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Investigation on dynamic behaviors of bubble evolution in underwater wet flux-cored arc welding

Jicai Feng[a,b], Jianfeng Wang[a,b], Qingjie Sun[a,b,*], Huanyao Zhao[b], Laijun Wu[b], Pengwei Xu[b]

[a] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China
[b] Shandong Provincial Key Laboratory of Special Welding Technology, Harbin Institute of Technology at Weihai, Weihai 264209, China

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ABSTRACT

Bubble evolution behavior has a significant effect on the process stability and weld joint quality in underwater wet flux-cored arc welding (FCAW). In this study the visual sensing of bubble evolution behaviors based on high-speed camera method have been explored in attempt to accomplish the study of the wet welding process. The effects of preset welding parameters on the bubble evolution behaviors are investigated in detail. Four typical bubble evolution modes during the wet welding process and their corresponding welding electric information are determined to describe the bubble behaviors along with arc characteristics. Results indicated that the bubble evolution of underwater wet welding is unstable and complicated, necessitating control by adjusting the welding parameters to obtain a more stable protective effect. And there is a matching relationship between the coefficient of variation, weld appearance and bubble evolution mode for certain welding parameters. For underwater wet FCAW, a stable welding process can be acquired with a lower floating frequency and a larger maximum diameter of the bubble without arc extinguishing.

1. Introduction

The increasing demand, for more and more metal structures serving in the sea, is favorable for exploring marine resources and conducting underwater activities. Considering the special service environment such as material fatigue, corrosion of sea water, excessive operational loads, and accident during assembly, maintenance and repair of offshore structures have necessitated research to accomplish some important requirements on underwater welding technology [1–3]. Actually, underwater wet welding is generally recognized to repair or even construct the most geometrically complex structures due to the simplicity of wet welding process without requiring additional mechanical protection equipment [4–6]. Unfortunately, since wet welding method is conducted directly in the water, the extreme conditions around the arc burning area caused by the water environment can cause a series of adverse effects. For example, the increased ambient pressure is prone to the existence of unstable arc burning [7,8]; the rapid cooling rate leads to the deterioration of the weld microstructure and final mechanical properties [9,10]; the oxidation of weld pool tends to cause it to generate more slag [11]; and the water dissociation accelerates the formation of detrimental porosity [12]. As a result, the above mentioned issues may deteriorate the welding process stability and resulting weld joint quality in underwater wet welding. The main reason causing these adverse effects is still attributed to the underwater wet welding process in direct contact with water. Hence, understanding the interaction mechanism of the complicated wet welding process and surrounding water has been strongly required and become one of the greatest challenges in underwater wet welding.

Early investigations are conducted mainly based on the metallurgical investigation and mechanical properties by using special methods in underwater wet welding. For example, Rowe et al. [13] reported that ferro-alloy additions were critical to improve the mechanical property of underwater wet weld. Similarly, Santos et al. [14] employed an oxyrutile electrode for the wet welding to obtain lower diffusible hydrogen content and excellent mechanical property. Sun et al. [15,16] suggested that ultrasonic-assisted wet welding was a promising way to obtain high-quality weld joints. Fydrych et al. [17,18] attempted to use temper bead welding technique to improve wet welding weldability of high strength steel,

* Corresponding author at: State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, 150001, China.
E-mail address: qjsun@hit.edu.cn (Q. Sun).

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thereby decreasing the maximum hardness of heat affected zone. Based on real-time induction heating, Zhang et al. [19] performed heat-assisted method in such a way as to decrease the cooling rate of underwater wet welded joint. Gao et al. [20] adopted the grinding + underwater ultrasonic impact treatment for improving the fatigue strength in the weld metal.

From the above studies, it is inferred that these methods have in part improved the weld joint quality based on metallurgical process. Furthermore, underwater welding process sensing has been recognized as an effective method for exploring the interaction mechanisms by the effect of harsh water environment. Spectroscopic study was already reported successfully to occur in underwater wet welding. Pan et al. [21] reported the underwater plasma was in local thermodynamic equilibrium using spectroscopic analysis under certain conditions. Spectroscopic study was also used to characterize the temperature of the underwater welding arc [22] and underwater arc plasma component [23]. Furthermore, Jia et al. [24] found the existence of H in the underwater arc plasma and spectral radiation was not affected by the water environment.

As far as the arc stability of underwater wet welding was concerned, there were many indices, such as dynamic characteristic, probability distribution, variation coefficients of current and voltage and voltage and current cyclorama, for the determination of arc stability [25,26]. They concluded that these indices certified the validity of assessing the arc stability in underwater wet welding. Tsai et al. [27] studied the rapid cooling and hydrogen embrittlement mechanisms in water, and claimed that the rapid cooling was mainly due to the surface heat conduction. By using three-dimensional finite difference method, Ghadimi et al. [28] investigated and analyzed the temperature profile, cooling time as well as thermal history curves of underwater wet welding. Visual sensing was also used as an arc physics investigation to assist underwater wet welding [29–31]. In Guo et al's study [29,30], the clear metal transfer process of underwater wet welding was successfully monitored by an X-ray transmission method. Applying the laser emitter method as backlight, Zhang et al. [31] also observed the images of molten droplets and analyzed the difference between the onshore welding and underwater wet welding. Their analysis results showed that the droplet was significantly repelled by the effect of the gas flow drag force, owing to the disturbances from the bubbles, and the drifting cathode jet force.

However, due to the particular feature of underwater wet welding, the welding arc burning and metal transfer process as well as weld pool behavior proceed in the periodically varying bubble around the welding area [32]. Consequently, the perturbation of the bubble is the key factor adversely affecting the stability of welding arc and metal transfer process due to the upward motion of the bubble [29,33]. All the issues mentioned above have a close relation with the dynamic behaviors of bubble evolution which has distinct characteristics in underwater wet welding, as a result of the special arc burning atmosphere. So the study of bubble evolution process has great significance in underwater wet welding. With the limit of the author's searching capability, although amounts of literatures are available on the improvement of welding process stability [34–39], only few of the studies have been reported so far to reveal the mechanism of the occurrence and influence of bubble evolution process in underwater wet welding. Tsai et al. [27] predicted the underwater bubble dynamics mathematically and concluded that heat loss in wet welding was closely related to the agitation of the rising gas bubble. Jia et al. [40] obtained the clear images of the bubble and displayed the bubble evolution process during underwater wet welding by high speed video camera along with dysprosium lamp. They found that the bubbles play a significant role in protecting the welding area and reflect the complex interactions in arc behavior, metal transfer, and weld pool solidification, whereas, the correlation of the bubble between the surrounding water and welding parameters could not be reflected.

Unfortunately, the mechanism of the occurrence and influence of bubble evolution process and correlating the welding parameters with bubble evolution process in underwater wet welding have not been revealed so far very well. Further, it has reached a consensus basically that studying how to control the bubble evolution process coupled with arc characteristic in order to design and optimize the bubble protective effect is of great importance for the further development of underwater wet welding technology. This study carries forward from the observation method developed by Jia et al. [41] to focus on the study of dynamic behaviors of the bubble evolution in underwater wet welding, and elaborate on the mechanisms of interaction between welding parameters and bubble evolution process. By using the high-speed camera method combined with their corresponding welding current and arc voltage waveforms, different bubble evolution modes are analyzed and classified in underwater wet welding. The influence of bubble evolution modes on weld appearance is further investigated to determine the optimal bubble evolution mode and control the bubble evolution behaviors.

2. Experimental procedure

2.1. Welding system

Bead-on-plate welding experiments were conducted at 0.5 m water depth in the experimental pool. E40 steel plate with 8 mm-thick was used as base material. Commercial CHT81Ni2 type self-shielded flux cored wire with a diameter of 1.2 mm was chosen as electrode material. A welding power source, Lincoln Electric® Power Wave® S350, was employed to generate sufficient heat source for fusing the electrode material and substrate. In this study, a constant-voltage mode was used to keep the arc voltage constant during welding. The welding process was conducted with direct current electrode positive (DCEP) conditions in all welds. Prior to welding, the E40 steel plates were cleaned to remove any contamination. When welding, all welds were developed in the flat position with a stationary welding torch and a welding table controlled to move at a speed of 1.5 mm s^{-1}, which allowed the high-speed video camera to keep stationary with respect to the bubble. From the point of view of controlling the bubble evolution, arc voltage and wire feed speed are the two main parameters having the greatest effects. Table 1 shows the welding parameters used in this paper.

2.2. Synchronous acquisition system of high-speed images and electrical signal

In order to investigate the relationship between bubble evolution and welding electrical signal, the welding electrical signal acquisition system and high-speed video camera system are established successfully at first, and then a synchronous operation system is realized, as illustrated in Fig. 1.

The high-speed video camera system consists of a high-speed camera (Olympus I-SPEED3) used for recording bubble evolution process with a sampling frequency of 2000 frams per second, and a background light source located at the other side of water tank opposite to the camera. In order to capture good contrast images of the bubble evolution process, a dysprosium lamp with a diameter of about 0.5 m was used as background light and projected towards the bubble. A background light blocked by the bubble cannot be visually viewed by camera, leading to the formation of a shadow image on the image screen.

The welding electrical signal acquisition system is composed of a Hall voltage sensor (LV 25-P), a Hall current sensor (HAC 800-S),