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Characterization of the underwater welding arc bubble through a visual sensing method

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ABSTRACT

To evaluate the effectiveness of arc bubble, the influences of controllable arc bubble on the process stability and microstructural evolution of welded joint under different welding conditions were investigated. The main welding conditions, including onshore welding, conventional underwater wet welding (UWW) and mechanical constraint assisted UWW (MC-UWW), were characterized and compared. The exerted mechanical constraint resists the arc bubble detachment and keeps the larger arc bubble attached to the weld pool surface for providing better protective effect of welding region. The adverse effect of surrounding water with its higher heat conduction is not negligible compared with onshore welding, and the mechanical coupling between arc bubble and constraint device plays a vital role in affecting the arc stability and joint quality. Microstructure analyses revealed that under the same welding parameters, the proportion of brittle microstructure in weld metal follows the order: UWW > MC-UWW > onshore welding. A more stable wet welding process can be realized by controlling the arc bubble detachment, which provides a new orientation for wet welding technique application.

1. Introduction

Underwater wet welding (UWW) has proven to be an effective way to join metals permanently under water, and it is established that the repair and maintenance of engineering products and marine constructions contain welded joints as demonstrated by Rogalski et al. (2017). The working principle of UWW process is well documented. In welding, the filler materials (flux-cored wire or coated electrodes), directly exposed in the water environment, contact with the workpiece and are then heated by means of energy produced by the passing of electric current in the form of resistance heat. In the heating stage, the flux in the filler materials are melted and the surrounding water is ionized or vaporized, to form the necessary shielding atmosphere. In this case, the bubble around the welding area, defined as arc bubble, is generated in the workpiece surface. Omajene et al. (2014) pointed out that arc bubble periodically forms, grows, rises up, breaks away and is generated again due to the difference in density of water and gas. Next is the arcing stage where the welding arc is ignited inside the bubble. In this stage, workpieces are mixed with filler materials at atomic scale and melted, to form a weld pool that upon solidification becomes a reliable and permanent welded joint. Although the UWW process offers low cost and simplicity of the process over other underwater arc welding method, the unstable burning of welding arc may occur during departure of the arc bubble, and poor joint quality is an important issue in wet welding process, as reported by Teng et al. (2017). If unsolved, the poor joint with defects can act as weak sites which could lead to the rapid fracture from the accident during assembly as demonstrated by Padilla et al. (2013), as well as offer favourable sites for premature failure via fatigue as revealed by Pessoa et al. (2006). Because of this, the improvement of welded joint quality is widely reported and have been an active subject of research for several decades, according to Gao et al. (2016).

Early experiments were focused on favourable metallurgical investigation by formulated consumables or using various auxiliary energy methods. Rowe et al. (2002) demonstrated the existence and importance of ferro-alloy additions in underwater wet welds during solidification. Santos et al. (2012) then adopted an oxyrutile electrode method for the wet welding of structural ship steels. Their results indicated superior mechanical property and lower diffusible hydrogen content. Fydrych et al. (2015) used a mercury displacement method for determination of diffusible hydrogen amount in underwater wet welding and found the relations between welding polarity, welding current, water salinity and diffusible hydrogen amount of deposited metal. Furthermore, modifying the composition of electrode coatings,

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such as, adding one or more of nickel (Pope et al., 1996), boron (Liu et al., 2017), rare earth metal (Kandavel et al., 2012), manganese (Surian, 1997), molybdenum (Silva et al., 2013), as well as titanium (Beidokhti et al., 2009) to the electrode coatings, is an alternative method to improve the microstructure and mechanical properties of weld metal by controlling the metallurgical characteristics. Recently further optimization of weld physical process and mechanical performance in wet welds derived by the development of a new variant of the UWW process where auxiliary energy method was applied. Fydrych et al. (2016) highlighted the importance of temper bead welding (TBW) technique on basic of the substantial reduction in the hardness of heat affected zone (HAZ). Wang et al. (2017) observed microstructure refinement and performance enhancement in hull structure steel under ultrasonic vibration solidification. Zhang et al. (2015) utilized heat-assisted method to decrease the cooling rate of underwater wet welds during solidification. In addition, Sun et al. (2016) utilized an ultrasonic exertion similar as Xie et al. (2016) in the wet welding of E40 steel. Keenan (1993) attempted to place thermal insulation adjacent to the fusion line in the underwater wet welding. The results showed the improvement of weld quality which was attributed to the reduction in the cooling rate. With respect to the above favorable effects, these methods have in part improved the joint quality and other associated phenomena based on metallurgical process. Due to the technical problems associated with arc bubble (namely the non-visibility of their images) by Zhang et al. (2016b), there are, however, only few studies mentioned above which highlight the importance of arc bubble in underwater wet welding.

Recent years have witnessed the sustained development of the UWW process based on arc bubble analysis. Tsai and Masubuchi (1979) investigated the underwater bubble dynamics, boundary heat loss and heat input mechanism. They concluded that the heat loss in the weld pool region was probably due to the agitation of such dynamic bubble growth. As such, if the minimum bubble volume became large enough to protect the weld pool zone, a reduction of cooling rate could be obtained as revealed by Guo et al. (2015b).

Furthermore, Guo et al. (2015c) utilized a X-ray transmission method to observe the metal transfer mode of underwater wet flux-cored arc welding, and found that a mixed mode of repelled globular transfer and short circuit transfer was observed for a certain welding parameters. In a follow-up work, Guo et al. (2016) found that the bubble also had an important influence on the metal transfer by making a gas flow drag force to the droplet in the direction of bubble floating. Guo et al. (2015a) also evaluated the wet welding stability analysis to further understand the protective bubble effect, and found that larger bubble size was favorable for stabilizing the welding process. Jia et al. (2016) found that the periodically evolving bubbles had an inevitable impact on the arc behaviour, and deduced that the drifting arc cathode caused the arc drifting and deviation. Further, Guo et al. (2015d) examined that bubbles floating obviously increased the resistance for metal transfer and the droplets tended to be repelled to generate a repelled spatter.

Moreover, Oliveira et al. (2013) studied on correlating the bubble phenomena with electrical signals in underwater wet welding and found a possible relationship between the bubble detachment and the variation in welding current. However, the clear images of the above mentioned bubble they provided are generally difficult to recognize as evidence by using the observation of traditional visible light method or x-ray transmission, which seriously limits the further development in the field of underwater wet welding process. Based on high-speed camera with a dysprosium lamp backlighted shadowgraphic method, Jia et al. (2016) obtained the clear images of arc bubble and reported that understanding the interaction mechanisms in the arc behaviors, metal transfer and bubble evolution contributed to improving the wet welding process stability. Feng et al. (2017) studied the evolution of dynamic bubble in underwater wet welding. They found that the dynamic bubble around the arc burning zone seemed to be unstable and had a strong effect on the process stability. However, the above studies only focused on the dynamic behavior of arc bubble and its associated phenomena, but did not pay attention to the influence of controllable arc bubble on the underwater wet welding process.

This investigation carries forward from the visual sensing analysis of clear arc bubble developed by Jia et al. (2014). A sustained deficiency in understanding the underlying mechanism for the controllable arc bubble and metallurgical process has driven further experimental efforts towards the development of the existing phenomena. To address this, here the influences of controllable arc bubble on the process stability and microstructural evolution of welded joint under different welding conditions, including onshore welding, conventional UWW and mechanical constraint assisted UWW (MC-UWW), were investigated. In particular, the differences under different welding conditions are highligted and explained by bubble evolution, arc stability analysis, weld geometry characteristics and microstructure analysis, which will lead to a better and more effective design in applications involving arc bubble evolution during underwater wet welding.

2. Experimental procedure

2.1. Imaging acquisition system

To investigate the relationship between the arc bubble and process stability in different welding conditions, the high-speed video camera system and welding electrical signal acquisition system are established successfully as illustrated in Fig. 1.

The high-speed video camera system consisted of an Olympus i-SPEED 3 high-speed camera used for capturing the images of arc bubble with a sampling frequency of 2000 fps (frames per second), and a background light source. In order to record good contrast images of arc bubble, a dysprosium lamp backlighted shadowgraphic method was used to provide background light. The dysprosium lamp mirror was about 0.5 m in diameter which was much larger than the size of the arc bubble. A background light blocked by the welding wire and arc bubble can not reach the camera. Hence, a shadow image of the welding wire and arc bubble on the image screen could be imaged and stored in a computer.

The welding electrical signal acquisition system mainly consisted of a LV 25-P Hall voltage sensor, a HAC 800-S Hall current sensor, a USB6221 data acquisition card with the maximum sampling frequency of 100 kHz and a computer. The welding current and arc voltage waveforms could be acquired by the Hall sensor during the wet welding process. On this basis, the data acquisition card and computer could process the welding electrical signal and store the instantaneous datas of welding current and arc voltage, which could be on-line monitored and off-line analysed.

2.2. Materials and welding procedure

Bead-on-plate welding experiments were prepared in the onshore welding, UWW and MC-UWW processes. Underwater wet welding was carried out at 0.5 m water depth (fresh water) in the water tank. Fig. 2 shows the schematic of the MC-UWW setup. As shown in the Figure, the setup consisted of a wet welding torch and the mechanical constraint system. The key part of mechanical constraint system was the brass cylinder with thickness 6 mm and diameter 30 mm, which was connected to a teflon cylinder (fixed to wet welding torch). The distance between the workpiece surface and lower surface of brass cylinder was 12 mm throughout the experiments so that better mechanical constraint effect on the arc bubble was achieved during the wet welding process. The wire stick-out used in the conventional UWW process and in MC-UWW process were the same and both 16 mm, which implied that the conductive nozzle did not extend from the axial hole of the brass cylinder. The wet welding torch and welding wire were fed through the axial hole of 12 mm diameter drilled through the two cylinders.