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Characterization of spatter in underwater wet welding by X-ray transmission method

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ABSTRACT

The spatter forming mechanism of underwater flux-cored wire wet welding is characterized by using a self-developed X-ray transmission system. Three representative spatter modes, droplet repelled spatter, explosive spatter and molten pool shock spatter, forming during underwater wet welding have been observed. The generation of droplet repelled spatter is due to the excessive repulsive forces for metal transfer. The diameter of this type of spatter is largest relatively, which can reach about 4.5 mm. In addition, explosive spatter, with size about 2.5 mm, is changed from the droplet with high horizontal speed caused by a slight explosion occurs at the touching location of the droplet and molten surface. Moreover, the dimension of molten pool shock spatter is smallest potentially among the spatter types during underwater wet welding, and it is only about 0.8 mm. It is generated from ridgy liquid column on the molten pool surface because of the relatively severe concussion of the molten pool. The size, macroscopic pattern as well as chemical composition of these three types of spatters are different.

1. Introduction

Underwater welding is widely used in the repair and maintenance of marine constructions such as submerged pipelines, offshore oil platforms, nuclear power plants as well as harbor devices [1–3]. Underwater welding techniques can be divided into two main types, wet and dry method. When comes to the wet method, the welding process is conducted directly in the water without any complicated device. Therefore, it is exceedingly easy for wet welding to implement for complex structures, and its cost is extremely low. It is noted that the flux-cored arc welding (FCAW) is the most commonly used underwater wet welding technology because of the potential for high deposition rates and adaptation to automated equipment. Considering the flux-cored wire arc welding, metal transfer, which describes the liquid metal flow that occurs from the welding consumable to the workpiece during the welding process, is crucial for mass transfer process. There are abundant studies which argue that metal transfer has decisive effect on the welding arc stability, weld formation and welding quality [4–7]. There is a vital occurrence that characterizes metal transfer in arc welding, which is called spattering [8]. The so-called spatter is defined as particles of molten metal expelled from the wire tip or the molten pool during welding. Therefore, welding spatter itself, which is nothing more than liquid metal droplets, is essentially the same regardless of welding process [9,10]. It should be stated that all spatter must be removed by means of some process such as grinding if the final appearance of the weld is important. The removal of this spatter takes time which thus increases the cost of the weld. In addition, previous studies have emphasized that spatter can also cause important metallurgical problems such as corrosion pits, micro-cracks at the spatter base material interface, and slag [11]. To sum up, welding spatter not only increases the welding cost, but also deteriorates the welding quality and stability. Therefore, lots of researches have been carried out to study the welding spatter in various welding techniques, and most of them focus on the mechanism of spatter production and reducing the spatter loss coefficient. Liao et al. have studied the spatter in gas metal arc welding (GMAW), and the main factor causing the spatter is maybe the bridge explosion, discontinuous globular repelled process as well as the misalignment of droplets transfer [12]. Chen et al. explained the mechanism of spatter production in the short-circuiting mode of metal transfer. It is shown that spatter is mainly generated due to CO gas explosion at the instant the short circuit breaks [13]. Li et al. observed two spatter types about droplet deviated spatter and droplet rebounded spatter during dry hyperbaric GMAW process, and explored the relationship between ambient pressure and welding spatter mode [14]. Kang et al. examined the welding spatter in short circuit transfer region, and a model for estimating the amount of spatter has been developed [15]. Although there have been many studies concerning welding spatter, almost all of these researches are just conducted for on-land welding, and few of the works are related with the welding spatter of underwater wet welding because of its more complex generation process. In fact, the shortage of suitable methods and equipment for these works is the main reason

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for this issue. Due to the method of high-speed photography can provide the images of the whole spatter process, so this convenient and visual analytical tool always employed by most of the researchers to analyze the spatter process with a visible light back-lighted shadow graphic method [8,9,16–18]. However, it is very different to control and apply the visible light in underwater environment because it will be reflected and refracted by the surrounding water. Therefore, the traditional method is not able to achieve clear images of the welding spatter during underwater welding. In this experimental study, a pioneering method is introduced to obtain precise spatter images of underwater wet welding. Basing on the images of welding spatter, the typical spatter characteristics of underwater wet welding have been studied, which is expected to bring some instrumental guidance in developing underwater wet welding process.

2. Experimental procedure

The base metal prepared for this experiment is Q235 mild steel with dimensions of 200 mm × 60 mm × 15 mm. The welding material is a rutile type self-shielded flux-cored wire with diameter of 1.6 mm. Moreover, an automatic control platform for underwater welding, SAF-FRO DIGI@WAVE500 welder and a set of matched automatic wire feeding system are used in this experiment. The water depth of experimental tank is 0.5 m. Welding polarity of direct current electrode positive (DCEP) is used during experimental welding and the welding voltage is 28 V, the current is 210 A with the 1.5 mm/s welding speed.

Because of the shorter wavelength than visible light, X-ray can traverse relatively thick objects without being much absorbed or scattered. Therefore, this unique property can help X-ray to overcome the adverse effect of the water surrounding and capture clear images of the spatter process during underwater wet welding. Successfully, a set of X-ray imaging system has been developed for imaging the spatter process during underwater wet welding, which consists of a micro-focused X-ray tube (HAMAMATSU MFX9181-02), an image intensifier (SIEMENS HIDEQ23) and a high-speed camera (OLYMPUS I-SPEED 3). X-ray tube voltage and beam current used during the experiment are 120 KV and 1 mA, respectively. The field of view is 9 in, and the focus size is 0.4 mm. The bit depth of the camera is 10 bit, and the spatial resolution of the imaging system is 30 LP/cm. The frame rate of high-speed camera is 2000 f/s. The schematic of the system is shown in Fig. 1. The optical path of X-ray is perpendicular to the welding direction. The width of the water tank is 200 mm, and the distance between X-ray source and image intensifier is 300 mm. The clear images of spatters have been obtained from welding experiments by using this X-ray imaging system. According to these X-ray images, the size of the spatter particle is measured. After underwater wet welding, the spatters are gathered and classified base on their size and energy dispersive spectrometer (EDS) is used to explore the compositions.

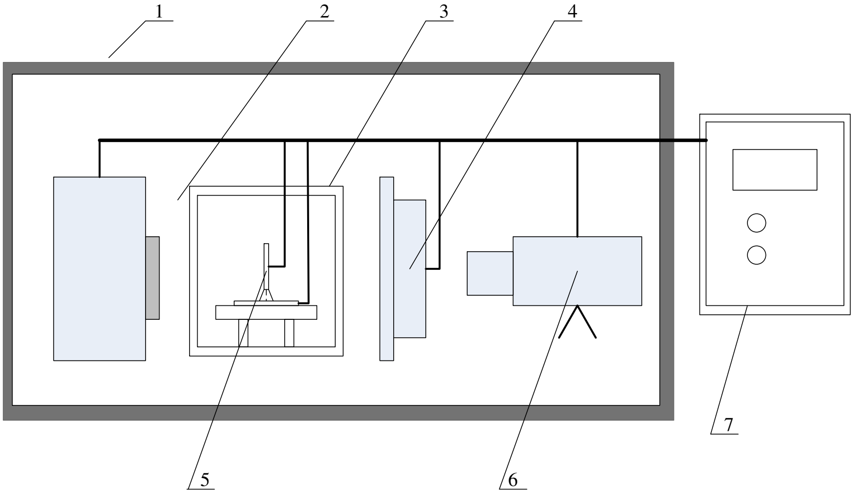
3. Results and discussion

During underwater wet welding, three typical spatter forming modes can be identified through observing the high-speed images of welding spatter process. They are droplet repelled spatter, explosive spatter and molten pool shock spatter. The specific forming process and mechanism of these spatter modes are all as follows.

3.1. Droplet repelled spatter

Fig. 2 gives a typical forming process of droplet repelled spatter. From 0.1815 s to 0.1970 s (frame a–b of Fig. 2), the droplet grows on the tip of the wire, and is repelled from the wire axis by the repulsive forces. At 0.1990 s (frame c of Fig. 2), the droplet detaches from the wire end, but does not transfer axially to the weld pool. On the contrary, as shown in the images of 0.2080 s–0.3525 s (frame d–f of Fig. 2), it moves upwards vertically, and is away from the molten pool gradually. As a result, this droplet is changed into the repelled spatter, and the average diameter of this kind of spatter is approximately 4.5 mm.

Considering the underwater wet welding, the droplets will be acted by gravitational (G), plasma drag force (F_1), electromagnetic force (F_e), surface tension (F_s) and the vaporization force (F_a) during the whole process of initiation and growing up on the tip of the wire. Generally, electromagnetic force (F_e), surface tension (F_s) and the vaporization force (F_a) are the retention forces on the droplets, but gravitational (G), plasma drag force (F_1) act as the driving forces of the droplets transferred. It should be noted that a particular gas flow drag force that can't be ignored in underwater wet welding process. Due to the underwater wet welding arc burns in a bubble induced by the water vapor and the gas generated by the decomposition of core ingredients of the welding wire, so the droplets also grow up in the bubble. The difference of density of gas and water invariably makes the bubbles detach and rise up in the water periodically. Consequently, the upward motion process of the



1-Plumbum shielded room 2-Micro-focused X-ray tube
3-Experimental tank 4-Image intensifier
5-Welding wire 6-High-speed camera
7-Control cabinet

Fig. 1. Schematic of X-ray imaging system.