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ORIGINAL ARTICLE

Arc stability indexes evaluation of ultrasonic wave-assisted underwater FCAW using electrical signal analysis

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Abstract

Ultrasonic wave-assisted underwater flux-cored arc welding (FCAW) has the potential to control the dynamic bubble and then improve arc stability. In this study, the four indexes evaluation methods to determine arc stability, i.e., oscillograms, cyclograms, probability distribution, variation coefficients of the welding current and arc voltage, were conducted to study the effect of ultrasonic wave on the arc stability. Results show that it is reasonable to evaluate the variation in arc stability with the welding parameters including wire feed speed and arc voltage, or without/with an ultrasonic wave by using the four indexes evaluation methods. Further, the control of the dynamic bubble induced by the exertion of ultrasonic wave can be used to explain why the arc stability is improved. The key points to excellent arc stability depend on both the designation of the welding parameters and reasonable control of the bubble with structural integrity. Therefore, through the novel method which combines optimized welding parameters with a stable bubble environment, the achieved welding process can effectively reduce the bubble disturbance and enhance the arc stability. Results presented in the paper aim to understand the combined influence mechanism of welding parameters and ultrasonic wave on the arc stability in underwater wet welding.

Keywords FCAW · Ultrasonic wave · Arc stability · Underwater wet welding · Bubble dynamics

1 Introduction

With the increasing exploitation of marine oil and gas resources and the increase of nuclear power plants and water-related facilities in China, underwater welding has become an indispensable technical means for repairing marine structures and pipelines, maintaining nuclear reactors and bridges, and salvaging sunken ships pass [1–3]. Among the many underwater welding methods, underwater wet welding plays a major role in the maintenance of underwater structures with its advantages of simple equipment, high operability, and low cost [4, 5]. The wet method refers to the welding of flux-cored wire or covered electrode directly exposed in the water environment. During the welding process, the water around the arc is rapidly vaporized or ionized due to the intense heating of the arc, and the flux-cored wire or covered electrode is decomposed, together forming a certain size of a bubble in which the arc is burned [6, 7]. At the same time, the arc and the weld pool formed on the weld bead are separated from the water through the bubble. However, accompanied by the influence of rapid cooling and ambient pressure caused by water, underwater wet welding typically suffers from poor weld quality, such as inferior arc stability [8, 9], high diffusible hydrogen content [10], brittle microstructures [11], and low mechanical properties [12], which deleteriously affect the reliability of the method and the safety of the structure after welding.

In order to obtain the desired weld quality, some researchers have developed some additional method to assist underwater welding process. For example, the temper bead welding technique can be applied to reduce the susceptibility to cold cracking and homogenize the microstructure in underwater wet welding [13]. Fydrych et al. [14] also presented that this technique has a significant effect on reducing the hydrogen content in a deposited metal. Zhang et al. [15] showed that the microstructure and mechanical performance of the joint

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can be tuned and optimized by combining real-time induction heating and underwater wet welding. Grinding treatment can also serve as a post-processing step to enhance the mechanical properties of repaired T-welded connections [16]. Besides, real-time modification of the welding process is generally required to restore the desired weld quality. Wang et al. [17, 18] stated that the bubble control by applying mechanical constraint played the role as the process enhancement in underwater wet welding. A hyperbaric and rotary gas block was designed to prevent water from entering the arc burning zone [19]. Shen et al. [20] further adapted this method by adding a preheating function before welding. Their results showed that better arc stability and improved microstructure and mechanical properties were obtained. Hence, any method by real-time modification of the welding process to improve the joint quality is of great significance in underwater wet welding.

Previous research showed that power ultrasound has made some achievements in the welding field [21, 22]. Actually, in recent years, power ultrasound immersed in water has attracted considerable attention. Liu et al. [23] applied the ultrasound to water-confined laser micromachining by exerting in situ ultrasonic wave to the laser ablation location and found that the water-cleaning effect was enhanced and a higher material removal rate could be made. Charee et al. [24] reported an ultrasonic-assisted laser machining of silicon in a closed chamber with water flow, in which the ultrasonic vibration was exerted on the workpiece bottom surface. The results indicated an increased laser-ablated groove depth and the enhanced material removal rate. Wang et al. [25] utilized a water-based ultrasonic vibration to enhance laser trepanning efficiency. Besides that, in the field of underwater wet welding, the application of power ultrasound has become a mainstream technique. Gao et al. [26] reported that underwater ultrasonic impact treatment can be used for relieving residual stress and extending the fatigue life of underwater wet welds. Wang et al. [27] believed that the excellent balance of the strength and the ductility was realized in weld metal with using ultrasonic vibration.

In underwater wet welding, the bubble can isolate the arc from the surrounding water and the arc burns in the continuously changing bubble. The rising and burst of the bubble produce an adverse effect on the arc; thus, the arc stability tends to be affected by the bubble [28–30]. However, the increase in bubble disturbance accompanied by reduced arc stability remains to be an unresolved issue in underwater wet welding. Herein, inspired by gas bubble dynamics in the liquid achieved via an acoustic field [31–33], the control of the bubble within the underwater wet welding holds the key to process enhancement. Recently, a new process, called ultrasonic wave-assisted underwater wet welding, was proposed by the authors [34, 35]. In the proposed process, in situ ultrasonic wave was applied to the arc burning zone (e.g., from above the workpiece using an ultrasonic horn), which was immersed in water. The ultrasonic wave acts on the bubble, and the latter is maintained a stable state, which may produce a related beneficial effect on the welding process, such as arc stability and also enhance the mechanical properties of the joints [34]. The ultrasonic control of the bubble provides the possibility to stabilize the arc and improve the weld quality; however, the underlying mechanism of this phenomenon is not clearly understood yet. So far, the arc stability of the ultrasonic wave-assisted underwater wet welding has been rarely reported, which is, however, highly significant for understanding the mechanism process.

Hence, the combination of ultrasonic wave and welding parameters (wire feed speed and arc voltage) should be comprehensively investigated to understand their effects and interactions on the arc stability in underwater wet welding, which can enable an insight into the mechanism process. Four indexes evaluation methods to determine arc stability, i.e., oscillograms, cyclograms, probability distribution, variation coefficients of the welding current and arc voltage, were conducted to examine the potential of the process enhancement. Related strengthening mechanisms by controlling dynamic bubble resulting from the addition of ultrasonic wave were also investigated. The findings of this work reveal a promising solution to improve the arc stability in underwater wet welding.

2 Experimental procedure

The schematic diagram of the experimental system is shown in Fig. 1. The system comprised a welding power source with a wire feeder, an ultrasonic power source, a hybrid welding torch, high-speed imaging unit, and electrical signal acquisition unit. The main body of the torch consisted of an ultrasonic transducer, an ultrasonic horn, and a conductive rod. The piezoelectric materials in the transducer converted electrical energy from the power source into ultrasonic vibration. Then the ultrasonic vibration was amplified by the horn and emitted from the horn end, i.e., acoustic radiator, and propagated through the water. Thus, the acoustic radiation field was formed between the acoustic radiator and workpiece surface. The conductive rod was assembled at the axial center hole of 8 mm diameter drilled through the transducer and the horn. Flux-cored wire fed by the wire feeder went through the conductive rod and then contacted with the workpiece for welding. During the welding process, water is heated up by the hot arc plasma, so a gas bubble is formed around the arc column and affords a gaseous environment for arc discharge. Meanwhile, the bubble in an acoustic field presents different dynamic behaviors compared with conventional underwater wet welding. As a result, the volume, shape, and motion of the bubble are changed and arc stability is improved accordingly.

High-speed imaging unit consisted of a high-speed camera and a dysprosium lamp. The dysprosium lamp provided a

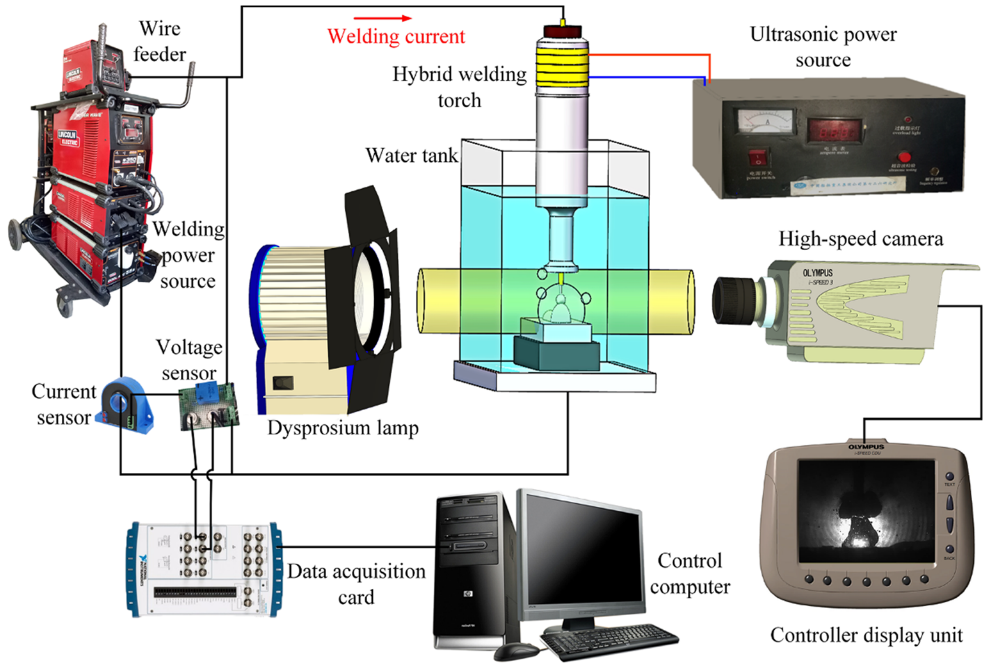


Fig. 1 Schematic diagram of the ultrasonic wave-assisted underwater wet welding system

backlight source and was placed on the opposite side of the high-speed camera. A high-speed camera was used to capture the clear images of the dynamic bubble with the frame rate of 2000 f/s. During the welding process, the hybrid welding torch was stationary and the workpiece was moved at a set welding speed. Electrical signal acquisition unit included Hall sensor (current sensor and voltage sensor), data acquisition card, and a control computer, which ran with the sampling frequency of 10 kHz. The instantaneous values of the welding current and arc voltage during the welding process could be detected by Hall sensor, then transformed by a data acquisition card, and finally stored in the computer.

The bead-on-plate welding was conducted at 250-mm water depth. The base metal was E40 steel with the dimensions of 200 mm × 50 mm × 8 mm. The filler material was a titanium type slag system flux-cored wire with a diameter of 1.2 mm. The welding process was performed by the Lincoln Electric® Power Wave® S350 power source with direct current electrode positive (DCEP) condition. A constant voltage mode was adopted during the welding process. The ultrasonic frequency was 15 kHz. The radiator with a concave surface was adopted, and its curvature radius was 38 mm. The distance between the radiator tip and the workpiece surface was 50 mm. The welding speed was 3.5 mm/s. The wire stick out length was 20 mm. The average length of the weld bead was set as 80 mm. Other welding parameters are listed in Table 1. Six sets of wire feed speed and six sets of arc voltage were used. For comparison, each set of welding parameters included both the exertion of ultrasonic wave and non-ultrasonic wave. After welding, the macroscopic morphology of the weld bead was cleaned with a wire brush. The cross section of the weld bead was extracted by wire cutting, then polished and etched with 4% Nital reagent for 5–10 s to obtain the weld geometric size.

3 Results

3.1 Oscillograms of the welding current and arc voltage

Figure 2 shows the oscillograms of the welding current and arc voltage varying with wire feed speed and arc voltage in underwater wet welding without and with ultrasonic wave,

Table 1 Welding parameters used in experimental groups

Experimental group	Wire feed speed (m/min)	Arc voltage (V)
1	3	32
2	5	32
3	7	32
4	9	32
5	11	32
6	13	32
7	9	22
8	9	26
9	9	30
10	9	34
11	9	38
12	9	42

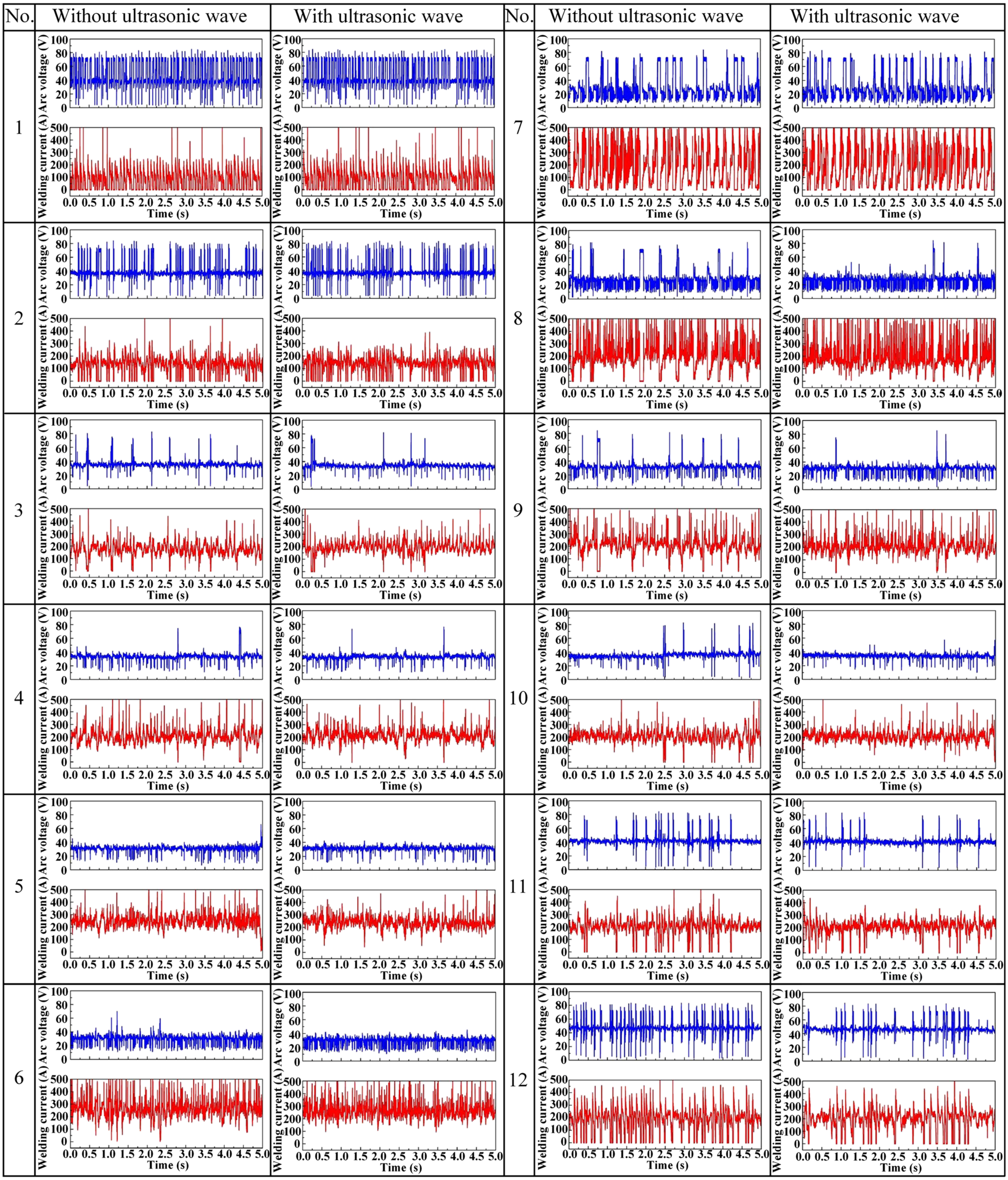


Fig. 2 Oscillograms of welding current and arc voltage varying with wire feed speed and arc voltage in underwater wet welding without and with ultrasonic wave

which can display the instantaneous values in a randomly selected 5-s period. It can be seen that the welding current and arc voltage waveforms fluctuate greatly during the welding process. The arc voltage is always not expected to rise to a larger value or to fall to a smaller value. Hence, the waveforms are mainly dominated by two unstable modes including larger arc voltage signal and the smaller arc voltage signal, while the proportion of these two modes varies with wire feed speed or arc voltage. As for the wire feed speed, a high proportion of larger arc voltage signal always exists at a small wire feed speed of 3.0 m/min. With the increase of wire feed speed, the proportion of larger arc voltage signal gradually decreases, and it almost decreases to zero when the wire feed speed is larger than 9.0 m/min. However, the proportion of smaller arc voltage signal decreases first and then increases with increasing wire feed speed, and the maximum proportion appears at the speed of 13 m/min. This implies that when the wire feed speed is relatively small, there is a high proportion of larger arc voltage signal in the waveforms; when the wire feed speed is relatively large, a high proportion of smaller arc voltage signal dominates; thus, the speed window for high arc stability is between 9 and 11 m/min.

With respect to the arc voltage, a high proportion of larger arc voltage signal always exists at a small arc voltage of 22 V. Meanwhile, the larger arc voltage signal will last for a while and then return to the normal value, which differs from the observed experiment results of wire feed speed. The proportion of larger arc voltage signal gradually decreases with the increase of arc voltage, and it almost decreases to the minimum value at the arc voltage of 34 V. With the further increase in arc voltage from 34 V, the proportion of larger arc voltage signal starts to increase again. However, the larger arc voltage signal does not last for a period of time, but returns directly to normal value. Similarly, with increasing arc voltage from 22 to 34 V, the proportion of smaller arc voltage signal rapidly decreases, and the minimum proportion occurs at the arc voltage of 34 V. As the arc voltage further increases, the proportion of smaller arc voltage signal shows a slight increase again. This indicates that when the arc voltage is relatively small, larger arc voltage signal and smaller arc voltage signal simultaneously dominate; when the arc voltage is relatively large, there is a high proportion of larger arc voltage signal in the waveforms; thus, the arc voltage window for high arc stability is between 30 and 38 V.

Observation and comparison of welding current and arc voltage waveforms without and with ultrasonic wave are also exhibited in Fig. 2. It is found that as wire feed speed or arc voltage varies, the welding current and arc voltage waveforms with ultrasonic wave present the same variation trend as that without an ultrasonic wave, whereas when an ultrasonic wave is applied, the fluctuating waveforms significantly improved to some degree. Some larger arc voltage signal or smaller arc voltage signal are reduced or even eliminated, which is beneficial to achieving better arc stability. However, the reduction in the degree of fluctuation cannot be quantitatively visualized by the oscillograms, although the difference between the two welding conditions can be observed by the naked eye.

3.2 Welding current and arc voltage cyclograms

Cyclograms indicate that the arc voltage is as a function of the welding current. Welding current and arc voltage cyclograms varying with wire feed speed and arc voltage in underwater wet welding without and with ultrasonic wave are shown in Fig. 3. It can be observed that as the wire feed speed or arc voltage varies, the evolution mode of the cyclograms presents various characteristics. At large wire feed speed or small arc voltage, the cyclograms are characterized by loop-locked quadrilaterals along with a high arc voltage area. This is attributed to the easy contact of flux-cored wire with weld pool under such welding conditions, yielding the formation of short-circuiting process and then causing the loop-locked quadrilaterals. The appearance of a high arc voltage area indicates arc extinction and worse arc stability in underwater wet welding. On the contrary, at small wire feed speed or large arc voltage, the cyclograms are mainly concentrated in the area of steady arc in conjunction with a high arc voltage area. In addition, some abnormal lines are detected at the cyclograms. This indicates that a certain degree of arc extinction or short-circuiting appears in the welding process. With the exertion of an ultrasonic wave, the evolution mode of the cyclograms is not changed under the same welding conditions, while the cluster degree of steady arc area is enhanced significantly and the proportion of high arc voltage area is lowered, resulting in an improvement of arc stability. The abnormal lines are also decreased due to the introduction of ultrasonic wave leading to the reduction in the destroying degree of the bubble.

To further characterize the dispersion degree of working point in the cyclograms, the proportions ($N\%$) of the arc extinction process, short-circuiting process, and arc abnormal burning process were calculated according to our previous categories [18]. Especially, the arc voltages of 15 V and 50 V are defined as threshold values for process characterization, respectively. If the arc voltage is greater than 50 V, it is determined that the arc extinction process appears. If the arc voltage is smaller than 15 V, it is determined that the short-circuiting process occurs. The proportion of the arc extinction process represents the ratio of data points with an arc voltage greater than 50 V to the total data points. The proportion of the short-circuiting process represents the ratio of data points with an arc voltage smaller than 15 V to the total data points. Note that arc abnormal burning process is the sum of the arc extinction process and short-circuiting process. The results are summarized in Fig. 4. As exhibited in Fig. 4a, it can be observed that the proportions of arc extinction process and arc abnormal burning process present similar variation trend and both gradually decrease with increasing wire feed speed when the speed is smaller than 7 m/min. Then they are maintained in a very smaller value than 1% when the speed is larger than 7 m/min, indicating an improvement in arc stability. For the proportion

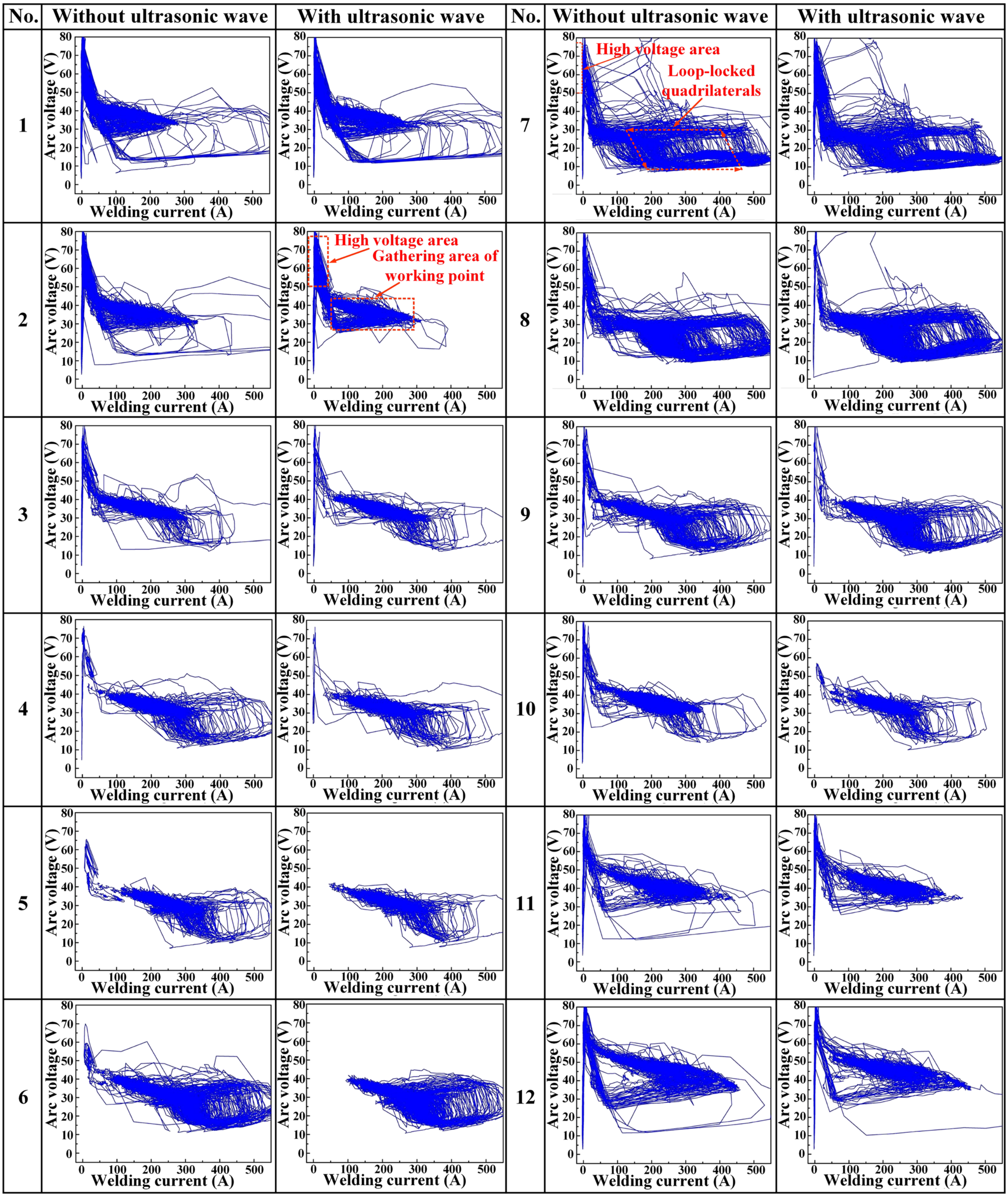


Fig. 3 Welding current and arc voltage cyclograms varying with wire feed speed and arc voltage in underwater wet welding without and with ultrasonic wave

of short-circuiting process, it seems to change very little compared with the other two proportions although there exist some differences with various wire feed speeds. Besides, the short-circuiting process is predominant at larger wire feed speed

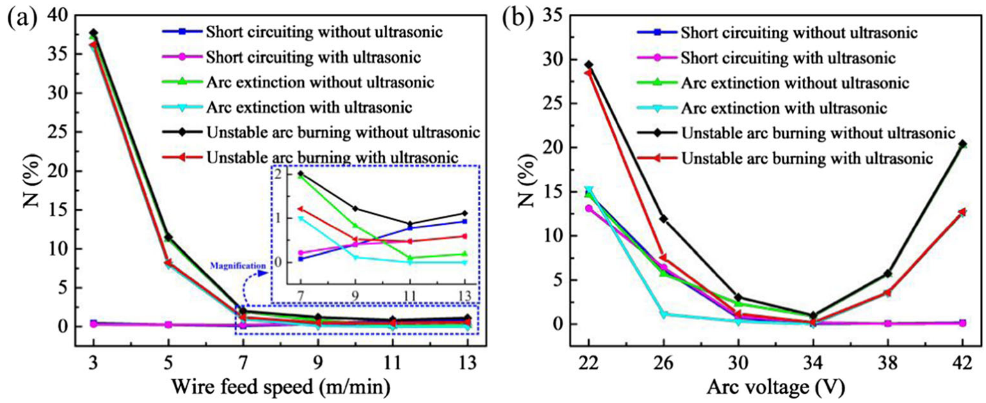


Fig. 4 Effect of wire feed speed (**a**) and arc voltage (**b**) on arc abnormal burning in underwater wet welding without and with ultrasonic wave

while the arc extinction process dominates at smaller wire feed speed by comparison.

As shown in Fig. 4b, the proportions of arc extinction process and arc abnormal burning process both first decrease to a minimum value and then increase to a large value as arc voltage increases. However, the proportion of short-circuiting process gradually decreases with the increase of arc voltage when the arc voltage is smaller than 34 V. Then it is maintained a constant almost equal to zero when the arc voltage is further increased. On the other hand, the arc extinction process dominates at the larger or smaller arc voltage range while the short-circuiting process is only predominant at smaller arc voltage by comparison.

It can be also seen from Fig. 4a, b that both conventional underwater wet welding and ultrasonic wave-assisted underwater wet welding present the same variation trend with wire feed speed or arc voltage. But the three proportions in conventional underwater wet welding are much larger than those in ultrasonic wave-assisted underwater wet welding. That is, the arc stability is enhanced to a large degree due to the exertion of an ultrasonic wave. Especially, minimum values at the wire feed speed of 11 m/min and at the arc voltage of 34 V are observed for the two welding conditions. Hence, the analysis of welding current and arc voltage cyclograms provides a good assessment for arc stability during the welding process.

3.3 Probability distribution of welding current and arc voltage

For a uniform distribution function, the probability density is equal to the probability of a period (the range of values of the event) divided by the length of the interval. It can be used to characterize the probability of random occurrence. Probability distribution (N%) of the welding current and arc voltage is also a valuable reference for evaluating the arc stability. Figure 5 shows the probability distribution of welding current and arc voltage varying with wire feed speed and arc voltage in underwater wet welding without and with an ultrasonic wave. As shown in Fig. 5a, there are three humps observed in the probability distribution of arc voltage. The low arc voltage hump on the left represents the short-circuiting area, the hump in the middle represents the stable arc area, and the high arc voltage hump on the right represents the arc extinction area. As the wire feed speed increases, the high arc voltage hump is reduced and the middle hump moves to the left. The maximum probability value of the high arc voltage hump is 16.4% at the wire feed speed of 3 m/min, while decreases to nearly zero at the wire feed speed of 11 m/min. It should be pointed out that the larger and narrower middle hump, the smaller high arc voltage hump and low arc voltage hump imply a reduced fluctuation of the arc voltage and then improved arc stability. Although the probability distribution of arc voltage is similar for the two welding conditions, the welding process with ultrasonic wave exhibits the smaller probability value of high arc voltage hump and low arc voltage hump compared with conventional underwater wet welding, thus producing excellent arc stability. Due to the increase of wire feed speed, the welding current increases accordingly; thus, the only hump in the probability distribution of welding current moves to the right, and the maximum probability value varies little. Furthermore, the probability distribution of some high or low welding current hump is also detected, and there exerts a significant difference in the probability value with various wire feed speeds.

As shown in Fig. 5b, there also exist three humps observed in the probability distribution of arc voltage. Because of the increase in arc voltage, the middle hump in the probability distribution of arc voltage moves to the right. The position of the other two humps does not change with arc voltage. The high arc voltage hump first decreases and then increase with the increase in arc voltage while the low arc voltage hump shows a decreasing trend when the arc voltage is smaller than 34 V and is then maintained in a very small value as the arc voltage further increases. In addition, there exists a hump observed in the probability distribution of welding current except for at the arc voltage of 22 V. This is due to the high proportion of larger arc voltage signal and smaller arc voltage signal under such small arc voltage, thus causing excessive

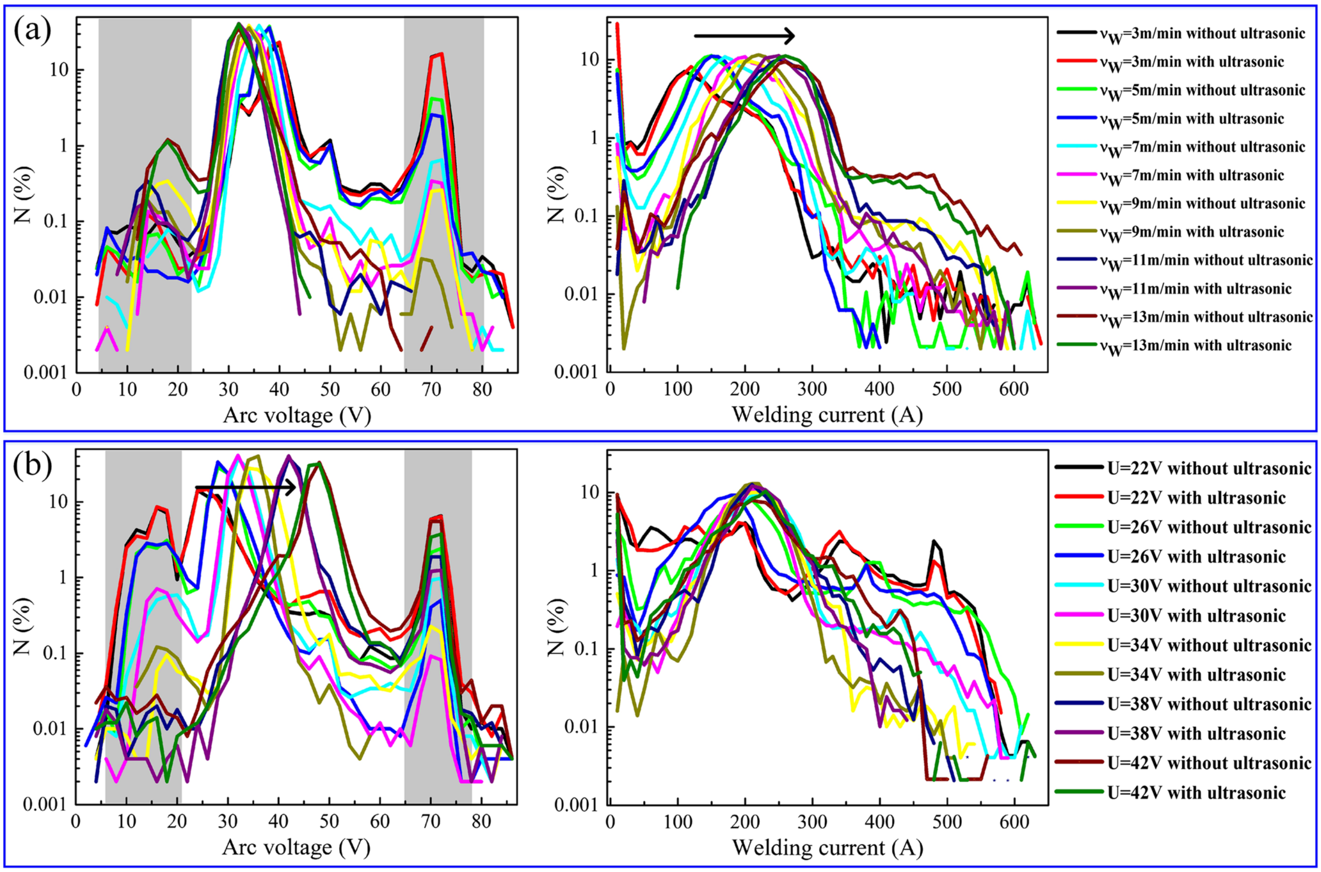


Fig. 5 Probability distribution of welding current and arc voltage varying with wire feed speed (**a**) and arc voltage (**b**) in underwater wet welding without and with ultrasonic wave

hump. The position of the only hump in the probability distribution of welding current does not change with arc voltage. But the probability distribution of some high or small welding current hump is also detected and changes with various wire feed speeds. Similarly, for each arc voltage, the welding process with ultrasonic wave indicates the smaller probability value of high arc voltage hump and low arc voltage hump compared with conventional underwater wet welding, thus also producing excellent arc stability. The observed results are consistent with previous results on the oscillograms and cyclograms of the welding current and arc voltage. Thus, the probability distribution of welding current and arc voltage uncovers a good role for arc stability during the welding process.

3.4 Variation coefficients of the welding current and arc voltage

The variation coefficient is determined as the ratio of the standard deviation and average for a set of data. Currently, it is also used in underwater wet welding to evaluate arc stability [29]. In general, the variation coefficient is inversely proportional to arc stability. Figure 6 shows the effect of wire feed speed and arc voltage on the variation coefficients of the welding current and arc voltage in underwater wet welding without and with an ultrasonic wave. As a result of the same waveforms mode in Fig. 2, the change trend in variation coefficients without and with ultrasonic wave agrees basically with each other even when varying wire feed speed or arc voltage. As shown in Fig. 6a, the variation coefficients of the welding current and arc voltage for the two welding conditions originally decrease to a minimum value at 11 m/min and then yield a slight increase with increasing wire feed speed. Under the same wire feed speed, the variation coefficients of the welding current and arc voltage with ultrasonic wave both present much smaller values as compared with those without an ultrasonic wave, indicating a better arc stability in the welding process with an ultrasonic wave. By comparing various wire feed speeds, the variation coefficients of the welding current and arc voltage at the small wire feed speed tend to result in a much higher value than those at the large wire feed speed. This is because a high proportion of larger arc voltage signal occurs at the small wire feed speed. According to the description above in Fig. 2, the excessive presence of the larger arc voltage signal in the waveforms indicates a declining arc burning process and plays the role as electrical signal fluctuations, which can further deteriorate the arc stability.

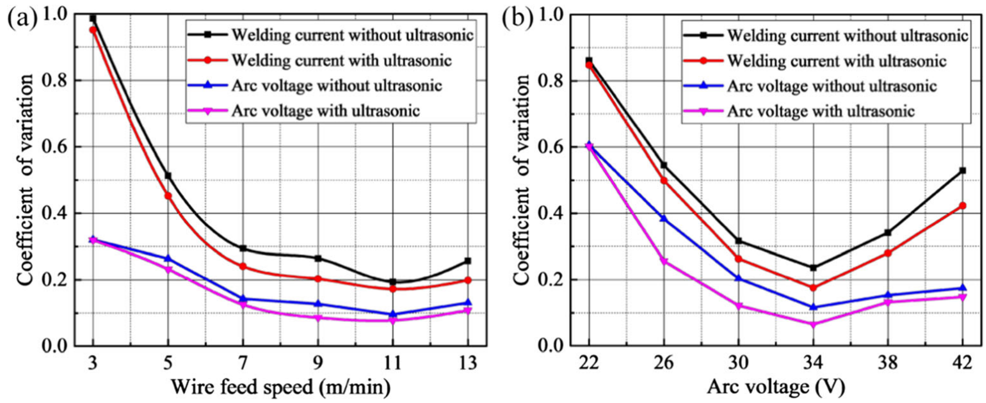


Fig. 6 Effect of wire feed speed (**a**) and arc voltage (**b**) on the coefficients of variation of welding current and arc voltage in underwater wet welding without and with ultrasonic wave

As depicted in Fig. 6b, the variation coefficients of the welding current and arc voltage for the two welding conditions first decrease to a minimum value at 34 V and then increase to a higher value as the arc voltage increases. Under the same nominal arc voltage, the variation coefficients of the welding current and arc voltage with ultrasonic wave both show much smaller values than those without an ultrasonic wave, which also indicates better arc stability in the welding process with an ultrasonic wave. By comparing various arc voltages, the variation coefficients of the welding current and arc voltage at the small arc voltage lead to a higher value than those at the large arc voltage. This is due to the co-existence of the larger arc voltage signal and smaller arc voltage signal at the small arc voltage as observed in Fig. 2, thus causing violent electrical signal fluctuations to promote the unstable arc. Besides, regardless of the welding current or arc voltage variation coefficient, there exists a minimum value at the wire feed speed of 11 m/min or at the arc voltage of 34 V for the two welding conditions. Due to varying wire feed speed or arc voltage, the improvement of arc stability by ultrasonic wave produces significant differences. Therefore, the variation coefficient analysis agrees well with the above three evaluation results. The ultrasonic wave has the potential to stabilize the welding arc due to the alleviation of the bubble disturbance.

4 Discussion

4.1 Verification of weld morphology

The conventional underwater wet welding was carried out at various wire feed speeds and arc voltages. However, all the welding processes are confronted with the same problem: part of the bubble rises caused by the uncontrolled buoyant force on the bubble, causing a disturbance to the arc and leaving insufficient bubble to protect the entire arc burning zone. This may lead to a great variation of arc stability. By the exertion of an ultrasonic wave, on the contrary, a very small part of the bubble rises from the lateral side and a stable, large bubble is produced in the weld pool surface, which can serve as a barrier to prevent excess water invasion into the arc burning zone during the welding process. Therefore, enhanced arc stability is achieved by the exertion of an ultrasonic wave in underwater wet welding. As mentioned above in the "Results" section, the four indexes evaluation methods to determine arc stability, i.e., oscillograms, cyclograms, probability distribution, variation coefficients of the welding current and arc voltage, have been conducted to assess the effect of an ultrasonic wave on arc stability. It is obvious that after applying an ultrasonic wave, the fluctuations of larger arc voltage signal and smaller arc voltage signal are reduced; some abnormal lines and high arc voltage area in the cyclograms are alleviated; the middle hump in the probability distribution is narrower and shows a higher maximum value; the variation coefficients of welding current and arc voltage both present much smaller values. Thus, the results on these four indexes evaluation methods agree basically with each other, which in turn indicates that the arc stability can be assessed by the analysis results obtained with four methods.

After analyzing the arc stability indexes evaluation by the four methods, the next step was to prove the correctness based on the weld morphology. Figure 7 shows the macro morphology and transverse section of the joints varying with wire feed speed in underwater wet welding without and with an ultrasonic wave. As shown, for each wire feed speed, some defects such as weld pits, spatters, or serpentine weld are observed in conventional underwater wet welding, which may further validate the appearance of decreasing arc stability. As the wire feed speed is larger than 9 m/min, a serpentine weld in the surface is always observed. When an ultrasonic wave is used, however, the weld appearance features a better performance no matter which wire feed speed is chosen, confirming the better arc stability and corresponding to previous analysis results of arc stability. Some defects such as weld pits, spatters, or serpentine weld are reduced or even eliminated. It should be also noted that a serpentine weld in the surface can be weakened but it is still found at the wire feed speeds of 11 m/min and 13 m/min even if an ultrasonic wave is used. This is due to

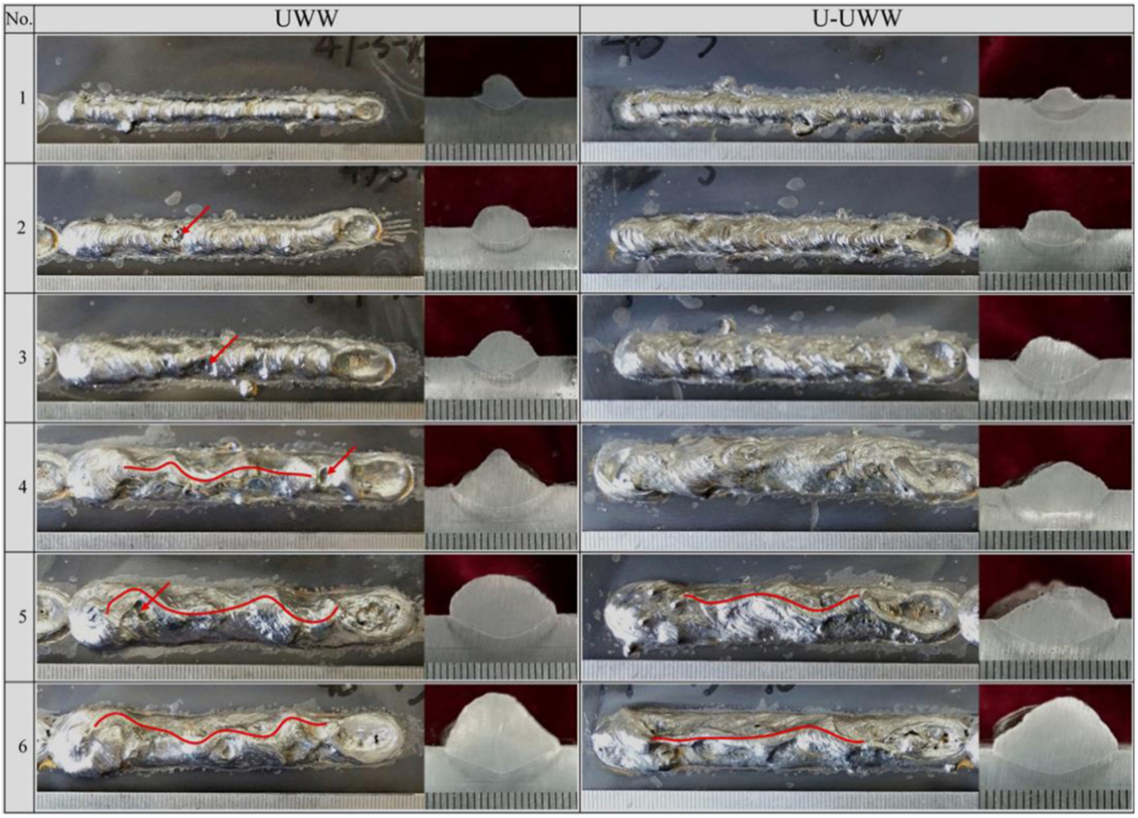


Fig. 7 Macro morphology and transverse section of the joints varying with wire feed speed in underwater wet welding without and with ultrasonic wave

the diminished control of the bubble by an ultrasonic wave caused by oversized bubble formed at the large wire feed speed. This will be discussed in the "Effect of bubble dynamics" section.

Figure 8 shows the macro morphology and transverse section of the joints varying with arc voltage in underwater wet welding without and with an ultrasonic wave. As shown, for each arc voltage, some defects such as weld pits, spatters, or serpentine weld are also observed in conventional underwater wet welding, which can further validate the appearance of decreasing arc stability. At the smaller arc voltage, uneven and discontinuous welds are formed due to the co-existence of the larger arc voltage signal and smaller arc voltage signal. At the larger arc voltage, some weld pits with tumors can be found since larger arc voltage signal dominates. At the middle arc voltage, there exists a serpentine weld in the surface though the electrical signals are relatively superior in conventional underwater wet welding. With the use of ultrasonic wave, however, the weld appearance indicates a better performance no matter which arc voltage is chosen, confirming the better arc stability and corresponding to previous results on arc stability. Some defects such as weld pits, spatters, or serpentine weld are reduced or even eliminated. But at the arc voltage of 22 V, the weld appearance with an ultrasonic wave is similar to that without an ultrasonic wave. This is because the ultrasonic wave does not seem to play a significant role in the bubble dynamics at the smaller arc voltage, which will be analyzed later. By comparing Fig. 7 with Fig. 8, it can be seen that arc voltage has a larger effect on the weld morphology than wire feed speed in the welding processes without and with an ultrasonic wave. The study on weld morphology shows a good reflection on the analysis of arc stability during the welding process.

Wang et al. [17] pointed out that the control of the bubble can not only minimize external disturbance achieving better arc stability but also provide a larger bubble attached in the weld pool surface resulting in more heat input into the weld and then enhancing the base metal fusion. Hence, the fusion ratio, determined as the percentage of molten base metal that occupies the whole weld metal, was used to characterize the fusion capacity by the exertion of an ultrasonic wave during the welding process. Figure 9 shows the effect of wire feed speed and arc voltage on the fusion ratio in underwater wet welding without and with an ultrasonic wave. As shown in Fig. 9a, with varying wire feed speed, the fusion ratio present significant difference for the two welding conditions. However, the fusion ratio with ultrasonic wave indicates an increasing trend compared with that without ultrasonic wave under the same wire feed speed. For example, when the wire feed speed is 5 m/min, the fusion ratio is about 0.44 and 0.47 for conventional underwater wet welding and ultrasonic wave-assisted underwater wet welding, respectively, and the

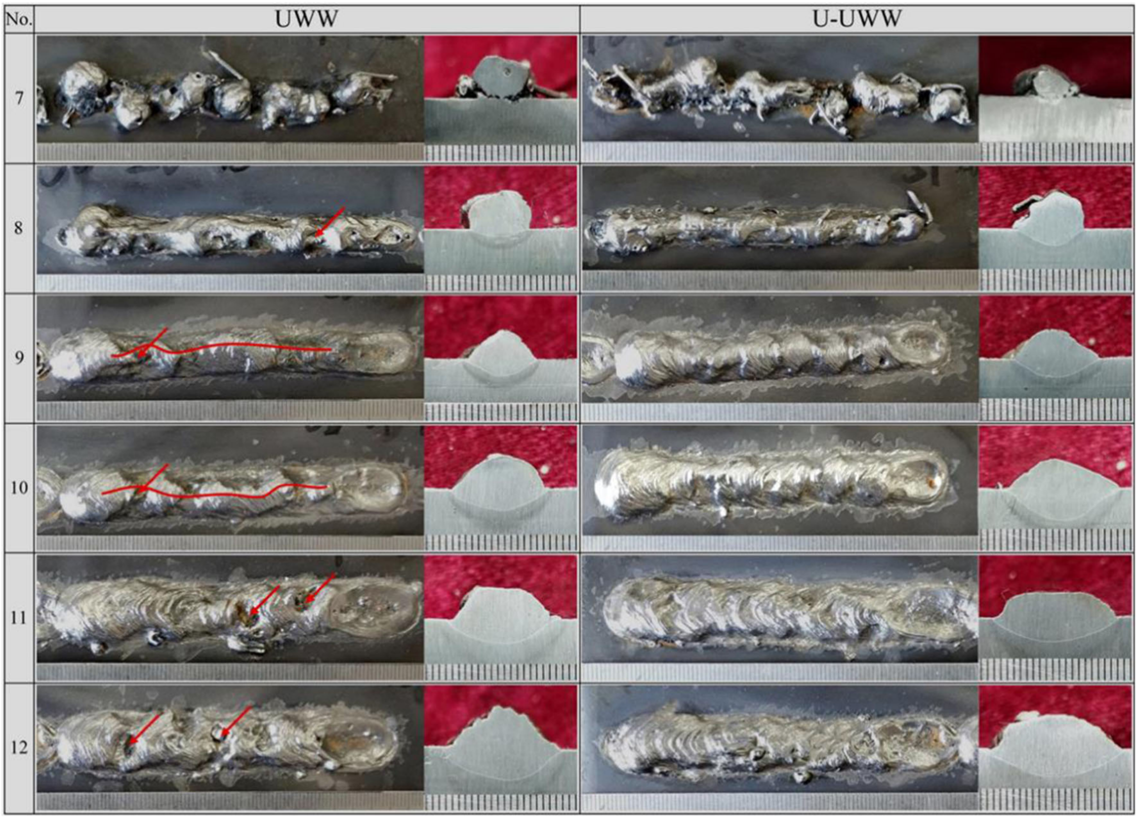
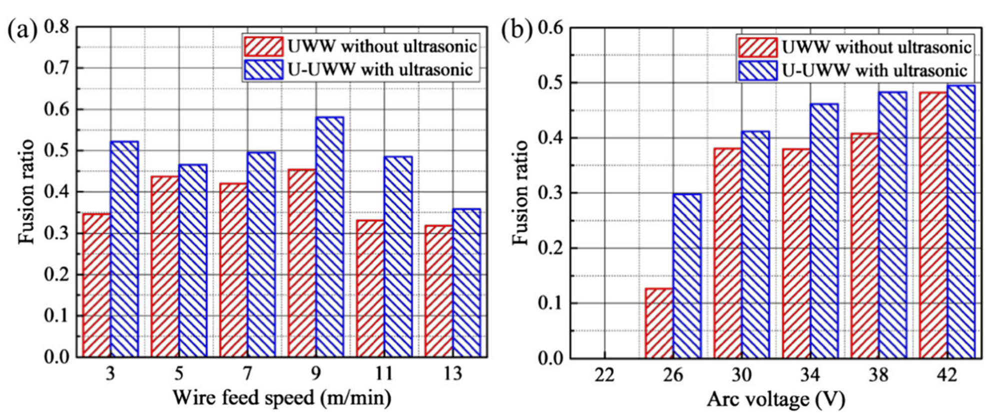


Fig. 8 Macro morphology and transverse section of the joints varying with arc voltage in underwater wet welding without and with ultrasonic wave

addition of ultrasonic wave increases it by 6.6%. When the wire feed speed is 11 m/min, the fusion ratio is about 0.33 and 0.48 for conventional underwater wet welding and ultrasonic wave-assisted underwater wet welding, respectively, and the addition of ultrasonic wave increases it by 46.5%.

As shown in Fig. 9b, with increasing arc voltage, the fusion ratio gradually increase for the two welding conditions. Especially, at the arc voltage of 22 V, the fusion ratio is not indicated because this arc voltage does not form a complete weld. In addition, the fusion ratio with ultrasonic wave also presents an increasing trend compared to that without ultrasonic wave under the same arc voltage. For example, when the arc voltage is 26 V, the fusion ratio is about 0.13 and 0.30 for conventional underwater wet welding and ultrasonic wave-assisted underwater wet welding, respectively, and the addition of ultrasonic wave increases it by 135.5%. When the arc voltage is 38 V, the fusion ratio is about 0.41 and 0.48 for conventional underwater wet welding and ultrasonic wave-assisted underwater wet welding, respectively, and the addition of ultrasonic wave increases it by 18.3%. By comparing Fig. 9a and b, one noticeable feature is that the fusion ratio is substantially increased no matter which wire feed speed or arc voltage is used. Hence, from the fusion ratio point of view, it can be inferred that effective heat input is more transferred to

Fig. 9 Effect of wire feed speed (**a**) and arc voltage (**b**) on the fusion ratio in underwater wet welding without and with ultrasonic wave



weld pool instead of radiating out through the water during the welding process with an ultrasonic wave; thus, a better weld fusion is guaranteed.

4.2 Effect of bubble dynamics

It is known that arc stability is mainly characterized by arc behavior and metal transfer, which are determined by welding parameters (welding current and arc voltage). That is, welding current and arc voltage are the main factors determining the arc behavior, metal transfer, and the resulting arc stability. However, in underwater wet welding, welding parameters not only affect the arc behavior and metal transfer but also have an impact on the evolution of a dynamic bubble [29, 30, 36]. Hence, arc stability is closely correlated with the external environment, especially the disturbance of a dynamic bubble in underwater wet welding. The arc burns in the bubble, so the protective effect is determined by the shape and stable duration of the bubble in the weld pool surface due to the rising of the bubble. In the present study, the ultrasonic wave is introduced to realize an effective control for the bubble. Moreover, the ultrasonic wave does not seem to play a direct role in the arc behavior and metal transfer inside the bubble. Thus, the influence of an ultrasonic wave on the arc behavior and metal transfer may not be the main concern in this study. Since the bubble dynamics vary with welding parameters, specific analysis is required for the specific welding parameters when an ultrasonic wave is applied.

As shown in Fig. 10a, at the smaller wire feed speed of 3 m/min without ultrasonic wave, a larger bubble can be formed in the weld pool surface providing an effective protection due to the use of large arc voltage of 32 V. However, successive arc extinction process is inevitably formed from 228.0 to 246.0 ms under the welding conditions. So larger arc voltage

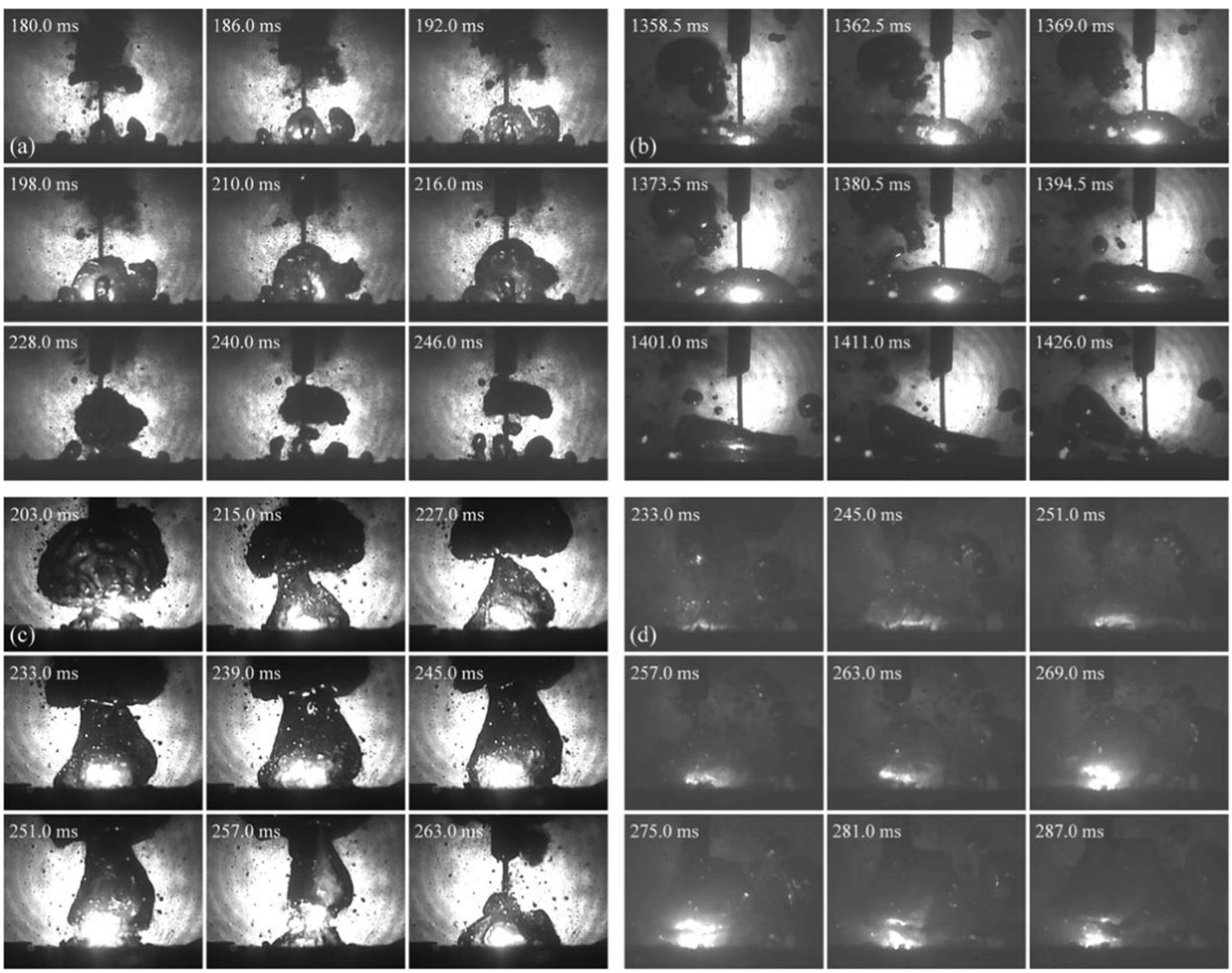


Fig. 10 Comparison of the bubble dynamics under different welding conditions. **a** At small wire feed speed of 3 m/min without ultrasonic wave. **b** At small wire feed speed of 3 m/min with ultrasonic wave. **c** At large wire feed speed of 13 m/min without ultrasonic wave. **d** At large wire feed speed of 13 m/min with ultrasonic wave

signal with a long-last time appears accordingly, as shown in Fig. 2. In this case, successive arc extinction process can result in a great reduction in arc stability even if there is a larger bubble in conventional underwater wet welding. Under the action of an ultrasonic wave, it can be seen that a large bubble still occurs and is attached in the weld pool surface, as shown in Fig. 10b. The motion trajectory of the bubble does not rise vertically but at an angle with respect to the axis of the wire. However, the arc extinction process can be also observed at 1426.0 ms as a result of the large arc voltage and small wire feed speed. As a result, the improvement in arc stability is not too obvious during the welding process with ultrasonic wave because such a small wire feed speed plays a dominant role in arc stability. The observed results are consistent with previous results on the analysis of arc stability and weld morphology in Fig. 7.

When conventional underwater wet welding is performed at a larger wire feed speed of 13 m/min, the bubble size is very large providing a good protection effect, as shown in Fig. 10c. Even if the bubble rises, the arc anti-interference ability is enhanced due to the larger arc stiffness caused by larger wire feed speed; thus, the arc extinction process rarely occurs, and the arc stability is also enhanced. By observing the welding electrical signals in Fig. 2, it can be seen that some smaller arc voltage signals are also observed due to the large wire feed speed and bubble disturbance, indicating the occurrence of short-circuiting process. With the action of an ultrasonic wave in Fig. 10d, the bubble lasts a longer time in the weld pool surface, and the bubble disturbance is also restricted, possibly causing a reduction in short-circuiting process, as confirmed in Fig. 2. Hence, arc stability is further improved when an ultrasonic wave is applied under the larger wire feed speed. However, due to the large bubble volume at this wire feed speed, the ultrasonic control of the bubble is more or less limited; thus, the improvement of arc stability is not too great and then a serpentine weld still appears. The observed results are consistent with previous results on the analysis of arc stability and weld morphology in Fig. 7.

As shown in Fig. 11a, at the smaller arc voltage of 22 V without an ultrasonic wave, the tip of the flux-cored wire is easily contacted with the weld pool, resulting in the appearance of successive short-circuiting process. But the short-circuiting process cannot be carried out smoothly and the flux-cored wire is prone to overheating and segment fusing due to such a small arc voltage and large wire stick out the length, as determined in Fig. 11a. In this case, a high arc voltage signal with a long-last time is formed accordingly, as shown in Fig. 2. In addition, the undersized bubble is also observed around the arc burning zone and maintained an erratic state which cannot provide effective protection. Hence, the combination of abnormal short-circuiting process and undersized bubble causes a great reduction in the arc stability. When an ultrasonic wave is applied, it can be seen that a relatively large bubble appears and is attached in the weld pool surface, as shown in Fig. 11b. Even though the relatively large bubble with an ultrasonic wave is produced, there exist arc extinction and bubble burst observed around the arc burning zone from 432.5 to 483.5 ms. This is because the abnormal short-circuiting process still appears during the welding process with ultrasonic wave, as shown in Fig. 2, and then plays the role of deteriorating the arc stability. As a result, the improvement in arc stability is not too obvious during the welding process with ultrasonic wave because such a small arc voltage plays a dominant role in arc stability. The observed results are consistent with previous results on the analysis of arc stability and weld morphology in Fig. 8.

In general, underwater wet welding usually uses a larger arc voltage than onshore welding [37]. If excessive arc voltage is selected, the arc stiffness may be lowered, which is not conducive to resisting the perturbation of the external environment. At the arc voltage of 42 V without an ultrasonic wave, the oversized bubble can be formed under such a large arc voltage, as shown in Fig. 11c. The oversized bubble may produce a large shock for the arc when rising, contributing to the arc extinction process from 221.0 to 227.0 ms and also undermining the arc stability. Although a very large bubble appears in the arc burning zone, the combination of lowered arc stiffness and excessive bubble disturbance leads to a great reduction in the arc stability. In this case, the disturbance of a dynamic bubble plays a decisive role in arc stability. Hence, when applying ultrasonic wave, the bubble disturbance is restricted to some degree. The bubble does not rise as a whole but there is always most of the bubble left in the arc burning zone, as shown in Fig. 11d, so that the impact of the bubble on the arc is lowered and the arc extinction process is reduced. Accordingly, the arc stability is improved by the exertion of ultrasonic wave. It should be noted that because the larger bubble produces greater buoyant force, the effect of ultrasonic wave on the bubble is weakened. On the other hand, although the ultrasonic wave is imposed, water pressure exists and the bubble also generates a lateral movement when the welding torch moves, which in turn affects the stability of the arc. The arc extinction process cannot be eliminated completely under such a large arc voltage with lowered arc stiffness, as confirmed in Fig. 2. These two aspects have caused the arc stability to still be reduced, although arc stability has been improved when ultrasonic wave is applied. The observed results are consistent with previous results on the analysis of arc stability and weld morphology in Fig. 8.

As shown in Fig. 12a, when appropriate arc voltage and wire feed speed are used, the arc burns smoothly and no arc extinction is observed even if the bubble disturbance still exists when rising. The dynamic disturbance of the bubble seems to have less influence on the arc stability in conventional underwater wet welding. This indicates an enhancement of arc stability, so the proportion of unstable arc burning process is

Fig. 11 Comparison of the bubble dynamics under different welding conditions. **a** At small arc voltage of 22 V without ultrasonic wave. **b** At small arc voltage of 22 V with ultrasonic wave. **c** At large arc voltage of 42 V without ultrasonic wave. **d** At large arc voltage of 42 V with ultrasonic wave

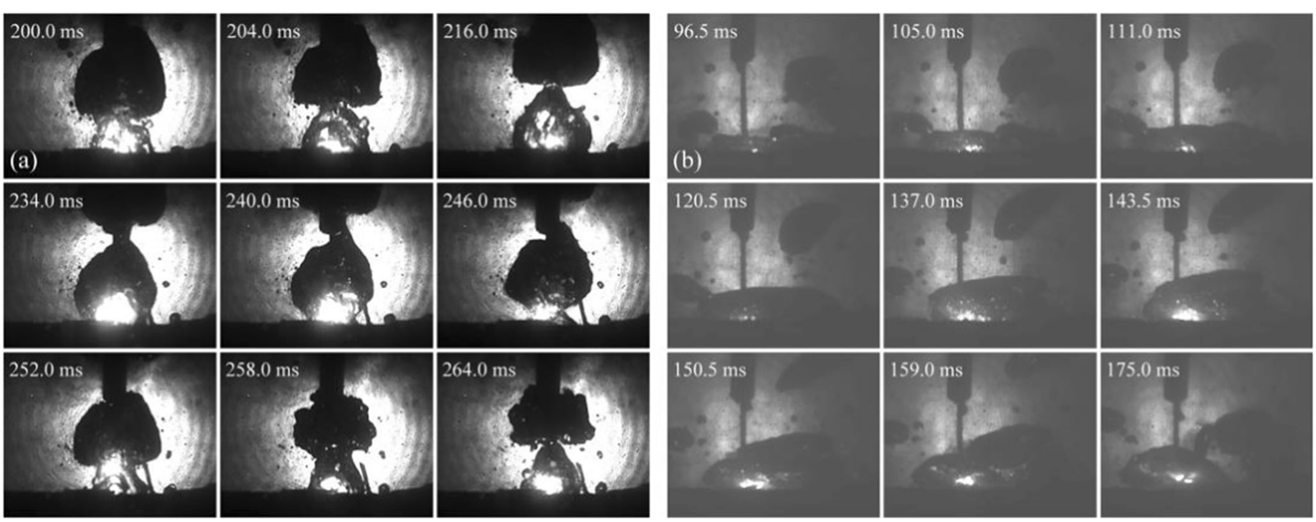


Fig. 12 Comparison of the bubble dynamics under different welding conditions. **a** At appropriate arc voltage and wire feed speed without ultrasonic wave. **b** At appropriate arc voltage and wire feed speed with ultrasonic wave

small, as shown in Fig. 4. When the ultrasonic wave is applied, the control of the bubble is exerted and the bubble shape has also changed. A large size bubble stays in the weld pool surface for a long time, as shown in Fig. 12b, which helps to achieve a more stable bubble and then enhance the arc stability further. Hence, suitable welding parameters plus a stable bubble environment induced by the addition of ultrasonic wave will significantly improve the arc stability during the welding process. Based on the above results, it can be concluded that the variation in dynamic bubble induced by the exertion of ultrasonic wave can be used to explain why the arc stability is improved.

5 Conclusions

In the present study, arc stability indexes evaluation of ultrasonic wave-assisted underwater wet welding has been explored. Some conclusions can be obtained:

(1) After applying ultrasonic wave, the fluctuations of larger arc voltage signal and smaller arc voltage signal are reduced; some abnormal lines and high arc voltage area in the cyclograms are alleviated; the middle hump in the probability distribution is narrower and shows a higher maximum value; the variation coefficients of welding current and arc voltage both present much smaller values. Thus, these four indexes evaluation methods agree basically with each other, which in turn indicates that the arc stability can be assessed by the analysis results obtained with four methods.

(2) By comparing different wire feed speeds, the short-circuiting process is predominant at larger wire feed speed while the arc extinction process dominates at smaller wire feed speed. By comparing different arc voltages, the arc extinction process dominates at both smaller arc voltage and larger arc voltage while the short-circuiting process is only predominant at smaller arc voltage.

(3) When the ultrasonic wave is used, the weld appearance features a better performance no matter which wire feed speed or arc voltage is chosen, confirming the better arc stability and corresponding to previous analysis results of arc stability. In addition, from the fusion ratio point of view, effective heat input is more transferred to the weld pool instead of radiating out through the water; thus, a better weld fusion is guaranteed.

(4) The variation in dynamic bubble induced by the exertion of ultrasonic wave can be used to explain why the arc stability is improved. The key points to excellent arc stability depend on both the designation of optimized welding parameters and reasonable control of the bubble with structural integrity.

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