

Article

Process Stability, Microstructure and Mechanical Properties of Underwater Submerged-Arc Welded Steel

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Abstract: In underwater wet welding, the unstable welding process caused by the generation and rupture of bubbles and the chilling effect of water on the welding area result in low quality of welded joints, which makes it difficult to meet the practical application of marine engineering. To improve the process stability and joining quality, a mixture of welding flux with a water glass or epoxy resin was placed on the welding zone before underwater welding. In this paper, welds' appearance, geometry statistics of welds' formation, welding process stability, slag structure, microstructure, pores and mechanical properties were investigated. It was found that with the addition of water glass in the mixture, the penetration of weld was effectively increased, and the frequency of arc extinction was reduced. Though the porosity rose to a relatively high level, the joints' comprehensive mechanical properties were not significantly improved. Notably, the applied epoxy resin completely isolated the surrounding water from the welding area, which greatly improved process stability. Furthermore, it benefited from the microstructure filled with massive acicular ferrite, the average elongation and room temperature impact toughness increased by 178.4%, and 69.1% compared with underwater wet welding, respectively, and the bending angle of the joint reaches to 180°.

Keywords: underwater wet welding; resin; process stability; microstructure; properties; slag; porosity



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1. Introduction

With the development of exploration for marine resources, it is necessary to build huge numbers of large-scale marine structures, such as oil drilling rigs, subsea tunnels and sea-crossing bridges in the ocean. Unlike structures on shore, offshore structures are frequently subjected to not only the working loads, but also additional loads caused by storms, waves and tidal currents, as well as seawater corrosion. Therefore, it demands higher requirements in the design and manufacture, material selection and joining quality of offshore facilities, which need to be fabricated or repaired by underwater welding. Underwater welding has become indispensable for marine engineering and is attracting more and more attention [1]. Underwater welding can be classified in three categories: dry, local dry and wet welding, which can be directly conducted in water without any special drainage facilities. Due to the advantages of simple equipment, low cost and flexible operation, underwater wet welding (UWW) has gained the most extensive application in marine engineering [2]. It is well known that the arc burns in bubbles formed by the decomposition of water vapor at high temperatures during the UWW process [3]. The arc stability is affected by the dynamics of bubble formation and detachment [4]. When the bubble breaks or leaves the welding area, the arc extinguishes, which deteriorates the stability of the welding process [5]. In addition, since the thermal conductivity of water is much higher than that of air, the cooling rate of an underwater joint is much faster than that in air. As a result, a hardened structure easily forms in the weld or heat affected zone (HAZ), reducing the strength and toughness of joints. The high content of diffusible hydrogen and defects, such as cracks, pores and

slag inclusions, would seriously hamper the quality improvement of the joints [6–8]. Up to the present, efforts have been putting on how to enhance the quality of UWW joints. Tsai believed that increasing the heat input and lowering the travel speed could reduce the cooling rate of thicker plate to some extent [9]. Wang et al. claimed that ultrasonic vibration could change the size and morphology of the prior austenite grains during solidification of the molten pool, and subsequently a high proportion of fine grain ferrite formed in the solid phase transition [10]. According to the results of Sun et al., ultrasonic wave improved the stability of arc and increased the number of granular bainite and acicular ferrite in the weld, thus improving the tensile strength and bending performance of joints [11]. Zhang et al. suggested that induction heating could reduce the cooling rate and cold crack sensitivity of UWW joints [12]. Fydrych et al. proposed the idea of using temper bead welding (TBW) technology to improve the weldability of high-strength steel and reduce the hardness of UWW welds [13]. Tomków et al. [14,15] researched the effects of waterproofing of electrodes on wet welded S460N steel, suggesting that both diffusible hydrogen content and hardness in the HAZ of the weld reduced by the use of electrodes with paraffin wax. In order to improve the fatigue performance of the underwater wet-welded joints, Gao et al. introduced a grinding + underwater ultrasonic impact treatment method and found that the use of a single grinding or ultrasonic impacting could not significantly improve the fatigue performance, while the combination of the two greatly improved it [16]. Compared with constant wire feed mode, the metal transfer process and welds' appearance could be improved by adopting a pulsed wire feed mode [17]. Wang et al. reported that mechanical restraints could prevent bubble detachment and keep it covering the arc column region, thus reducing the proportion of brittle microstructure in the weld [18].

According to the current research status, the process stability or joint quality of UWW can be partially improved. However, the employment of auxiliary energy and the complexity of operating procedures would obviously increase the total cost and further limit the application of UWW in marine engineering. To enhance the welding quality and operation simplicity, welding flux mixed with either water glass or epoxy resin was placed to the welding area in advance during the UWW process. The process stability, microstructure and mechanical properties of joints under three conditions were investigated.

2. Materials and Methods

Two special mixtures were used in the experiment: one composed of 40 wt% bisphenol-A epoxy resin and 60 wt% flux-HJ350 by stirring, another of 40 wt% water glass and 60 wt% flux-HJ350. Bisphenol-A epoxy resin with a relative density of 1.16 g/cm³ was used in this experiment. Table 1 shows the chemical composition of welding flux HJ350 and water glass. Mixtures with a thickness of 35 mm were placed in advance on the base plate surface before underwater welding.

Table 1. Chemical composition of HJ350 and water glass.

	SiO ₂	CaO	Al ₂ O ₃ + MnO	CaF ₂	FeO	K ₂ O	Na ₂ O
HJ350	30–35	10–20	27–37	14–20	≤1.0	-	-
Water glass	30.24	-	-	-	-	3.53	10.87

A low carbon steel Q235B with the dimensions of 300 mm × 150 mm × 8 mm and rutile type underwater flux-cored wire with a diameter of 1.6 mm were chosen as the base material and consumable, respectively. Both the chemical composition of base material and weld metal are shown in Table 2.

Table 2. Chemical composition of base metal and weld metal.

	C	Si	Mn	S	P
Base metal	0.20	0.30	0.70	0.035	0.045
Weld metal	0.11	0.15	0.30	0.025	0.020

A constant voltage Pulse MIG-500 power with DCEP polarity was employed in all welding processes that were carried out in a water tank ($250 \times 700 \times 500$ mm), as shown in Figure 1. The specific parameters are shown in Table 3. An electrical signal acquisition system was used to monitor the stability of arc voltage and welding current during the welding process.

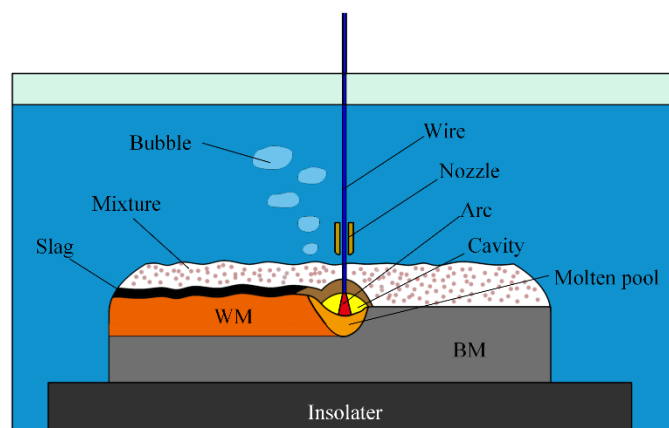


Figure 1. Schematic of underwater submerged-arc welding.

Table 3. The specific parameters during welding.

Arc Voltage (V)	Wire Feed Rate (m/min)	Welding Speed (mm/min)	Wire Extension (mm)	Water Depth (m)
30	5	130	15	0.3

The cross section of the weld was polished with 120, 240, 400, 600 and 800 mesh sandpaper, then polished with $2.5 \mu\text{m}$ diamond polishing agent and corroded with 3% nitrate alcohol solution. Vernier caliper was used to measure the geometric parameters of welds. Leica-DM2700 metallographic microscope (Leica Microsystems Ltd., Wetzlar, Germany) was used to observe the microstructure of the joints. The morphology analysis of the fracture of the impact specimen was performed on a JSM-7800F field emission scanning electron microscope (JEOL, Ltd., Tokyo, Japan) with the function of EDS.

Ten different fields of each weld sample collected by the metallographic microscope were randomly selected to analyze the porosity distribution in the three processes. Then, the ratio of the pore area to the total area was calculated based on the pixel point method. Finally, the average value of the 10 metallographic diagrams was treated as the porosity of each sample.

The tensile strength and bending tests were carried out on an MTS SHT4505 universal testing machine (MTS Systems Corporation, Eden Prairie, MN, USA) with loading rate of 1 mm/min, after all the specimens were polished. The impact toughness values at room temperature were determined with an impact test machine. Vickers hardness of the joints were measured from the center of the weld to the base metal, while the loading force and duration were 100 g and 10 s, respectively.

3. Results and Discussion

3.1. Welds Appearance

The bead-on-plate weld appearance obtained by traditional UWW is shown in Figure 2a. Apparently, spatter scatter appeared on both sides of the weld with irregular ripples, and many pores existed in the arc crater. However, no obvious defects were found in the cross section of the weld, as shown in Figure 2d. Various pores appeared in both the surface and arc crater of the weld produced by underwater submerged-arc welding with the mixture of water glass and flux in the welding area (WG-USAW), as demonstrated in Figure 2b. A few visible pores appeared in the upper cross section of the weld, as shown in Figure 2e.

A weld with perfect appearance, fine regular ripples, no spatter and pores was produced by underwater submerged-arc welding with the mixture of epoxy resin (EP-USAW), as displayed in Figure 2c. In addition, no evident defects emerged in its cross section, as shown in Figure 2f.



Figure 2. Bead-on-plate welds appearance and cross section of different welding. (a,d) UWW; (b,e) WG-USAW; (c,f) EP-USAW.

3.2. Geometry Statistics of Welds Formation

The geometric parameters of welds obtained by three methods are statistically shown in Figure 3. Notably, the weld width of EP-USAW reaches to 19.23 mm, 28.9% higher than that of UWW, which gained the smallest value among the three of them. Meanwhile, the weld reinforcements were 4.93 mm, 3.3 mm and 4.62 mm. The ionization degree of plasma in the arc may climbed to a high level due to the decomposition of a large number of alkali metal oxides in the water glass, which increased the arc force impacting the effect on the molten pool. As a result, both the penetration and fusion ratio of the WG-USAW joint reached the maximum values, 6.63 mm and 67.9%, respectively.

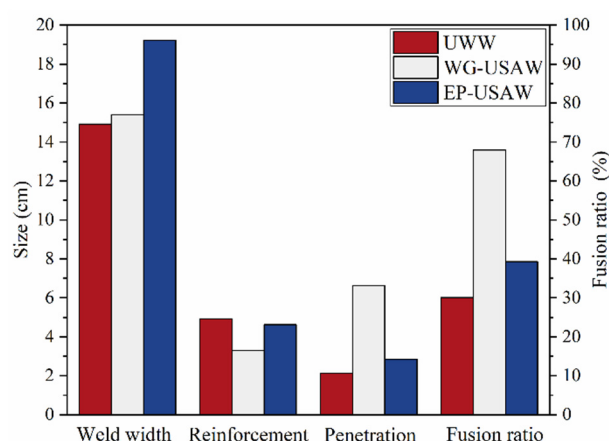


Figure 3. Geometry parameter statistics of welds formation.

3.3. Welding Process Stability

In the UWW process, the existence of bubbles and water flow in the welding area seriously interfered with the underwater imaging system, which made it impossible to obtain a clear arc image to evaluate the process stability. Additionally, the arc was covered by the mixture in the USAW process, so it was more difficult to image the arc through conventional visual inspection methods. Therefore, the fluctuation degree of voltage and current in the welding process was taken as an evaluation index reflecting the stability of

the arc in this paper. The welding process stability was affected by the periodic break and detachment of bubbles in the UWW process, of which the typical feature is arc extinction, and short circuit frequently occurred, as shown in Figure 4a. Compared with the UWW, the fluctuation of WG-USAW was improved by means of reducing the arc extinction and short circuit, as shown in Figure 4b. While in the EP-USAW, arc extinction and short circuit hardly happen, and the process tends to be more stable, as shown in Figure 4c.

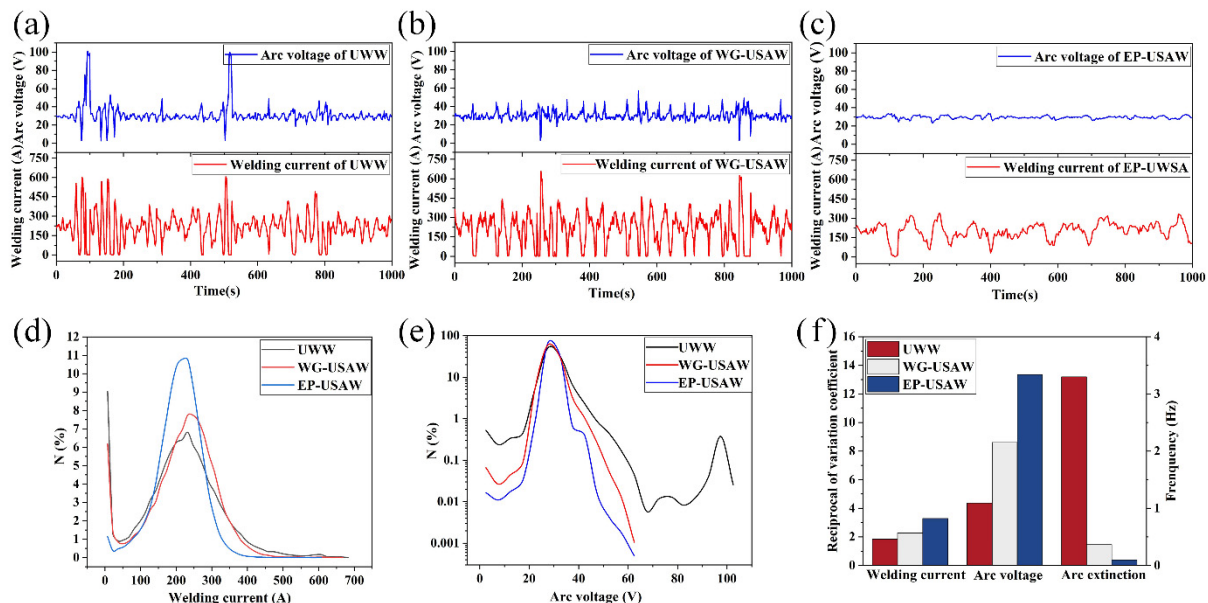


Figure 4. Analysis of welding process electrical signals. (a–c) waveforms under different conditions; (d,e) probability density distribution of welding current and arc voltage; (f) reciprocal variation coefficients and arc extinction frequencies.

To further investigate the stability of welding processes under three conditions, the probability density distribution of the electrical signals was calculated. As shown in Figure 4d, the current of EP-USAW has the highest degree of concentration, while the probability densities of low current in the other two cases both exceed 6%, indicating that relatively serious arc extinction has occurred. Among the probability density distribution, all the arc voltages demonstrate peaks near the preset value of 30 V, as shown in Figure 4e. Furthermore, a sub-peak appears in the high voltage zone of UWW, which means that arc extinction is more likely to occur under this condition, deteriorating the process stability and welding quality.

Statistically, the smaller the coefficient of variation, the less the electrical signal fluctuation is and the more stable the current or voltage is. Since the coefficient of variation is small, the reciprocal of them is taken as an indicator to assess the stability of the welding process. Compared with the other cases, both the reciprocal variation coefficient of welding current and arc voltage gain the largest values in EP-USAW, implying the most stable welding process. It is found that the arc extinguishing frequency of UWW reaches as high as 3.3 Hz, while the counter value of EP-USAW holds around 0.09 Hz, as shown in Figure 4f.

In conventional UWW, the arc extinction deteriorates process stability due to the frequent breaking of bubbles [18]. In the WG-USAW, though the water solubility of water glass makes it difficult to completely isolate the surrounding water from the welding area, the arc burning environment could be improved to some extent. However, the epoxy resin is insoluble in water, which might completely isolate the surrounding water from the welding area in EP-USAW. Eventually, the arc burns stably in a modified environment without the interference of bubble breaking.

3.4. Slag Structure

Crack propagate through the slag of UWW and WG-USAW, which makes the weld metal be directly exposed to the water environment at relatively high temperature, as illustrated in Figure 5a,b. Removing the remaining mixture afterwards, it was found that the relatively dense slag without cracking was integrated with part of epoxy resin and flux in EP-USAW, as shown in Figure 5c. SEM results show that there were many cracks between the dendritic grains of slag in UWW and WG-USAW, while the slag morphology of EP-USAW was smooth and crack-free, as shown in Figure 5d–f, respectively.

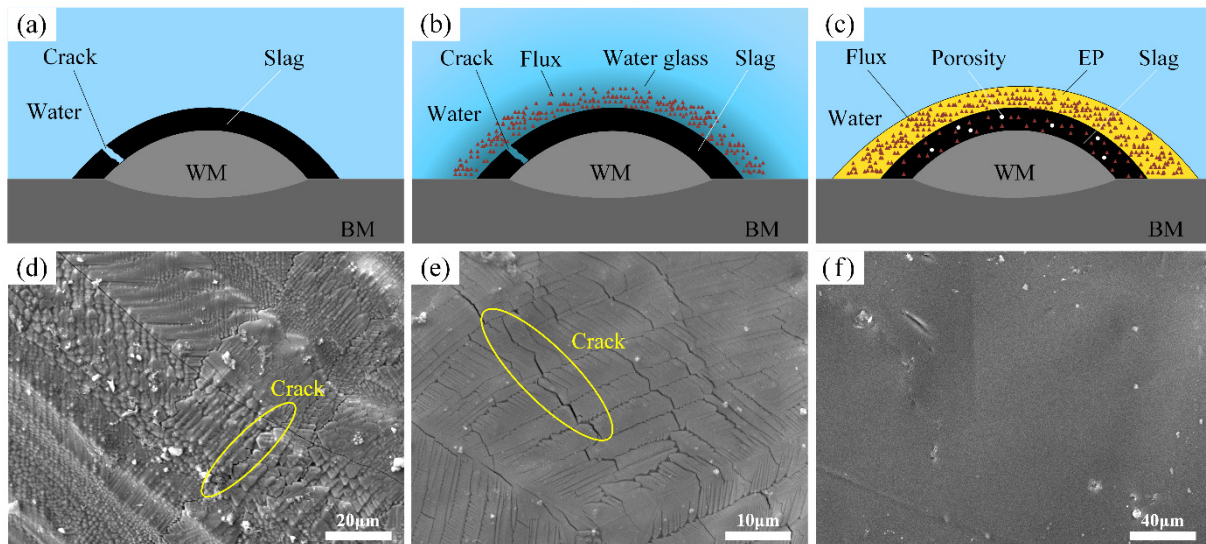


Figure 5. Slag structures of different welding processes. (a–c) Schematic of slag macrostructures for UWW, WG-USAW and EP-USAW; (d–f) SEM results of UWW, WG-USAW and EP-USAW.

Bogusz et al. point out that the stronger the directionality of the phase, the larger the unequal axis, the greater the internal stress generated inside, and the more likely the slag is to crack [19]. In UWW process, the dendrite grains strengthen the longitudinal connection of the slag during the fast-cooling stage, which encourages the generation of a large longitudinal restraining force in the slag, hence crack occurs. Similarly, in WG-USAW process, once the slag cracks, it is no longer able to prevent the water to seep in since water glass is easily dissolved in water. However, in EP-USAW process, the epoxy resin could completely isolate the surrounding water from the welding area and slow down cooling rate of slag, thereby forming a solid slag which will serve as a shield for weld metal.

3.5. Microstructure

The microstructure of UWW weld is composed of a huge number of coarse irregular bulk ferrite (BF), while that of WG-USAW is mainly occupied with coarse pro-eutectoid ferrite (PF), a small amount of bulk ferrite (BF) and acicular ferrite (AF), as shown in Figure 6a,e, respectively. The weld structure of EP-USAW is filled with massive fine acicular ferrite (AF), a little pro-eutectoid ferrite (PF) and bulk ferrite (BF), as shown in Figure 6i. Due to fast cooling rate in UWW, the transformation of weld structure from austenite to ferrite carries out at a temperature much lower than A_{c3} , which weakens the atomic activity. As a result, the newly formed ferrite will retain the characteristic of the original coarse austenite. In WG-USAW process, despite the use of mixture reducing the cooling rate to some extent, the cracking of the slag will lead the high-temperature weld metal to directly contact water. Thus, coarse pro-eutectoid ferrite forms in the weld. In EP-USAW process, the epoxy resin in the mixture can completely isolate the surrounding water and greatly reduce the cooling rate of the weld [20,21]. Consequently, a tiny part of pro-eutectoid ferrite precipitates at the original austenite grain boundary, and the remaining

part transforms into fine acicular ferrite during the subsequent cooling process. In short, compared with the conventional UWW and WG-USAW, a large amount of acicular ferrite forms in the weld of EP-USAW, which is beneficial to the mechanical properties of joints.

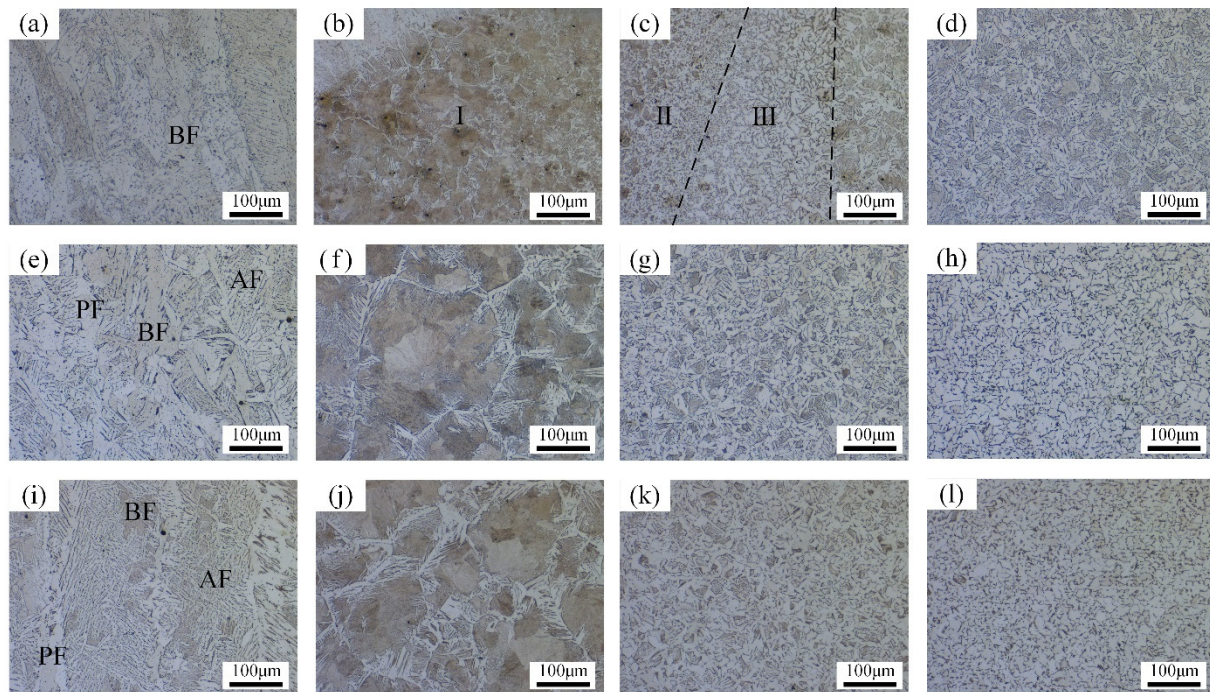


Figure 6. Microstructures of welds and HAZs. (a,e,i) weld metal for UWW, WG-USAW and EP-USAW; (b,c), HAZ of UWW; (d) base metal; (f–h) HAZ of WG-USAW; (j–l) HAZ of EP-USAW.

Figure 6d shows that the microstructure of the base metal mainly consists of pearlite and ferrite. The heat-affected zones obtained by the three welding methods are similar in structure, and can be classified as coarse grain region (CGR), fine grain region (FGR) and partial fine grain region (PFGR). In UWW, since the CGR is subjected to a peak temperature much higher than A_{c3} , thus allowing austenite grains to grow. Side-plate Widmanstatten ferrite forms at the grain boundary during the subsequent rapid cooling process and the remaining austenite transforms into bulk pearlite, as shown in Figure 6b. The peak temperature of FGR is slightly higher than the effective upper critical temperature A_{c3} which allows the austenite grains to nucleate. During subsequent cooling, such austenite grains transform into fine pearlite and ferrite. Due to the high heating rate and limited carbon diffusion time in the process of UWW, nonuniform austenite transforms into ferrite and pearlite with the same characteristics as marked with II in Figure 6c. In addition, the peak temperature of PFGR is just higher than the effective lower critical temperature A_{c1} , and the original eutectoid pearlite transforms into austenite, which will transform into fine pearlite and ferrite during the subsequent rapid cooling process. The original coarse irregular pro-eutectoid ferrite is basically unaffected, as marked with III in Figure 6c. The grains of WG-USAW and EP-USAW are significantly coarser than that in the CGR of UWW, especially the EP-USAW which has more Widmanstatten ferrite which expands deeper into the pearlite grain than the other two, as shown in Figure 6f,j. This is because during the EP-USAW process, the employment of epoxy resin can effectively separate the surrounding water from welding area, slowing down the cooling rate, and allowing the grains of CGR have more time to grow. Similarly, FGRs distributed with fine pearlite and ferrite appear in HAZs of the three welding methods, while the average grain size of WG-USAW and EP-USAW is larger than that of UWW, as the cooling rate reduces during the two processes, as shown in Figure 5g,k. Both of the PFGRs of WG-USAW and EP-USAW are composed of fine pearlite and massive ferrite with different sizes, as shown in Figure 6h,l. The average

widths of HAZs in three processes are 3 mm, 6 mm and 7 mm, respectively. Obviously, the HAZ widths of WG-USAW and EP-USAW are much larger than that of UWW, indicating a great cooling rate reduction effect during the two processes.

3.6. Pores

Pores can reduce the effective bearing area and service life of welded joints, which may have catastrophic consequences. Santos pointed out that when underwater welded joints fail, they often crack from tiny defects such as pores [22]. Therefore, pore distributions in the joints produced by the three methods were analyzed. It was found that there were a certain number of pores in all the welds, most of which scatter in the upper part of the welds, as shown in Figure 7. The porosity of each sample was calculated by measuring at least 25 different fields of the cross section. The statistics of the UWW, WG-USAW and EP-USAW are 0.5%, 0.75% and 0.35%, respectively. The reason for the high porosity of WG-USAW is that the deeper penetration increases the rising time of the bubbles in the liquid weld metal, and part of bubbles remain in the solid weld metal after failing to escape [23]. However, the isolation effect of the epoxy resin effectively reduces the cooling rate of the joint and provides longer time for most of the bubbles to rise out of the weld, which account for the minimum porosity in EP-USAW.

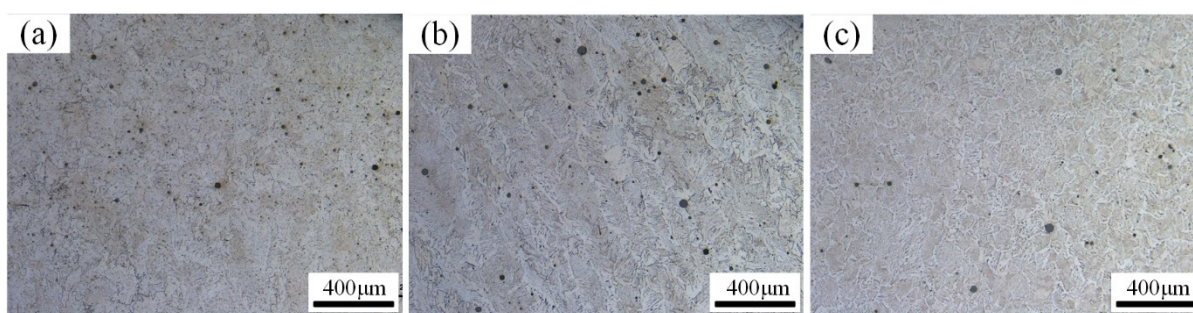


Figure 7. Pores distribution in the welds. (a) UWW, (b) WG-USAW and (c) EP-USAW.

3.7. Mechanical Properties

The mechanical properties of V-groove butt joints obtained by the three methods are shown in Table 4. The joint of EP-USAW gains the largest average elongation of 15.31%, much higher than the other two. Besides, the average ultimate strength of them is 417 MPa, 448 MPa and 459 MPa, respectively. Though the strength of WG-USAW joint is slightly lower than that of EP-USAW, both are higher than that of UWW. In addition, cracks are found in the bending samples of UWW and WG-USAW, while the maximum bending angles are 35° and 68°, respectively. Whether in the face or root bending test, all the bending angles reach to 180° and no cracks appear in the EP-USAW samples. In summary, the outstanding mechanical performance of WG-USAW and EP-USAW joints could contribute to the presence of acicular ferrite with interlocking structure in the welds, which prevent the crack propagation and dislocation movement during the joints undergo plastic deformation.

Vickers hardness distributions of the joints are shown in Figure 8. The average hardness of UWW weld is 155.2 HV, which is equivalent to that of the base metal. While the maximum hardness of CGR in HAZ, reaches to as high as 243.3 HV, as shown in Figure 8a. The hardness of WG-USAW weld fluctuates in a narrow range with average value of 160.7 HV, while the maximum value 223.6 HV of the HAZ still appears in the CGR, less than that of UWW, as depicted in Figure 8b. The hardness distribution of the EP-USAW joint is shown in Figure 8c, and the maximum values of weld and HAZ are 161.8 HV and 183.8 HV, respectively. It is worth noting that there is not much difference among the welds' hardness in the three methods, whereas the HAZ hardness of the UWW is the highest. Due to the rapid cooling rate in UWW, the degree of carbon diffusion is limited, which

promotes the production of supersaturated phase of carbon in the CGR, thereby increasing the hardness of HAZ. What is more, the HAZ hardness of the EP-USAW is the lowest compared with that of UWW and WG-USAW. The reasons for this are as follows. The mixture greatly reduces the cooling rate of HAZ by means of isolating the surrounding water from the welding area, which makes the carbon have more time to diffuse during the phase transformation stage, thus reducing the hardness of the HAZ in EP-USAW.

Table 4. Mechanical properties of the joints.

Welding Method	Sample No.	Elongation (%)	Ultimate Strength (MPa)
UWW	1	6.0	423
	2	6.8	413
	3	8.4	415
WG-USAW	1	9.2	445
	2	8.2	458
	3	7.5	442
EP-USAW	1	13.7	463
	2	12.7	463
	3	19.5	451

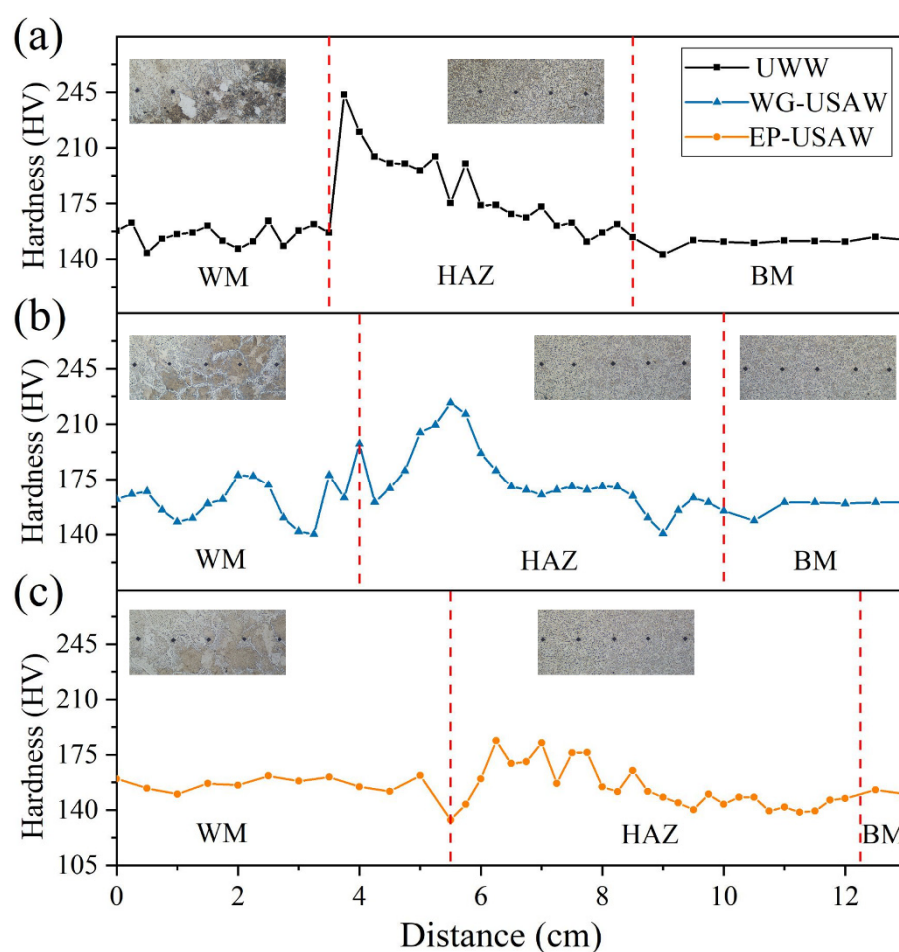


Figure 8. Vickers hardness distributions of welded joints. (a) UWW, (b) WG-USAW and (c) EP-USAW.

The average room temperature impact toughness values of the three joints are 40.4 J/cm², 53.2 J/cm² and 68.3 J/cm². The toughness enhancement of WG-USAW and EP-USAW joints can be attributed to not just the protection from the mixture and solid slag but also the microstructure optimization of weld metal. SEM results show that river-like patterns

occupy the fracture surface of impact samples in UWW, indicating a typical cleavage fracture mode, as shown in Figure 9a. Surprisingly, both river-like patterns and dimples are observed in the fracture surface of WG-USAW, as shown in Figure 9b. They are full of dimples with minor internal inclusions on the ductile fracture surface of EP-USAW, as marked in Figure 9c. EDS result shows that these inclusions are mainly composed of ferro and manganese oxides, as shown in Figure 9d.

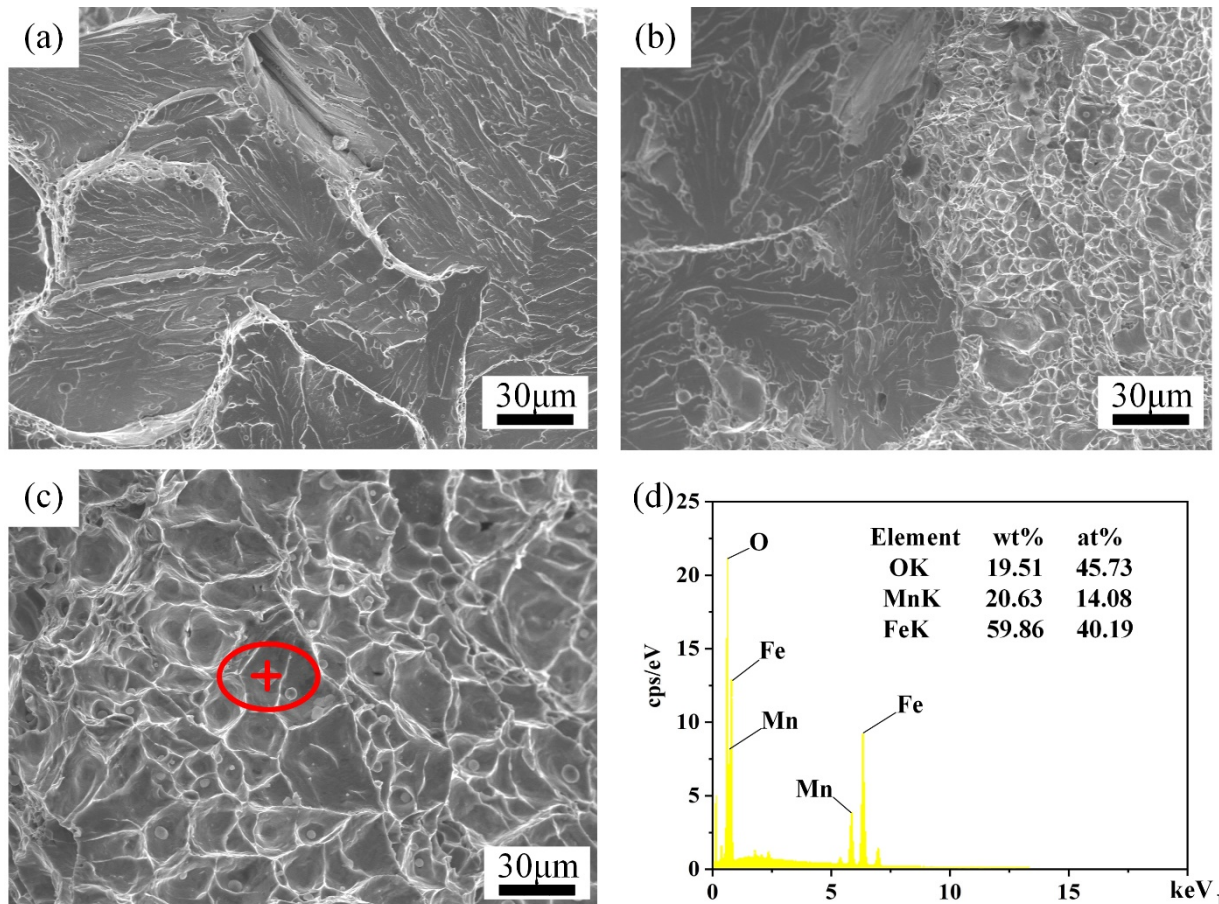


Figure 9. SEM fracture of the impact toughness tests. (a) UWW, (b) WG-USAW and (c) EP-USAW (d) EDS results of the inclusions.

4. Conclusions

In this investigation, the influence of the mixture added with water glass or epoxy resin on the process stability, microstructure and mechanical properties of joints have been explored. The main findings and conclusions are summarized as follows.

1. The addition of mixture with water glass significantly increases the process stability, weld penetration and ultimate strength, but deteriorates the weld formation, furthermore, the porosity of the joint is as high as 0.75%, which may hinder the comprehensive improvement in mechanical properties of the joint.
2. The epoxy resin in the mixture completely isolates the surrounding water from the welding area, which modifies the arc burning environment and welds formation, thus greatly improving the process stability.
3. Compared with the other two methods, the microstructure of the joints obtained by using the epoxy resin-containing mixture is filled with massive fine acicular ferrite, and the comprehensive mechanical properties are completely improved.
4. Compared with underwater wet welding, the joints' average elongation, ultimate strength and room temperature impact toughness of underwater submerged-arc

welding with the mixture of epoxy resin increased by 178.4%, 10.1% and 69.1%, respectively. The bending angle of the joint reaches to 180°. The HAZ maximum hardness is reduced by 24.5%.

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