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Microstructure and mechanical properties of ultrasonic assisted underwater wet welding joints

Q.J. Sun [a,b,*], W.Q. Cheng [b], Y.B. Liu [a,b], J.F. Wang [a,b], C.W. Cai [c], J.C. Feng [a,b]

[a] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, No. 92 West Dazhi Street, Harbin 150001, China
[b] Shandong Provincial Key Laboratory of Special Welding Technology, Harbin Institute of Technology at Weihai, No. 2 Wenhuaxi Road, Weihai 264209, China
[c] School of Information and Electrical Engineering, Harbin Institute of Technology at Weihai, No. 2 Wenhuaxi Road, Weihai 264209, China

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ABSTRACT

A new weld method, ultrasonic assisted underwater wet welding process (U-FCAW), was explored in order to achieve high performance welding joints. The addition of ultrasonic can form an acoustic field between the workpiece and the ultrasonic radiator. The joints were welded by ultrasonic assisted underwater wet welding process (U-FCAW) and underwater flux cored arc welding (FCAW), respectively. The effect of ultrasonic on the arc stability, microstructure and mechanical properties, such as tensile, bending and hardness distribution, was investigated. The results indicated that arc stability improved when ultrasonic was applied. The amount of martensite (M) and upper bainite (BU) was decreased, while the granular bainite (BG) and acicular ferrite (AF) increased, when ultrasonic was applied during welding. The tensile strength and the bending properties were substantially enhanced. The fracture occurrence of the welded joints during tensile testing was transferred from the joint to base metal, compared to FCAW. A 46% and 48% increase was found in the tensile strength of the upper and lower layers, respectively. The maximum angle during bending test was increased from 21° to 84°.

1. Introduction

Underwater wet welding is widely used in offshore industries such as marine construction, engineering pipelines repairing and nuclear power plants. It is performed in water without using any additional auxiliary equipment and has a lower cost compared to other underwater welding methods [1]. However, underwater wet welding has its limitations, mainly attributed to the poor arc stability and high martensite content, therefore, resulting to low tensile strength and poor bending resistance [2].

Previous studies on underwater wet welding have been focused on the metallurgical aspects of the welds, obtained with different compositions of the electrode rod, coating or waterproof materials [3–5]. Santos et al. developed the oxyrutile electrode for AWSD3.6 Class A welds, combining lower porosity and superior performance regarding toughness and ductility [6]. N. Guo et al. studied the effect of Ni on the microstructure and mechanical properties of underwater wet welded joints. It was found that the addition of Ni was helpful for suppressing the formation of the coarse strip PF in the columnar grain zone of the welded metal [7]. In addition, some researchers have attempted to use auxiliary equipment to improve underwater wet joint properties [8–9]. Fydrych et al. used the temper bead welding technique to improve steel weldability in water environment and decreased the maximum hardness of heat-affected zone of S355J2G3 steel joints from over 400 HV10 to below 350 HV10 [10]. H. T. Zhang et al. developed the real-time induction heating-assisted underwater wet welding method, decreasing the content of martensite and upper bainite (BU) phases and increasing the pro-eutectoid ferrite and acicular ferrite phases, thereby improving the mechanical properties of the wet welded joint [11]. Gao et al. proposed the grinding + underwater ultrasonic impact treatment (UUIT) method and improved fatigue performance by 61% to 217 MPa [12].

Ultrasonic assisted underwater wet welding was developed in this paper. Ultrasonic is a type of high frequency mechanical wave, which was widely used in traditional welding, operating in air and has a positive effect on welded joints. The weld microstructure was refined when ultrasonic wave was directly applied on the workpiece [13–16]. The welding arc was altered and the weld penetration increased when ultrasonic was used in TIG welding [17–19]. When ultrasonic was applied in GMAW method, the ultrasonic was applied on the metal transfer process by means of an acoustic field formed in air around the arc. The metal transfer frequency increased with the radiation force was brought into the metal transfer process [20–21]. Although ultrasonic assisted welding process performed in air conditions was examined by many previous studies, there is little discussion focused on the ultrasonic assisted underwater wet welding. Moreover, there are almost no reports on the effects of ultrasonic assisted underwater wet welding on arc stability and mechanical properties of welded joints, during real-

* Corresponding author at: Shandong Provincial Key Laboratory of Special Welding Technology, Harbin Institute of Technology at Weihai, NO.2 West Culture Road, Weihai 264209, PR China.

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time welding process. Water has higher density than air does, therefore, the ultrasonic wave would have a more effective propagation in water. Since the ultrasonic wave can generate a more effective acoustic field, the bubbles generated during wet welding process could stay for a longer time under the ultrasonic radiation force, which could therefore improve the stability of the arc in the bubbles. The microstructure and mechanical properties of welded joints could be improved as a result of the increased arc stability. Thus, ultrasonic assisted underwater wet welding should be comprehensively investigated to understand these effects on the underwater wet welded joints.

The aim of the present work is to study the ultrasonic assisted underwater wet welding (U-FCAW). In this study, E40 steel was welded by ultrasonic assisted underwater wet welding (U-FCAW) and traditional underwater flux cored arc welding (FCAW) respectively. The arc stability was studied and the microstructures of weld center and fusion zone are analyzed. The tensile and bending properties, and the hardness distribution were also investigated.

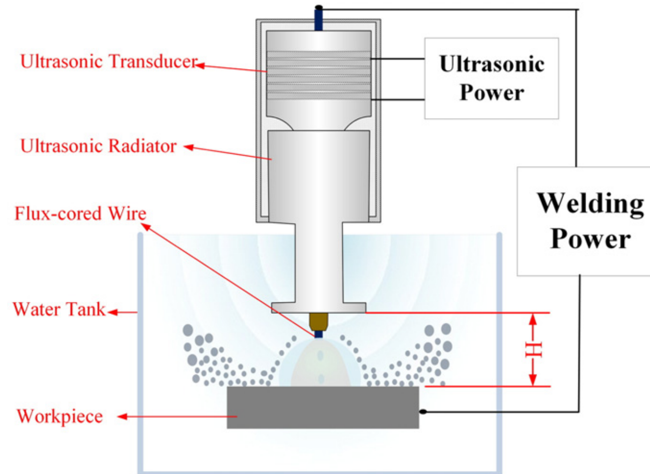

Fig. 1. Schematic of ultrasonic assisted underwater wet welding (U-FCAW).

2. Materials and experimental procedures

The base metal was E40 steel with dimensions of 200 × 50 × 8 mm. A single-V weld groove was performed with a 30° angle with a 2-mm root face and 2-mm root opening. The filler material was E81T1-ClA4-Ni2 of AWS A5.36, which the diameter is 1.2 mm. The chemical compositions of base metal and filler material are shown in Table 1.

The schematic of ultrasonic assisted underwater wet welding (U-FCAW) is shown in Fig. 1. The equipment includes a welding system, an ultrasonic system and a composite welding torch. The composite welding torch can be divided into an ultrasonic transducer, an ultrasonic radiator and a wire conductive rod. The ultrasonic transducer transforms electrical signals into ultrasonic vibration and the wavelength is amplified by the ultrasonic radiator. The ultrasonic wave emits from the bottom of the ultrasonic radiator. The welding wire is fed through the wire conductive rod, which is in the axial hole of the ultrasonic transducer and ultrasonic radiator.

The welding process was carried out by ultrasonic assisted underwater wet welding (U-FCAW) and traditional underwater flux cored arc welding (FCAW) under the same welding parameters. The welding current was 170 A and the arc voltage was 36 V. The welding process was performed in fresh water at a depth of 0.3 m. The ultrasonic frequency was set at 15 kHz. The radiation height (H) (the distance between the ultrasonic radiator and the workpiece) is an important ultrasonic parameter, related to the ultrasonic field. Ultrasonic assisted arc welding studies examined the effects of different radiation height (H) on ultrasonic field and welding quality in air conditions [17,20]. Hence, the result could show the effect of radiation height (H) on the arc stability and the process of weld formation, then, the optimum parameters can be selected.

The arc was obtained by a high speed camera (Olympus ISPEED3, Japan). The morphology of the microstructure of the fractured surfaces was observed by optical microscopy (Olympus GX51, Japan). The tensile and bending tests were conducted on a universal testing machine (WOW-50, China) with a capacity of 30 kN, at room temperature. The fracture analysis was performed by scanning electron microscopy (TESCAN VEGA) and the corresponding energy dispersive X-ray spectra were attached. The hardness tests were performed on a universal testing machine (HVST-1000Z, China).

Table 1
Chemical composition of base metal and filler material (wt.%).

	C	Mn	Si	P	S	Cr	Ni
E40	0.15	1.06	0.25	0.13	0.65	0.04	0.01
E81T1-ClA4-Ni2	0.058	1.06	0.34	0.012	0.0057	0.021	2.37

3. Results and discussion

3.1. Arc stability

The arc morphology was observed by a high-speed camera. Fig. 2 shows the method of image processing of the arc. A lower contrasted area is around the arc, as shown in Fig. 2(a). In order to achieve a clear welding arc, the iterative threshold method was developed to process the binary image. Fig. 2(b) is the arc image after processing. Fig. 3 shows the arc image of different radiation height (H) values. It can be observed from Fig. 3 that the FCAW welding is an unstable process. The arc that was affected by ambient water is relatively easy to extinguish, leading to a serpentine weld. However, the arc of U-FCAW welding process becomes more stable, especially when the radiation height (H) ranges from 50 mm to 70 mm, where the arc size actually decreases uniformly. The 'serpentine' phenomenon in the weld formation disappears when the radiation height (H) is lower than 70 mm. However, weld spattering increases as the radiation height (H) decreases. In underwater wet welding, the bubbles induced by water vapor and gases can isolate the arc from the surrounding water. The arc burn in bubble during welding process. The bubble is detached and rise up in the water periodically, due to the difference of gas and water densities, during the underwater wet welding process. Consequently, the arc extinguishes when the bubble detaches from the molten pool and the new bubble has yet not increased in size. Ultrasonic can provide an additional downward force, thus decreasing the detachment rate of the bubble. The time of instability is significantly decreased as a result of a lower arc extinguish rate. Arc stability is clearly improved with the use of ultrasonic and the weld formation has been improved at a certain height of the radiator (H) region.

3.2. Cross section parameters

Fig. 4 demonstrates the effect of ultrasonic radiation height (H) on weld geometry. The colorful bar in the image shows the average weld width, reinforcement and penetration of FCAW. The pink line describes the penetration that varies with ultrasonic radiation height (H). The penetration was substantially increased when the ultrasonic wave was applied in the underwater wet welding process. The penetration was increased up to 126% when the radiation height (H) was 20 mm. With the assistance of the ultrasonic, the arc extinction was decreased, a downward ultrasonic force and increased heat input lead to the increased penetration. The red line shows the weld width of different radiation height (H). Ultrasonic has some influence on weld width, which can increase it by 20% when the radiation height (H) is 20 mm. The blue line represents the reinforcement of the U-FCAW welded joint. Compared