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Review of the Recent Trends of Process Monitoring and Control for Double-Wire GMAW Process

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ABSTRACT Recently, double-wire gas metal arc welding (GMAW) process is more and more prevalently employed in industrial applications and attracted many academic researches. This paper reviewed the recent trends of researches and applications of this process. Three main aspects were included in this paper. The first was the operational process analysis of the process, and the reviewing work was divided into two catalogues: twin-wire GMAW process and tandem GMAW process, which were two main energy delivery and control formations of the process. This part focused on some negative phenomena, such as arc interruption, during the welding process and their effects on the products quality and process stability. Some works about using different current waveforms combinations and their effects on the welding process were discussed. Also, the works of numerical simulation for this process were mentioned in this part. The second part was about process stability monitoring, and corresponding works focused on establishing quantitative process stability estimation model. The last was the improvement of process control method, and the works mainly focused on the adjustment and modulation of the current waveforms, in order to eliminate negative phenomena, improve the process stability and obtain the products with high quality. Finally, some suggestions about future works were presented. This paper can provide references and enlightens for current academic researches or actual industrial applications in the double-wire GMAW process relative areas.

INDEX TERMS Double-wire GMAW process, arc interruption, process stability, current waveform.

I. INTRODUCTION

Welding technology is very important in modern industrial manufacturing occasions, and to maintain the competitiveness and technological leadership, manufacturing industries and welding scholars are always looking for novel processes to increase the welding productivity [1]. High-efficiency welding technology has been a hot spot in the field of welding for a long time. Among various welding technologies, arc welding dominates majority of practical applications. During the arc welding process, an electric arc is generated between a workpiece and an electrode, and then resulting arc heat is used to melt the wire and workpiece. Due to the operation has high deposition and economic efficiency, the gas metal arc welding(GMAW) process is widely employed in industries and many significant advancements about the process have been taken place recently [2]. As high requirements of deposition and production rates in reality, single-wire welding cannot sufficiently satisfy the practical demands, the existing technology has been improved in various aspects. The multiple-wire welding technology is one of such improvements which have been proposed to increase the deposition rate [3], so as to improve the productivity during the applications.

As the most investigated and frequently employed multi-wire welding technology, double-wire formed arc welding was first proposed in the middle of the last century, and was used in submerged arc welding [4]–[6]. However, because of the particular characteristics, the double-wire submerged

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arc welding can only be applied in flat position of welding. To overcome this limitation and make the technique apply in more various occasions, the idea of double-wire GMAW process was introduced in 1989 [7], and commonly used in both of metal inert gas(MIG) and metal active gas(MAG) arc welding processes [8], [9]. Recently, as a high efficient GMAW technique, double-wire technique is more and more employed in different occasions to obtain weld bead with better quality and higher efficiency when compared to conventional single-wire GMAW process [10], such as in ship panel production [11], mining face equipment [12], and so on. One former work [13] demonstrated that using high-power double-wire GMAW process can remarkably reduce the energy consumption when compared to that using standard GMAW process, through corresponding comparative experiments. Therefore, massive practical usages of the double-wire GMAW process is attracting more and more scholars and experts' attentions to its characteristics exploration, process monitoring, control strategy improvements, and other relative aspects, no matter in academic, and in practical manufacturing and production occasions.

Double-wire GMAW process is equipped with two wires, which can be fed from one or two power sources. The process has two main but distinct forms, which are respectively twin-wire/twin-arc GMAW process, and tandem GMAW process. The first form has a comparatively simple structure. The two electrical arcs are fed from one power source or the same two power sources, and have the same values of some electrical parameters, such as the same output frequency, the same electrical current, and the same wire feed speed. Also, the two wires are in one contact tube and not insulated each other. Under the circumstance, the main characteristics of the two arcs are the same and the variations during the welding process are so limited. On the other hand, if the two electrical arcs are fed from two distinct power sources, and during the process, two arcs can be independently controlled and the two wires are insulated with each other in the contact touch, this is the type of tandem GMAW process. In this type, apart from welding feed speed, many process parameters about the power sources and two arcs, such as electrical currents, output frequency, may be different. Moreover, the two wires can be collaboratively controlled by means of a power source synchronization instrument. Hence, the control can be so flexible, and the variation manners are so abundant. This paper mainly focused on these two common types of double-wire GMAW processes, other recent sophisticated forms, such as double-electrode GMAW process, or integrated power source mode which combined the twin-wire and tandem forms [14], are not included. Figure.1 [15] shows the schematics of these two types of double-wire GMAW process.

It can be easily noticed that in the tandem GMAW system, the control actions can be more elaborated because two electrical arcs can be set in two distinct forms and different potentials, even can one electrical arc is fed by AC power while other arc is fed by DC power, and the two wires can

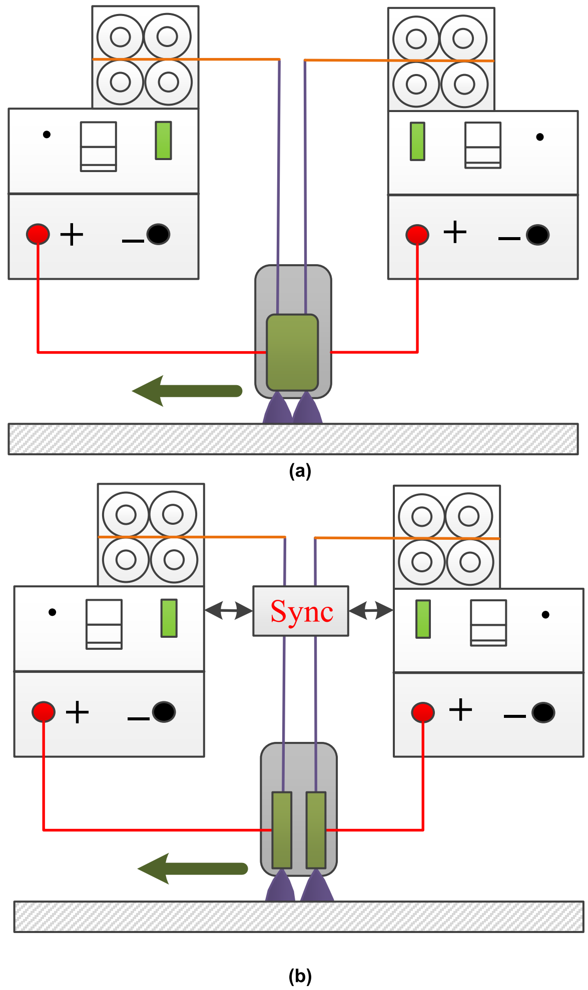


FIGURE 1. Schematic of two types of double-wire GMAW process: (a) twin-wire type, (b) tandem type.

be set in various types. In essence, tandem GMAW process can be considered as two parallel and independent conventional GMAW processes, which allow the deposition rate be doubled without increasing the arc pressure [16]. For the usual twin-wire/twin-arc welding system, the two arcs have so limited adjusting modes, so users can only adjust the relative position of the two wires, such as positioned in-line, in parallel or in any angles, as shown in Figure.2 [2].

For these two types of double-wire GMAW Processes, Fang *et al* [12] made comparative experiments for one low-alloy high-strength structural steel. The experimental and analyses results showed that the tandem GMAW process can obtain a narrower heat affected zone (HAZ) and finer microstructure compared to the twin-wire GMAW. In addition, the weld obtained from tandem GMAW process had better mechanical properties, such as higher tensile strength, absorption energy and impact absorption, as well as lower welding heat input, which can decrease the distortion of welds. The work also provided the mechanism analysis of the phenomena.

In this paper, the recent trends of the double-wire GMAW process, mainly about the operational process analysis of the

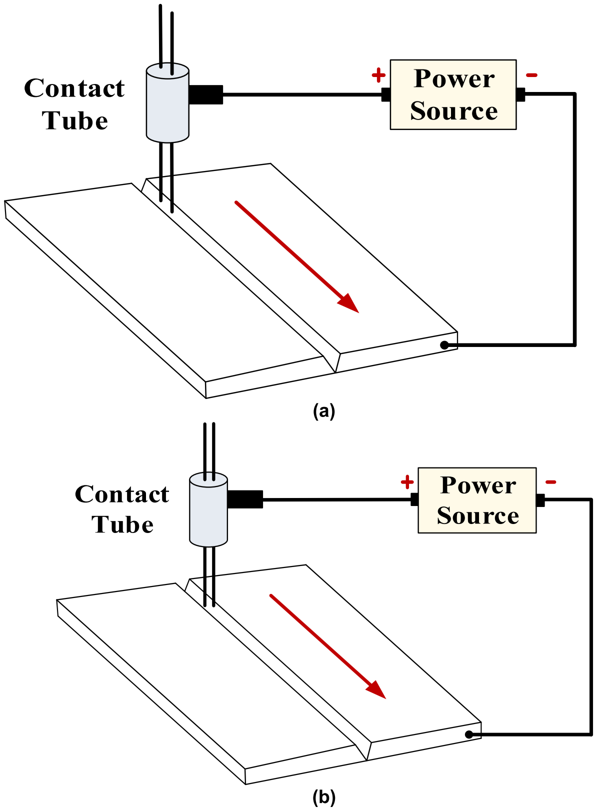


FIGURE 2. Process diagram for twin-wire welding process: (a) wires in series: One after another and (b) wires in parallel: one beside another.

process, process monitoring and the improvement of process control method, were reviewed. Though this technology has been prevalently employed in various areas, the number of relative published contributions were still comparatively limited, when compared to other types of GMAW processes. It may because this process has more complex structure, and some new advanced techniques and improvements may be properly applied in other GMAW process which had simple structures. Despite all of this, this process has been seriously considered by many scholars and experts. The rest of this paper will be organized as follows. Section. II reviews the works which were related to the operational process characteristics analyses. In this section the tandem and twin-wire GMAW processes are separately reviewed. Also, not only the works based on actual experimental researches, but also the numerical simulation works are included. Section. III considers the process monitoring of the process, three methods for process stability analysis have been included. Section. IV focuses on the improvement of process control of the process, which is mainly about the current waveform improvement, and other methods whose goal is improving the control performance. Finally, section. IV offers some concluding remarks and suggestions for future works.

II. THE OPERATIONAL PROCESS ANALYSIS OF THE DOUBLE-WIRE GMAW PROCESS

The double-wire GMAW process is an improvement on the basis of single-wire GMAW process. The double-wire arrangement can improve the production efficiency and have some remarkable advantages, at the same time, some unique problems can also be induced during the welding process. During the operation process, the electrical signals associated by the two wires, such as voltage, current and frequency, are controlled by one or two power sources. Though the existence of two arcs can improve the weld bead and increase the productivity in reality, their mutual interference due to electromagnetic attraction, can induce various negative phenomena. The negative phenomena included arc interruption, short/open circuit, and so on, may seriously affect the microstructure, weld shape, mechanical properties, and other relative performances of the products.

To explore the characteristics of these phenomena and take measures to solve the problems to improve the welding process and the quality of welding products, a lot of researches and experts made corresponding experiments and deductions about the issue. As stated in preceding section, twin-wire GMAW process and tandem GMAW process are two main forms of the double-wire GMAW process. To make the characteristics analysis clearer, the following reviews in this section will respectively focus on these two processes.

A. TWIN-WIRE GMAW PROCESS

Compared to tandem GMAW process, the twin-wire GMAW process has a comparatively simple operation mode. Moinuddin and Sharma [17] conveyed new observations on arc stability in anti-phase synchronized synergic-pulsed twin-wire arc welding. The current researches believed that the dissimilar currents at two wires can induce instability of welding arcs, which can result in considerable influences on the weld microstructures, hardness, heat affected zone and size or shape of the weld bead. The work utilized the separation of arc in time by anti-synchronization and a synergic pulse to control arc instability, when the current of the leading wire was larger than that of the trail wire, and made more effective results. The work concluded that the same values of lead and trail currents can induce arc instability, due to the large current at the lead arc can compensate for the energy lost in heating fresh material. Similarly, the same group also made further researches [18]. The work pointed out the anti-phasing cannot eliminate the mutual interaction between two arcs during the twin-wire GMAW process. The work also analyzed the relations between the process parameters, microstructure of the weld metal and HAZ. Then the work proposed that the dissimilar diameters and currents at lead and trail wires can effectively utilize the welding heat by melting more materials per unit energy consumption, and the current and diameter in the lead wire had a greater influence on the microstructure and mechanical properties than those of the trail wire. Hence, higher current and larger diameter of the lead wire can coarsen the grains and reduce the hardness of the weld bead. Ye *et al.* [19], [20] established a synchronous acquisition system to online collect some process information, which included the arc length variation, voltage and current, and then obtained some important conclusions about the effects of one arc on the other arc in the aspects of spray transfer, droplet transfer, arc length variation, and other relative points, according to the experimental observation and corresponding analyses. Moreover, Chen and Wu [21] studied the effect of arc length on weld appearance and metal transfer in the twin-wire GMAW process using CO_2 as the shielding gas. Under the circumstance, increasing of the arc length can induce the mode of metal transfer changes from short-circuiting transfer to globular transfer, and to spray transfer, and obtain a stable spray transfer process is difficult. The electromagnetic interference between the two arcs can be so strong when the arcs achieved a certain length, at the same time the welding spatter was so serious, and the weld appearance became so bad. Also, Groetelaars *et al.* [22] did a similar work but drew slight different conclusions. The work also employed two electronically inter-connected power sources with the same potentials and used different voltage and contact tube–piece distance (CTPD) combinations to obtain three types of arc lengths: short, medium and long. According to a series of experiments, the work concluded that increasing of the arc length can induce great influences on the magnetic interaction of the arcs, and modify the types of transfer from short circuit to spray, which can cause the attraction between the drops. Under the circumstance, more suitable (less convex) weld bead profiles, with greater thermal efficiency (larger welded area) and a higher rate of deposit, can be obtained during the process. It can be observed that the above two previous contributions obtained the same effects of different arc lengths on the metal transfer but different effects on the appearance of the weld bead. It was because the different metal transfer can induce different influences on the weld bead formation under different other welding conditions, such as weld speed, materials of the parent metals, and so on. However, both of two works concluded that the control of the arc length was so important during the double-wire GMAW process.

B. TANDEM GMAW PROCESS

On the other hand, there were more works about the tandem GMAW process. To improve understanding about arc interruptions in tandem GMAW process and explore how the current pulsing synchronism between the arcs related to the arc interruption, Reis *et al* [23] proposed to evaluate the influence of parameters of adjacent arc and also of a single arc, which were subjected to magnetic deflection, on the occurrence of arc interruptions/extinctions. Also, Chen *et al.* [24] observed three modes of arc interruptions, which were background arc interruption, pulse rise arc interruption and short-circuiting arc interruption, and derived that the arc interruption was resulting from over-elongation of background arc caused by the electromagnetic attraction from the peak arc at the other wire, and the electromagnetic attraction was closely related to the phase differences between currents of leading wire and trailing wire. Then according to corresponding experiment analysis, the work concluded that the effect of phase difference of the currents between two wires on weld appearance and also provided the relative reasons. In addition, Wu *et al.* [25] also focused on the effect of arc phase difference on the tandem GMAW process. The work used a high-speed photography to record metal transfer during the tandem GMAW process in three modes, which were synchronous, alternating and independent phases, at the same time recorded the voltage and current waveforms, and then analyzed the effects of different phases on the behavior of metal transfer. Through a series of experiments and corresponding observations and analyses, it can be concluded that the metal transfer was all a ‘‘one drop per pulse (ODPP)’’ spray transfer mode in three phases, but a stable metal transfer was easier to achieve in the alternating phase. Desired fish scale ripples can be acquired in three phases, and the most pronounced ripples appeared in the alternating phase. Also, the phase had little effect on the weld width and reinforcement. However, penetration can achieve the deepest in the alternating phase, and minimum in the synchronous phase. In the aspect of microstructure, in the alternating phase, the columnar grains were discontinuous, and the directions of ferrites were more chaotic. Approximate conclusions can also be drawn in their other recent paper [26], which focused on the double-wire double-pulsed GMAW process. The work considered the double pulse synchronous (DPS) and double pulse alternating (DPA) phases, and the leading and trailing power sources used the tandem mode. Through employing a high-speed photographic platform to capture the double arc profile photos in both alternating and synchronous phases modes in the experiment, Wu *et al.* [27] discovered that in high-power applications, the current ratings were so high, so that judging the stability by inspecting arc interruptions was not feasible, as the interruptions were effectively eliminated despite significant arc interference. The work also concluded that the high-power welding with high current rating, double arc interference in the alternating phase mode was relatively larger, while in the synchronous phase mode, better double arc stability could be achieved. All these conclusions were important to choose proper current phase mode. Moreover, Ueyama *et al.* [28] investigated the effects of interwire distance and shield gas mixture ratio on the abnormal arc voltage and arc interruption. Experimental observations and corresponding analyses showed that the abnormal phenomena frequently occurred in the reverse phase condition, in which one arc was in pulse peak current period and the other was in the base current period. Apart from the influence of the phase on their abnormal phenomena, the work also explored that the effects of three different interwire distances on the occurrence of those phenomena. Also, the work concluded that CO_2 percentage in an Ar-CO_2 mixture shield gas had a significant effect on the abnormal arc voltage and arc interruption, and the effects varied as the different percentages.

C. NUMERICAL SIMULATION OF THE DOUBLE-WIRE GMAW PROCESS

In addition to use actual experiments to observe and analyze the phenomena, numerical simulation can be also employed in this process. Tušek [29] used different mathematical

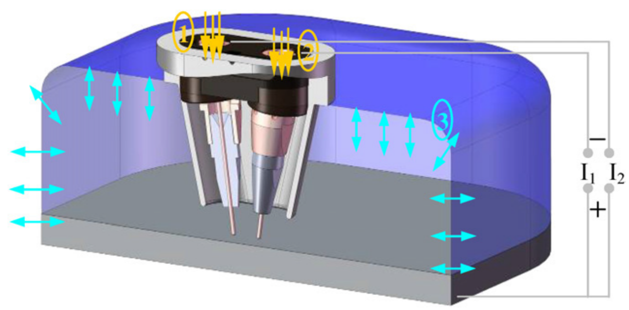


FIGURE 3. Schematic of the numerical simulation model of an anti-phase-synchronized tandem GMAW process.

models to calculate the melting rate in single-wire and double-wire GMAW process. Though the model could be tested to be accurate enough in practice, it cannot consider more elements in reality and outputs were so limited, and other more characteristics were also required to be obtained. Schnick *et al.* [30] developed a transient three-dimensional model of an anti-phase-synchronized tandem GMAW process using a professional software package ANSYS CFX to explore the arc behavior and gas quality during the process. This work modified the standard equations of computational fluid dynamic to take into account the electromagnetic and radiative phenomena that occur in thermal plasmas, and other relative equations. The model used a mirror-symmetric geometry of the torch, parent and the fluid region (arc plasma), as shown in Figure.3 [30].

Using this model, the work studied the interactions between two arcs and the resulting arc deflection, as well as to investigate arc contamination within the shield gas. The model demonstrated a strong arc deflection, especially during the base-current phase, and also presented the influences of the arc deflection and instabilities on the shield gas flow and the occurrence of air contamination in the arc plasma region. The results improved the understanding of the causes of periodic instabilities and weld seam imperfections, such as porosity, spatter, and other elements. Finally, the work made suggestions to improve the quality of the shield gas and avoid weld seam imperfections. Also, Ding *et al.* [31] developed a numerical model based on fluid dynamic and electromagnetic theories to simulate the dynamic metal transfer process in tandem GMAW process, and to compare with the model of single-wire GMAW process. It was found that droplet transfer non-axially in former process and axially in latter process, and the reason can be attributed to the electromagnetic force between two arcs. The model can modify and improve the mathematical relation between welding current and surface tension coefficient, and the relations between welding current, surface tension coefficient and electromagnetic force can also be obtained. In addition, Wu *et al.* [32] also established a three-dimensional numerical model to study the temperature and fluid flow field during the twin-wire GMAW process. The work mainly investigated the weld pool formation, convection and stability during the process. Two flow patterns, which were ''push-pull'' and outward flow pattern, were positive during the process of weld pool formation. Also, the arc force between two arcs, surface tension normal force and liquid channel were considered, and all of these elements contributed to obtain satisfactory weld bead.

Also, all above numerical works provided actual experimental results and obtained a good agreement between the numerical simulation and experimental results. It can be seen that the seriously designed numerical model can supply some further characteristics information about the process, which cannot be observed from the actual experiments, and improve some previous experimental results which employed different mathematical models. Though the modelling process is more complex than that in conventional GMAW or other process, and relative works were so limited because more elements should be considered, it can be realized and provide more useful and valuable calculation results to explore the reasons of negative phenomena occurring and improve the quality of weld bead.

According to the review works in this section, it can be observed that the double wires can not only benefit to the productivity and energy efficiency during the application, but also induce various problems in reality. The problems were resulting from arc interruption or other problems, which seriously affect the stability of welding process and metal transfer, and in further induce poor weld bead geometry. This is a main feature of the double-wire GMAW process. Many researches took a lot of efforts to explore the process characteristics, and then took measures to reduce or eliminate the negative influences and improve the process. Two wires can have different phases combinations, such as synchronous, alternating and independent phases, and researches used various methods to explore the effects of different phases on the arc stability, characteristics of weld bead, and so on. Some comparisons between using different operational parameters, or double-wire and single-wire, were conducted, and many corresponding conclusions had been drawn. In addition, it can be seen that the previous works about the tandem GMAW process were relative more than that about twin-wire GMAW process. It may because that tandem GMAW process can have more variation forms than that of twin-wire GMAW process, so that have more abundant operational modalities. Also, the tandem GMAW process was employed more prevalent in actual applications, and corresponding works were more than those of twin-wire GMAW process. Moreover, though the double-wire GMAW process has a complex structure, numerical model was employed to explore the characteristics which actual experiments cannot be obtained. Currently, majority of numerical simulations used partial mathematical model to simulate some local variations, because the process included more varying elements which cannot be precisely modelled. The numerical models can provide some useful information to help researchers understand and analyze the process. Based on the reviewed contributions in this section, it can be concluded that in the aspect of operational process analysis of the double-wire GMAW process, though some contributions based on actual experiments and numerical simulation have been presented, the systemic and comprehensive researches about the relations between parameters variations, and process and products outputs were still so limited and required further researches in the future.

III. PROCESS MONITORING OF THE PROCESS

Unlike other simple welding systems such as resistance spot welding process which has few key operational parameters [33], [34], the double-wire GMAW process has various input process parameters. Hence, proper multi-parameter matching is so important for obtaining stable welding process and weld beads with satisfactory quality. During the double-wire GMAW operation process, obtaining a stable welding process is so important and an important preliminary condition to obtain welding products with high quality. Recently, some methods whose goals were online monitoring and quantitatively estimating the process was presented.

Though the process stability is so important to assure the product quality and improve the efficiency, the relative works for the double-wire GMAW process were so few in recent researches. This may because the online process monitoring for double-wire GMAW process involves interdisciplinary efforts, and accurate process monitoring requires not only thoroughly understanding the process characteristics, but also introducing proper mathematical tools to analyze the process by means of important parameters. In this aspect, the authors of this paper have conducted some useful works and made some significant achievements, which were distributed into three published papers.

In the first work [35], sample entropy-based approach, which was used to calculate the system disorder phenomena, was employed to evaluate the stability of double-wire pulsed MIG welding process. Four parameters, which were pulse width, peak current, base current and frequency, were selected to calculate the sample entropy and corresponding standard deviation. According to actual experiments and corresponding analyses, the results showed that more stable the welding current, the smaller the value and the standard deviation of the sample entropy under the same parameters. The work put forward a new idea to quantitatively evaluate the process stability of the process, and the experimental results showed that the method can preferably quantify the welding current stability. Based on the first work, we also realized the accurate quantitative evaluation of the process stability by means of arc sound signals collected in the second work [36]. The original arc sound signals were collected and processed using Short-Time Fourier Transform (STFT), and then the spectrogram of the signal was calculated. Then detailed analyses showed that the variation of the maximum power spectrum density (PSD) was closely related to the process stability. According to the information and sample entropy in the preceding work, quantitative evaluation calculation method was developed. Finally, 100 specimens were employed to testify the evaluation method, and accuracy rate could reach 90%. In addition, short time energy analysis and calculation were also used for arc sound signals to evaluate the process stability in the third work [37]. This work employed the arc sound signal as the information transmission media. After collected the short time energy of the signal, two variables, which were energy distribution possibility and cumulative distribution function (CDF), were collected, and then a stability eventuation criterion which combined the two variables could be proposed to quantitatively evaluate the stability of the process. At last, 60 samples in other experiments with different welding conditions were conducted to validate the effectiveness of the evaluation method.

Process monitoring and analysis is very important during the double-wire GMAW process, however, relative works were so limited. Above works realized the online quantitative evaluate the process stability by means of some process parameters and variables. However, though above methods can realize the preliminary goal, the stability analyses and corresponding calculation were accomplished after the welding process instead of real time calculation. It may because the process involves a lot of parameters and elements, and the algorithms and relative functions may require a great many calculations, as well as no effective online analysis methods were presented. The authors believe as the prevalent usages of this process, more and more effective process monitoring and analysis methods will be proposed, including using various mathematical tools by means of kinds of collected process parameters.

IV. IMPROVEMENT OF PROCESS CONTROL OF THE DOUBLE-WIRE GMAW PROCESS

To obtain the weld beads with more satisfactory quality, a lot of scholars and experts took many efforts to improve the double-wire GMAW process. Some measures have been effectively taken according to the special features of the process.

First, Ruan *et al.* [38] used SiO_2 activating flux partially on the Al-alloy plate to explore the mechanical properties and microstructures of the joint using optical, scanning microscopy and energy dispersive spectroscopy during a twin-wire GMAW welding process. The observation results showed that the microstructures of the joints with and without the activating flux had no obvious difference, and the HAZ of the joint with activating flux was slightly wider than that of the joint without flux, also, the penetration of the former joint was deeper than that of the later joint. In addition, the effects of activating flux on the micro-hardness and strength may be so limited.

To improve the heat delivery and quality of weld bead, Wu *et al.* [39] proposed to add a double pulses low-frequency modulation for a high-power double-wire GMAW process. The double pulses included a consecutive weak and strong pulse, as shown in Figure.4.

where I denoted the current, L denoted the leading current, T denoted the trailing current, b and p respectively denoted the base and peak values of the current, w and s respectively denoted weak and strong pulses, and av was an abbreviation

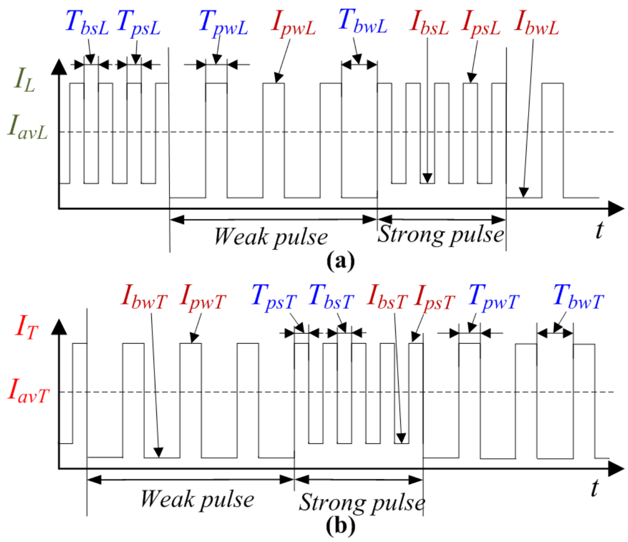


FIGURE 4. Schematic figure of the double pulses current waveforms: (a). Leading current, (b). Trailing current.

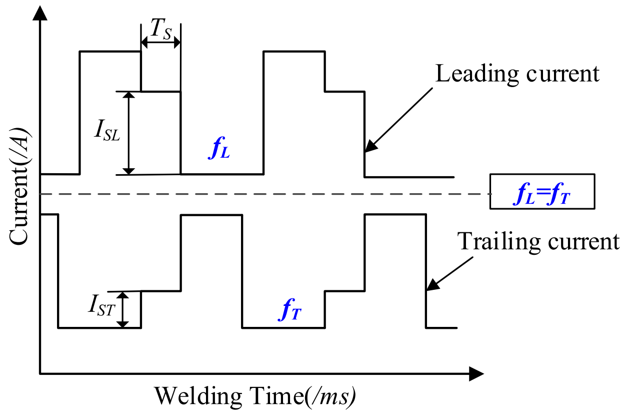
of "average". It can be seen that the leading current and trailing current are composed of alternate weak pulses and strong pulses. For the leading current and trailing current, the frequencies of the strong and weak pulses can be different, so there were so many different pulses combinations during the applications. Hence, in the work, the new added low-frequency modulation control referred to periodically switch the intensity of pulse in weak and strong alternatively, so the arcs and heat inputs during the process can also vary with the low-frequency modulation frequency and the corresponding duty cycle. The work obtained the mathematical relations between the modulation parameters of the double pulse and the output voltage and current by means of constructing a mathematical model of double pulse low-frequency modulation. To make the model accurately describe the process characteristics, a correction coefficient was added to overcome the physical characteristics of the circuit. Based on achieved stable welding process and perfect weld bead shape, the effects of some important parameters, such as modulation frequency, duty cycle, on the weld size and microstructure, can be obtained. The final results showed that this new control method can effectively control the heat input and improve the forming characteristics and microstructures of the weld beads. The modulation frequency imposed significant effects on shape of the weld bead and the grain size, and the weak and strong pulses of low-frequency modulation can have many positive functions in optimizing the quality of weld bead. Also, the same group used a data collection and high-speed photography to study the double arc interference and dynamic behavior characteristics for this type of GMAW [40]. It was found that severe double arc interference can affect the stability of the process. The double arc deflections of the strong and weak pulse were also analyzed. It was concluded that the deflection of double arc in the strong pulse stage of the synchronous and alternant phases was more severe that the weak pulse stage, and the trailing arc stiffness was lower than that of leading arc stiffness, more prone to deflection. The degree of arc deflection in different occasions were also presented. Finally, it was discovered that the double arc in the synchronous phase can maintain the stiffness, and produce less magnetic arc blow, fewer spatters, a finer fish-scale ripple appearance and superior weld bead uniformity. Moreover, they conducted some comparative experiments between single pulsed and double pulsed double-wire tandem GMAW processes, respectively using low carbon steel [41] and aluminum alloy [42] as the base metals. Under these two modes, the relative experiments can obtain high quality weld beads with slight spatter, without humps and undercut. Also, compared to the single-pulse double-wire GMAW process, double-pulse double-wire GMAW process can obtain more apparent weld beads, and the bead had larger bead width. In addition, double pulse tandem GMAW process did not reduce the porosity, however, the stirring effect was reinforced by the double pulse, which can promote the escape of pores to the upper section of the weld bead. Also, growth of the grains in the molten pool was interrupted by the stirring effect of double pulse tandem GMAW process. Hence, the double pulse tandem GMAW process can refine the grain, which can obtain finer grain microstructure and higher microhardness of the weld beads when compared to that using single pulse double-wire GMAW process.

Apart from above works using a double pulse modulation on the double-wire GMAW process which increased the control complexity, and might induce new problems to affect the process ability and quality of the weld bead, other methods of adjusting the current waveform of the double wires/arcs can also be employed to improve the performance of the process. At first, out-of-phase was used in the process because it was supposed that able to minimize the magnetic interaction between arcs in the twin-wire GMAW process and reaching stable operations. However, Scotti *et al* [43], Motta *et al.* [44], [45] investigated the effect of the out-of-phase current pulses on the behavior of both of metallic transfer modes and voltaic arc configurations. Comparison between in-phase, out-of-phase pulsing and no pulsed setting. The final results showed that the out-of-phase current pulses can reduce the deviation of the arcs at current levels below the transition current, but the features cannot be obtained when the current above the transition current. During the process, the lag time was an important condition which was relative to the profile of the weld penetration. Also, there was no significant difference in the bead shapes whether or not out-of-phase pulsing was employed, as well as the bead finishing or arc stability. Hence, to save costs, conventional power sources can be used to replace the sophisticated integrated pulsing power sources during the process.

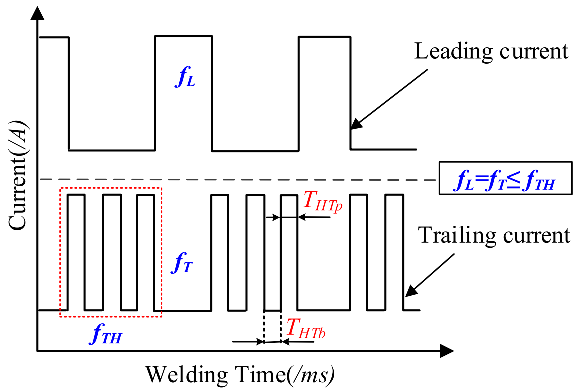
In addition, other modes of adjusting current waveforms can also be employed to improve the quality of products and process stability. For the leading wire current and trailing wire current, there are some different combinations of the frequencies and phases, such as two current waveforms having the same frequencies but inverse phases (SFIP) or having the same frequencies together with the same phases (SFSP). Ueyama *et al.* [46], [47] believed that pulse timing control can reduce the arc interference in tandem GMAW process, they used a method of delaying the pulse off timing of the trailing arc by 0.4-0.5ms from that of leading arc, together with independent arc length control for the two wires by means of different control systems, the two arcs can maintain stable without arc interrupt and stable arc length control can be established. In these two works, SFSP were used. Also, on this point, authors of this paper made some relative works, and some significant and useful achievements have been gained. As for the current waveform, we developed two methods to achieve the goal, respectively were symmetrical transition waveform control method and multi-frequency waveform control method. In our former work [48], SFIP was used, and a symmetrical transition period was added when the welding current was switched between peak and base values. In the work, the symmetrical transition period can alleviate the current change between peak and base values, so that the mutual interferences of the two wires can be reduced, at the same time the magnitude of the welding currents cannot be reduced, which meant that the amount of energy delivered was not decreased. The schematic of this method can be shown in Figure.5 (a) [48]. While in the latter work [49], SFIP was used, a multi-frequency modulation was added to the waveform in the peak stage of trailing wire current, under the situation that the two wires current waveforms had the same frequencies but inverse phases. This adjustment can decrease the duration when both leading wire current and trailing wire current were in the base stage; meanwhile, the duration may be more dispersive by means of high frequency modulation. It can decrease the possibility of appearance of some unsteady phenomena, such as arc interruption. The corresponding schematic of the method was shown in Figure.5(b) [49].

It can be noticed that in these two works, the leading current and trailing current waveforms employed the mode which had the same frequency but inverse phases. In addition, no matter added symmetrical transition period or multi-frequency modulation in the trailing wire current, more parameters were introduced in the system, such as the leading transition current I_{SL}, double wires transition time T_s and trailing transition current I_{ST} in Figure.5 (a), as well as trailing wire current peak modulation frequency f_{TH}, trailing wire high frequency peak time T_{HTp} and trailing wire high frequency base time T_{HTb} in Figure.5(b). To obtain these multi-parameter control system, orthogonal tests and corresponding range analyses were employed, then key parameters were selected, and their values can also be confirmed. Finally, actual experiments were conducted and the results showed that these changes can obtain weld bead with high quality and at the same time the process stability can be improved.

In addition, it can be seen that the work [49] has some similar points to the work [39], both of the two works introduced high-frequency modulation to the original current waveform. Actually, the trailing current in the Figure.5 (b) can also be considered as a form of double pulse. However,



(a)



(b)

FIGURE 5. Current waveform adjusting methods. (a) Symmetrical transition period. (b) Multi-frequency modulation.

the work [39] had more complex structure than that of the work [49]. We suggested that to achieve control actions with high performance, low complexity was also an important element, however, to deal with the system with different actual operational environment and condition, more appropriate system design and configuration should also be seriously considered during the applications.

Moreover, the commonly used current waveform during the GMAW process with different types was square waveform. Recently, in double-pulsed GMAW process, to alleviate the sudden change of the current amplitudes differences between peak and base values in the square waveform, other waveforms, such as trapezoid waveform [50] and sinusoidal waveform [51], were proposed to make corresponding improvements. Similarly, this kind of improvement was also introduced to the double-wire GMAW process. Chen *et al.* [52] used sine wave pulse modulation control method in the double wire MIG welding. The work believed that the sine-wave modulation had advantages of high speeds in double wire welding, and can strength the energy mixing transfer, form the scales of the weld and reduce the bubble generation. Also, more control parameters were introduced, and the work used the orthogonal tests and analyses to confirm the values. Final experiments verified that the control method can have large value range of welding parameters, super robustness, easy operation and an ideal fish-scale pattern weld, and the welding process was stable. We think this improvement can also be further improved in the future and supposed to obtain better performance.

Furthermore, apart from the current waveform, wire feed speed was also an important parameter during the double-wire GMAW process. The authors of this work analyzed ten factors which affected the wire feed speed and conducted corresponding correlation analyses, and then four significant parameters were selected [53]. Then the four parameters were employed to establish a mathematical model to predict the optimum wire feed speed using support-vector-machine (SVM) tool. The final experiments verified the model can effectively predict the parameter and weld bead with high quality can be obtained.

In the future, other methods which have been used in other type GMAW process to improve the process ability or quality of the welding product, such as the bypass coupling technology [54], [55] used in twin-wire indirect and double-sided arc welding process, may also be tried to be used in double-wire GMAW process.

No matter which type of welding technology were employed, improvement of control method was so important. According to review various published contributions in this section, apart from few works concerned the activating flux to improve the welding quality, majority of works considered the configuration and adjustment of the current waveforms for the double wires. Double pulsed for double-wire was a good improvement and some satisfied achievements had been obtained, however, more parameters had been introduced. Also, authors of this papers proposed adding symmetrical transition period in the waveforms, or adjusting one waveform to be a double pulse, the experiments showed that good welding products and stable welding process can be obtained. However, majority of preceding publications obtained proper operational performances under some special conditions, and few general improvements can be proposed. Especially for some aspects, different works drawn some different, even opposite conclusions. It may because this process has complex structure, and the mechanism of forming weld beads with high quality and stable process involved many elements. Also, it can be noticed that many improvements were proposed based on other forms of GMAW process. Comparatively, the control improvements about double-wire GMAW process were a bit limited when compared to other forms of GMAW process. By means of serious researching relative improvements used in other forms of GMAW process, the future improvements about this process will be more and more improved, especially can employ artificial intelligent tools [56], [57] for process analysis and control, or technique innovations, such as bypass coupling technology, and so on.

V. CONCLUSION AND FUTURE WORKS

This work reviewed the recent trends of operational characteristics analysis, process monitoring and improvement of control methods for the double-wire GMAW process, and the operational characteristics analysis was to serve the latter two aspects. According to the different configurations of the power sources for the double wires, the double-wire GMAW process could be divided into two catalogues: twin-wire GMAW process and tandem GMAW process, and the latter has a more complex structure and more elaborated control forms. For this type of arc welding process, there are some special negative phenomena affecting the process stability and quality of the welding products. One remarkable phenomenon is arc interrupt, which can significantly affect the quality of welding products and process stability. Majority of works about the characteristics research and analysis focused on this issue. Kinds of waveforms combinations with different phases for double arcs were employed to investigate the levels of arc interruption, and many measures were taken to reduce or eliminate the negative influences on the process, so as to improve the performance of the process. Also, numerical model was established to simulate the models and some characteristics which cannot be obtained by experiments were obtained. However, though a lot of remarkable achievements have been obtained, many published contributions were based on the special welding environments and experimental conditions, which lacked enough mechanism analyses and corresponding achievements. Hence, in this aspect, some further improvements will be required in future.

In addition, process monitoring and control process improvement are very important in all welding operations. Compared to other types of welding processes, the corresponding works about double-wire GMAW process were so less. In the aspects of process monitoring, the previous works focused on the establishing quantitative estimation method for the process stability by means of precise data collection and mathematical analyses. In the aspect of control process improvement, apart from using activating flux to improve the performance, a lot of works focused on current waveforms adjustment and improvement. A remarkable work was the double pulse for double wires/arcs were employed, and corresponding analyses about the different phases and parameters were also presented. Moreover, other adjustment methods, such as symmetrical transitions period and double pulses in the trailing wire, were also applied in reality. It can be seen that these methods can improve the quality of welding products and process stability under the experimental conditions. However, the methods may be dependent on special welding environments and operational conditions, and lack generality and not able to comprehensively extent to all systems with the similar structures.

Moreover, according to review the recent contributions, it can be noticed that majority of works about the double-wire GMAW process were proposed based on the other types of welding operations, especially the single-wire GMAW process, which is a good developing trend for improving this process, because they have approximate structures and operational principles. Especially for the new technologies, such as acritical intelligent, or bypass coupling technology, which has been prevalently employed in other types of welding processes, will be supposed to be used in double-wire GMAW process. According to this review work, there will be a big challenge in the future to develop advanced process characteristics analysis, process monitoring and control process improvement for this process, in order to realize high efficiency and high quality products output. However, combining further exploration about principle and characteristics of the process, and referring to other mature technologies, it is expected to improve this process in different aspects, and make corresponding works more general and can be extend to be widely employed in various environments based on further research in the future.

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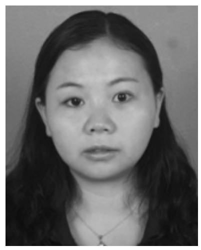

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