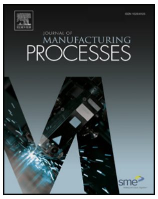
Journal of Manufacturing Processes 34 (2018) 238–250

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



Analysis and improvement of underwater wet welding process stability with static mechanical constraint support

Jianfeng Wang[a,b], Qingjie Sun[a,b,*], Yunlu Jiang[c], Tao Zhang[b], Jiangkun Ma[b], Jicai Feng[a,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
[c] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

ARTICLE INFO

Keywords:
Underwater wet welding
Mechanical constraint
Arc voltage
Arc stability
Weld morphology

ABSTRACT

A process variant of underwater wet welding (UWW), i.e., mechanical constraint-assisted UWW process, was developed. Through the visual sensing of arc bubble and welding electrical signals, the optimum parameters of mechanical constraint system were determined. Variations of arc stability, arc burning process, and weld morphology with arc voltage were investigated under the same mechanical constraint condition. Results indicated that the coefficients of variation for the two processes initially dipped to a minimum and then gradually increased to a higher value with increasing arc voltage, but the change rate of variation coefficient in UWW was much more pronounced than that in mechanical constraint-assisted UWW (MC-UWW). When the arc voltage was lower, the proportion of short circuiting process was so high. Thus, there was room for further reduction by mechanical constraint. But the further reduction room became still effective when the arc voltage was larger because the proportion of arc extinction process was already large enough. Weld morphology results showed that the increment of weld penetration decreased from 0.91 mm to 0.18 mm with the increase of arc voltage when mechanical constraint was applied. In addition, the increment trend was very significant when arc voltage was within the range of 20 V to 28 V. For the welding conditions in this study, a suitable voltage range in conjunction with optimum mechanical constraint condition can be determined to achieve a more stable welding process in MC-UWW.

1. Introduction

As the exploitation of onshore energy tends to be saturated and the resource shortage is increasingly intensified, the marine industry becomes the inevitable choice for human to seek new energy supplies. At present, the technology for the exploitation of marine resource has witnessed rapid development, and various supporting technologies and equipment are changing rapidly with each passing day, which greatly promotes the deepening development of marine activities [1]. Hence, there is a big demand for underwater welding technology for the repair and maintenance of offshore structures with high quality [2,3]. Due to the direct contact with water, underwater wet welding (UWW) shows great advantages in process simplicity and cost saving because it doesn't require any additional protection equipment such as hyperbaric vessel [4–6]. However, conventional UWW still has some limitations, especially unstable arc burning process as well as the deterioration of microstructure and mechanical properties [7–9], which restricts the further application of UWW process.

To overcome these problems, researchers elaborated on the working principle of UWW process. In welding, the flux from the filler material (flux-cored wire or coated electrode) is melted and the surrounding water is vaporized or ionized, creating a protective space for the welding zone. Subsequently, the arc bubble is generated from the decomposed flux and vaporized or ionized water [10]. Next is the arcing stage where arc burning process is able to proceed in the arc bubble. Considering the difference in density of water and arc bubble, arc bubble can periodically form and detach when detachment force is larger than retention force. In addition, the size, shape and dynamic behavior of the arc bubble are constantly changing and periodically rupturing. With bubble detaching from the welding zone, the welding process can be badly impacted by the poor bubble protection and water invasion [11]. Incomplete arc burning process is also inevitable [12]. As a result, the perturbation of the arc bubble features an adverse effect on UWW process. Hence, revealing the interaction mechanism of the dynamic arc bubble and complicated welding process is strongly required and still faces a big challenge in UWW.

Owing to the inherent property of underwater wet welding, the arc burning process, droplet transfer, and weld pool solidification work in

---

[*] 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).

https://doi.org/10.1016/j.jmapro.2018.06.007
Received 4 March 2018; Received in revised form 21 May 2018; Accepted 6 June 2018

the dynamic arc bubble [13]. Many papers have focused on the arc bubble effect on process stability in underwater wet welding. Tsai and Masubuchi [14] analyzed the relationship of dynamic underwater bubble and heat loss, and found that heat loss in weld pool was affected by the oscillation of the rising bubble. In addition, more rising bubbles in the unit time caused more arc heat to be taken away, leading to the reduce in arc temperature [15]. Jia et al. [16] reported that the evolving bubble was closely related to the arc behavior, and inferred that the arc deviation was a result of the drifting arc cathode. Some investigations also attempted to correlate the process of bubble evolution with welding electrical signals [17,18]. A possible relationship between the bubble evolution and electrical signal variation was established. Further, it was found that larger bubble volume contributed to stabilizing the welding process [19]. In Guo et al.'s study [20,21], the clear metal transfer process was observed using an X-ray transmission method. Zhang et al. [22] also monitored the metal transfer process by applying laser emitter method as backlight. Their analysis results indicated that the generation of repelled transfer mode in underwater wet welding was mainly caused by the drifting cathode jet force and the gas flow drag force in the direction of bubble floating due to its perturbation [16]. It was also noted that if the force was too large, the molten droplet was inclined to be repelled from the weld pool to produce a spatter [23]. The water flow was also a crucial factor influencing the bubble detachment and the resulting process stability [24]. Great progresses have been achieved in the bubble dynamic effect on the wet welding process. However, most of the previous reports are only available on the dynamic behavior of arc bubble and its associated effect, but the requirement for arc bubble control is especially critical.

The control of arc bubble may become a promising method in underwater wet welding. Recently researchers have developed some modified UWW processes based on this idea. Guo et al. [19] evaluated that the protective effect of arc bubble changed with arc voltage. Feng et al. [18] reported that welding parameters had a strong effect on bubble volume. They found that bubble volume was dynamically increased with the increase of arc voltage and/or welding current but within limits. Although the process stability is improved to a certain extent by increasing bubble volume through changing welding parameters, simply enhancing the arc voltage and/or welding current may lead to the increase in welding heat input. In this case, the improper microstructure and mechanical properties can be badly damaged by high heat input. Sound joint with superior process stability and acceptable mechanical properties is difficult to be obtained by modifying welding parameters. Meng et al. [25,26] reported a local cavity method made on the both sides of weld bead and the floating of arc bubble was obviously restricted. Clukey [27] provided a suggestion that utilizing a deep narrow groove in UWW process which might help form a stable welding process. Sun et al. [28] and Wu et al. [29] developed an acoustic-control arc bubble method in UWW process where ultrasonic effect was exerted on arc bubble. The ultrasonic wave interacted with the arc bubble, the latter was limited to floating, and the process stability was improved. Although the control of arc bubble can be realized with the aid of these measures, there is still plenty of room for improvement on the basis of previous researches, such as high equipment cost, low visibility of welding area, and high operation difficulty. Effective control of arc bubble without perturbation is still a big challenge. Hence, the design of a simple and practical, easy-to-use welding method is of great significance in order to achieve the control of arc bubble.

In our previous work, mechanical constraint-assisted UWW (MC-UWW) was established to evaluate the effectiveness of arc bubble through a visual sensing method [30]. The brief research showed that the MC-UWW process contributed to the good weld appearance and the enhanced weld penetration. In addition, the controllable arc bubble by mechanical constraint was found to be attached to the welding region for providing a better protective effect. In the present study, the MC-UWW was introduced to improve the process stability by combining the optimum mechanical constraint condition and varying arc voltage, which is widely used in practical manufacturing. Moreover, conventional UWW process was set the same task for a comparison between the two processes and highlighting the advantages of the MC-UWW process. The standard of the mechanical constraint was evaluated through the visual sensing of arc bubble and welding electrical signals. Combined with the mechanical constraint, the relationships among arc stability, arc burning process, weld morphology and various arc voltages were analyzed in detail. Results presented in this study aid in understanding the mechanism of arc voltage influence on process stability in MC-UWW.

2. Experimental procedure

2.1. Welding system

Bead-on-plate welding experiments were conducted at a depth of 0.5 m in freshwater. E40 steel was chosen as base material with gauge dimension of 200 × 100 × 8 mm. The filler metal was CHT81Ni2 self-shielded flux cored wire with the diameter of 1.2 mm. MC-UWW experiments were carried out in bead-on-plate weldment, as the schematic diagram and the actual assembly device shown in Fig. 1. The key element was the mechanical constraint system that was placed before the welding operation. The system was composed of a brass cylinder and a teflon cylinder, which were connected with each other through a screw thread. The welding torch was fed through the axial hole drilled through the two cylinders, through which the welding wire can be ignited with workpiece for welding. Then the mechanical constraint system was fixed to the welding torch through a screw thread. The angle between the assembly device and workpiece is maintained 90°, in order to ensure the better mechanical constraint effect on the arc bubble during the wet welding process.

In the experiments, the diameter of brass cylinder (*D*) and the height between the workpiece surface and the lower surface of brass cylinder (*H*) were controllable parameters for evaluating the degree of mechaincal constraint on arc bubble. The optimum parameters would be ditermined in Section 3.1. After determination, the effects of arc voltage with and without mechanical constraint on arc stability and weld morphology were investigated systematically. Six different arc voltages, 20 V, 24 V, 28 V, 32 V, 36 V and 40 V, were used and two types of welding processes with and without mechanical constraint were realized; 12 experiments were implemented and compared in this paper. The wire stick-out distance in all the experimental groups was 16 mm. The detailed experimental parameters used in this paper are shown in Table 1. In this study, the welding power source, Lincoln Electric® Power Wave® S350, was employed and worked in constant-voltage mode during welding. The welding process was operated in direct current electrode positive condition for all welds. Before welding, the

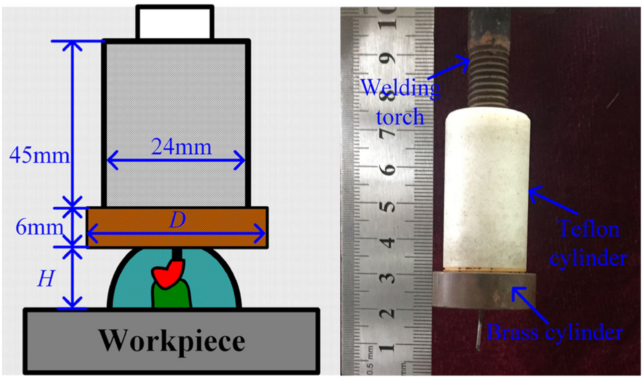


Fig. 1. Schematic view of the mechanical constraint assisted underwater wet welding.