch angle on arc morphology and weld-bead formation g) TIG 0°, MIG 35°, h) TIG 0°. MIG 45°, i) TIG 0°, MIG 55°[27]; Comparison of arc patterns of different welding methods, j) MIG, k) TIG + MIG and l) MIG + TIG[28]

welding process exhibited good stability. As shown in **Figure 5h** and **5i**, TIG arc force caused reflux of molten metal to suppress undercut, when TIG arc was trailing. But the arc stability was poor when the TIG current was smaller than 100 A. Roslan et al.[31] studied the influence of the TIG current on the stability of TIG-MIG hybrid arc. It found that the introduction of the TIG arc significantly increased the stability of the MIG arc, even when the TIG current was only 60 A. When the TIG current increased to 120 A, the strong electromagnetic force increased the length of MIG arc, resulting in a decrease in droplet size and a significant increase in transfer frequency.

Chen et al.[32] conducted a high-speed square-wave AC TIG-MIG hybrid welding experiment to explore the influence of different polarity ratios (proportion of negative half-wave duration of AC TIG) on the stability of the welding process and bead formation. When the polarity ratio was 0, the hybrid arc had numerous breaks, and the welding process was unstable, as shown in **Figure 5j**. When the polarity ratio reached 10%, the shape of the hybrid arc expanded and contracted periodically. The hybrid arc had fewer breaks, welding defects such as undercut, humping and spatters were suppressed, and the weld was well formed as a whole, as shown in **Figure 5k**.

Ogundimuy et al.[33] studied the effect of heat input on the welding efficiency of 304 austenitic stainless steel using a TIG-MIG hybrid arc. It found that obvious grain coarsening appeared in the weld with an increase of heat input. The elongation, tensile strength and mechanical properties all showed a downward trend. Abima et al.[34] used the Taguchi method to optimize the parameter combination for thr TIG-MIG hybrid welding of AISI 1008 mild steel. The results showed that the contribution rates of gas flow rate, TIG current and MIG voltage to the tensile strength and yield strength of the joint were 40 %, 27 % and 21 %, respectively. Increasing gas flow rate and TIG current, while reducing MIG voltage, can improve the tensile strength and yield strength of the joint.

The above researchers conducted experiments on parameters such as shielding gas, welding current, electrode polarity, and relative position, respectively. Each factor affected the welding process and bead quality to varying degrees. The type of shielding gas not only affected the difficulty of realizing non-contact arc initiation, but also changed the arc shape and droplet transfer mode. The arc stability was higher and there were fewer spatters when the TIG current was greater than the MIG. When the polarity of the two arcs was the same, the hybrid arc could be fully coupled, and the MIG could realize non-contact arc initiation in DCEP mode. The MIG arc was more stable when the TIG torch was leading,

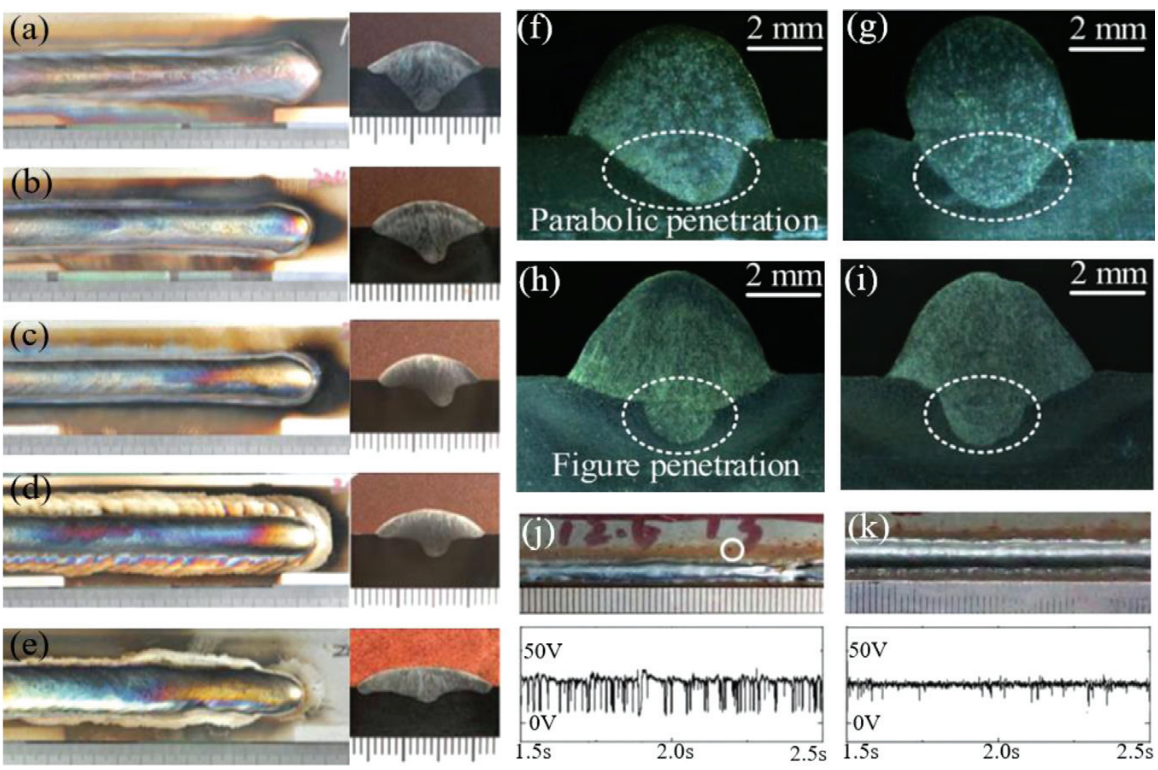

Figure 5: Weld-bead shape and cross-section: a) I_{TIG} = 500 A, I_{MIG} = 270 A, b) I_{TIG} = 400 A, I_{MIG} = 270 A, c) I_{TIG} = 300 A, I_{MIG} = 270 A, d) I_{TIG} = 200 A, I_{MIG} = 270 A, e) I_{TIG} = 0 A, I_{MIG} = 270 A[29]; Weld cross section f) TIG + MIG: I_{TIG} = 50 A, I_{MIG} = 250 A, g) TIG + MIG: I_{TIG} = 100 A, I_{MIG} = 250 A, h) MIG + TIG: I_{MIG} = 50 A, I_{TIG} = 250 A, i) MIG + TIG: I_{MIG} = 100 A, I_{TIG} = 250 A[30]; Weld bead shape and voltage waveform (j) Polarity ratio 0; (k) Polarity ratio 10[32]

which could effectively suppress the undercut defect. At present, the welding parameters have been controlled within a relatively good range, but there was still a lack of in-depth exploration of the mechanism of the effects of various welding parameters on the TIG-MIG mixed heat source, which should be given attention in the future.

4 NUMERICAL SIMULATION OF WELDING PROCESS

The welding process involved heat transfer, mass transfer, electromagnetism, and metallurgy. Various physical fields interacted and coupled with each other, with numerous influencing factors.[35] Numerical simulation has become an important technical means to optimize the welding process parameters, predict the welding quality and reveal the welding mechanism with the rapid development of computer science and technology.[36] In recent years, scholars have studied the behaviour of the molten pool and the arc from the perspectives of temperature field, electromagnetic field and flow field.

Kaneemar et al.[37] analysed the effects of welding torch angle and TIG current on the TIG-MIG hybrid arc. By reducing the angle of the welding torch, the electrode tips were brought closer, the current from the wire to the tungsten electrode disappeared and the repulsive force between the two arcs increased, as shown in **Figure 6a**. When the TIG current was low, the current flowed into the base material was small and had no obvious effect on the weld penetration. When the TIG current was higher than 200 A, most of the TIG current flowed into the base material, and the weld penetration increased with the increased of TIG current.

Chen et al.[38] established adaptive plane and volumetric heat source models for TIG and MIG respectively based on experimental observations. It studied the effects of welding torch angle on temperature distribution and weld morphology, and compared them with experimental results. As shown in **Figure 6b**, the heat-source algorithm could accurately predict the welding process regardless of whether the TIG torch was tilted backward or forward. In subsequent research, Chen et al.[39] optimized the arc heat and force model of TIG-MIG hybrid welding by considering the influence of arc deflection and deformation of the molten pool's surface. The results showed that the arc heat distribution of the TIG-MIG hybrid welding was more uniform compared with single MIG, and the peak of heat density was reduced by 5 %. The redistribution of arc force in TIG-MIG hybrid welding was

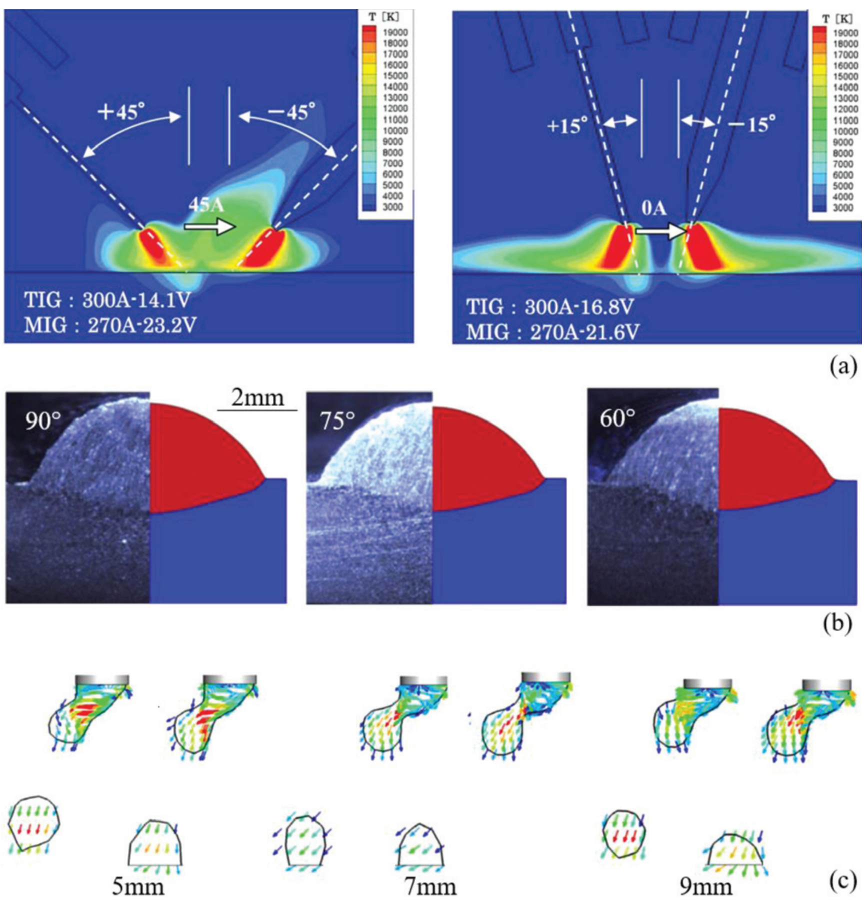

Figure 6: a) Temperature field distribution at different torch angles[37], b) Comparison between experimental and simulated cross-sections at different TIG angles[38] and c) Droplet flow field distribution[41]

beneficial to reduce the backward fluid flow and promote the lateral flow of molten metal. A layer of 0.8-mm-thick molten metal was formed under the hybrid arc, which effectively absorbed the impingement of droplet and further decreased the backward fluid flow.

Lou et al.[40] simulated the temperature field of the workpiece at different distances between the wire and tungsten. When the distance was less than 8.5 mm, the two molten pools formed by the TIG and MIG arcs can be merged into a common molten pool. The two molten pools formed an "8" shape when the distance was 10 mm. There was a low temperature region between the two molten pools, and the tensile strength of the joint was the strongest. The two molten pools became independent of each other when the distance reached 12 mm. Cui[41] and Han et al.[42] analysed the droplet transfer, as shown in **Figure 6c**. When the distance between the wire and tungsten was 7 mm, the interaction between the two arcs was the strongest. The deflection angle between the MIG arc and the droplet was the largest, and the backward droplet momentum could promote the backward fluid flow in the molten pool. The increase of backward fluid-flow velocity of the molten metal promoted the generation of undercutting. Zhao[43] analysed the effects of metal vapor and distance between the wire and tungsten on the arc shape and droplet transfer. The metal vapor could reduce the temperature in the MIG arc column, expand the conductive path between the two arcs, and enhance the coupling effect of the two arcs. The coupling effect almost disappeared, and the two arcs showed their own arc shape when the distance between the wire and tungsten increased to 9 mm.

Wu et al.[44] proposed a self-adaptive arc heat and pressure-distribution model for TIG-MIG hybrid welding to study the influence of process parameters on the bead formation. It found that the ratio of transverse outward velocity to backward velocity of the molten metal decreased when the welding speed increased from 1.5 m/s to 2.0 m/s. Molten metal was difficult to fill the weld toes, resulting in undercut defects. Abima et al.[45] used a Gaussian heat source model to simulate the temperature field distribution of AISI 1008's TIG, MIG and TIG-MIG hybrid welding. It found that the temperature distribution of the MIG molten pool was roughly the

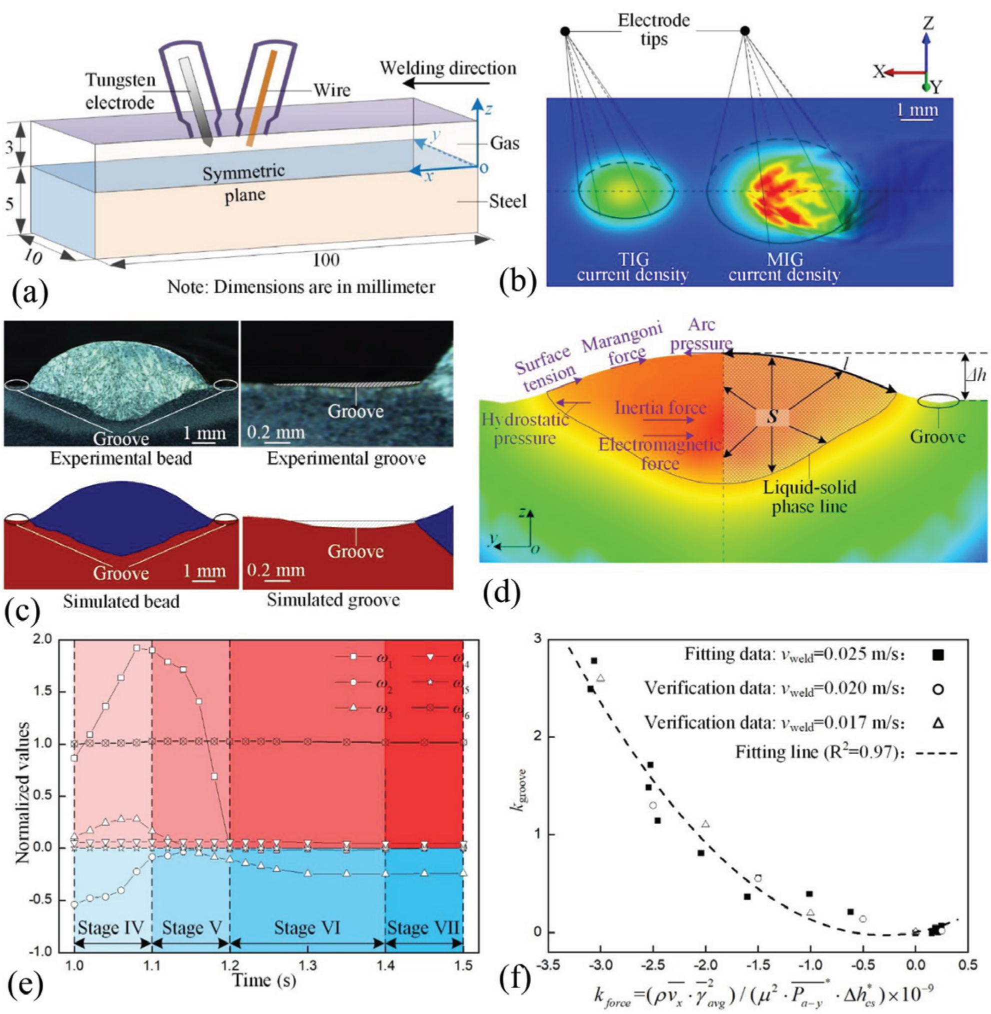

Figure 7: Numerical analysis of the behavior of the molten pool and the suppression mechanism of undercut defect in TIG-MIG hybrid welding

same as that of TIG molten pool, but the peak temperature of the MIG was lower than that of TIG. The peak temperature of TIG-MIG hybrid welding pool was lower than that of single arc, and the temperature gradient was smaller. As the joint of the TIG-MIG hybrid welding had a higher heat input and slower cooling rate, the pearlite structure of coarse dendritic crystal was formed, which decreased the hardness.

The author developed a 3D model, including droplets and molten pool to investigate the phenomenon of multi-coupling transport phenomena in TIG-MIG hybrid arc welding, as shown in **Figure 7a**. The integrated distribution of "arc current density-arc pressure-electromagnetic force-arc heat" was proposed, which could be adapted to the evolution of the molten pool's surface, as illustrated in **Figure 7b**. The comparison between experimental and simulated results on the bead cross-section was shown in **Figure 7c**. The heat and force state of the molten pool was analysed to investigate its influence on the bead formation, as demonstrated in **Figure 7d**. Sensitivity and dimensional analyses proved that the groove sizes could be predicated based on the molten pool's characteristics, including the stress state of the liquid metal, the morphology, and the fluid flow patterns, as illustrated in **Figure 7e** and **7f**. It revealed the quantitative relationships among the welding parameters, the behaviour of molten pool, and the weld bead formation, promoting the implementation of digital twinning technology in the manufacturing industries.

The above scholars analysed the effects of welding torch angle, between wire and tungsten, metal vapor, welding speed and temperature field on the arc shape, molten-pool behavior, droplet transfer and weld microstructure. The hypothesis and models were validated through experiments, and good consistency was achieved. The experimental verification process lacked accurate and continuous physical quantity measurement, which will result in some errors with the numerical simulation data. In the future, numerical simulation of TIG-MIG hybrid welding, a multi-factor “arc-droplet-molten pool” integrate model considering metal vapor should be established. Exploring the influence of the attractive and repulsive forces between the two arcs and the heat-force distribution of the arc on the workpiece, reveal the hybrid welding mechanism, and provide a theoretical basis for optimizing welding parameters.

5 CONCLUSIONS AND PROSPECTS

This paper summarized the research progress of TIG-MIG hybrid welding in recent years from three aspects: welding process improvement, welding parameter optimization, and welding process numerical simulation. The following conclusions can be drawn:

(1) The improvement of the TIG-MIG hybrid welding process enhanced the arc stability and optimized the heat distribution, which increased welding quality and efficiency.

(2) Shielding gas, electrical parameters and electrode relative position all affected the welding process and bead quality to varying degrees. The appropriate combination of welding parameters helped to achieve superior and efficient welding.

(3) The combination of numerical simulation with a small number of experiments could analyze the arc coupling, droplet transfer and molten pool behavior from the aspects of temperature field, electromagnetic field and flow field.

At present, the research of TIG-MIG hybrid welding has made a great breakthrough, but there are still unresolved problems. The author believed that future research should focus on the following aspects:

(1) The external energy fields, such as ultrasound, vibration, laser assisted and eddy current heating, could be used to promote the thermal coupling of the two arcs to develop a new hybrid-arc welding process with wider adaptability and higher welding efficiency.

(2) Establish an integrated multi physical coupling model of "arc-droplet-molten pool" to comprehensively analyze the mechanism of bead formation through reasonable simplifications and assumptions.

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