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# Effect of hydrostatic pressure on protective bubble characteristic and weld quality in underwater flux-cored wire wet welding

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ABSTRACT

The metal transfer and protective bubble images, real-time electric signal data and weld appearance were obtained in different simulated water depth wet flux-cored arc welding. The electric signal results showed that the high hydrostatic environment deteriorated the stability of the wet welding process. The poor weld appearances with porosity were displayed when it was welded in deep water. The weld dilution rate descended from 51% to 40% with increasing water depth from 0.5 m to 90 m because of arc shrinking and heat input reduction. The reduction of protective bubble size and duration caused by high water pressure was unable to maintain a stable burning arc. With increasing water depth, the increase of pores in welds strongly deteriorated the mechanical property of joints. The process of gas generation and its escape from the droplet during the droplet transfer were observed. The rise of pressure compressed gas pores and prevented the gas from escaping, which resulted in the increase of pores.

## 1. Introduction

Underwater welding has been widely used in the repair and maintenance of marine constructions such as submerged pipelines, offshore oil platforms as well as harbor devices. It was universally recognized that underwater welding can be classified into dry welding, local cavity welding and wet welding. Li et al. (2017) pointed that the wet welding, especially underwater wet flux-cored arc welding (FCAW), was applied widespreadly in the construction and repairing of offshore steel structures due to its easy operability and extremely low cost. According to Scotti et al. (2012) and Pires et al. (2007), the metal transfer process played a key role in welding quality owing to the importance of its effect on welding arc stability, molten pool behavior and weld formation. Therefore, the further study of the droplet transfer phenomenon is very important for the development of a welding technique. A stable arc is required to obtain high-quality welds during underwater wet welding.

Guo et al. (2015) indicated that the arc burning and droplet transfer occurred in the bubbles which were induced by water vapor and gas generated by the decomposition of core components in the welding wire. Wang et al. (2017) reported that the extreme conditions around the arc burning area and bubbles caused by the water environment such as the increased hydrostatic pressure, the rapid cooling rate and the water dissociation could cause a series of adverse effects. For instance, Łabanowski (2011) suggested that the increase of pressure would deteriorate the arc stability and increase the loss of alloying elements. Terán et al. (2014) pointed that rapid cooling rate caused the imperfection of weld microstructure and the deterioration of the weld mechanical properties. Ozaki et al. (1977) found that the water dissociation accelerated the formation of detrimental porosity. It was obvious that the increased hydrostatic pressure with depth of water was a crucial factor that influenced the welding process stability and quality. To achieve a reliable implementation of the welding process under hyperbaric environment, it is necessary to conduct a further research about the welding arc and metal transfer behavior in these conditions.

However, the researches of metal transfer and arc stability under hyperbaric environment were mainly focused on dry welding. Allum (1982) pioneered the study of hyperbaric TIG welding, and reported that the TIG arc voltage increased with the increase of ambient pressure while the welding current and arc length were maintained constantly. Suga and Hasui (1986) proved that the erosion of the electrode tip increased as the GMAW arc burning in the simulated hyperbaric chamber. Enjo et al. (1989) studied the MIG welding arc behavior of 0–6 MPa in Ar atmosphere and found that the arc became unstable with the increase of ambient pressure. It's worth noting that many spattered droplets and fine particles were produced as the pressure increased. Fostervoll et al. (2009) suggested that the DCEN mode was more suitable to ensure the arc stability in the dry hyperbaric GMAW. Azar et al.

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(2012) pointed that more energy was required to stably burn arc and successfully transfer droplets into the weld pool at high pressures. In addition, according to the research published by Li et al. (2014), a novel spatter generating process, named as droplet rebounded spatter, often occurs when the ambient pressure was over 0.4 MPa. They proved that the electromagnetic force was the driving force of droplet to be rebounded. Zhou et al. (2008) studied the arc static characteristics of gas tungsten arc welding under high ambient air pressure. They found that the arc gradually contracted but remained stable as the pressure increased from 0 MPa to 0.7 MPa. Jia et al. (2013) analyzed the spectrum of arc plasma and proved that H atoms became involved due to the decomposition of water. Świerczyńska et al. (2017) reported that the growth of the welding current, arc voltage and salinity of the water caused a decrease of diffusible hydrogen content in deposited metal.

Up to now, a clear description of the underwater welding metal transfer and arc stability under hydrostatic atmosphere have not been reported yet. Therefore, the experimental platform was built to conduct experiment of underwater wet welding under several water depths. The metal transfer and arc stability were studied by X-ray imaging technology and welding electrical signal acquisition technology. The effects of hydraulic pressure on protective bubble phenomenon and on weld imperfections were explained in this study.

## 2. Experimental procedure

The underwater flux-cored wet welding process was conducted in the hyperbaric chamber, which was designed to simulate the underwater hydrostatic environment, as shown in Fig. 1(a). For safety and operability, the internal pressure was designed to change between 0.1 and 2.1 MPa. The 5xxx Aluminum alloy was adopted as the material of the hyperbaric chamber because of its relatively well weldability and low density. So, the energy attenuation could be reduced as much as possible when the X-ray penetrated the chamber. In addition, as illustrated in Fig. 1(b), the experimental platform also included regulating gas storage, automatic welding control system, welding power source, X-ray imaging system and electric signal acquisition system. Thereinto, X-ray imaging system consisted of a micro-focused X-ray tube, an image intensifier converting the X-ray transmitted image to the visible image and the high-speed camera. Optronis CR series high-speed camera operating at 1000 fps frame rate and 256 × 256 resolutions was used. The welding current and voltage signals were acquired in real time by Hall sensors and data acquisition cards at a frequency of 10 kHz.

Welding torch, wire feed system, motion platform and workpiece were set inside the chamber. Low-alloy steel plates (Q235) with dimensions of 120 mm × 60 mm × 16 mm were used as the base metal for bead-on-plate welding. The V-groove with 45° was prepared on 120 mm × 60 mm × 11 mm EH40 plates in the V-groove welding. The schematic of joint to be welded is shown in Fig. 2(a). Welding with DCEP polarity was conducted in a water tank which was set in the chamber. The chamber was filled with the pressurized air to simulate a hydrostatic pressure environment. In this study, five sets of welding experiments were designed to explore the influence of hydrostatic pressure environment on protective bubble characteristic and weld imperfection during underwater wet welding. The hydrostatic pressure environment of 0.5, 30, 50, 70 and 90 m were simulated respectively. A rutile type self-shielded flux-cored wire with diameter of 1.6 mm was used and wire feed speed was set on 6 m/min. The distance from contact tip to workpiece and welding speed were 15 mm and 3 mm/s, respectively. Considering the arc shrinking due to high pressure, the welding voltage was set as 45 V to succeed the arc.

The droplet transfer and bubble characteristic were evaluated by analyzing consecutive frames of the video during the welding process. The sizes of droplet and bubble could be obtained with the known diameter of wire (1.6 mm). In the same way, the mean velocity of bubble rising could be calculated from its generation to collapse. The X-ray nondestructive testing images as well as cross-section of welded joints were acquired to evaluate weld imperfections. Transverse tensile and Charpy V-notch impact test were conducted to evaluate the mechanical properties of welded joints. Fig. 2(b) and (c) display the types and dimensions of the specimens for the weld metal mechanical properties evaluation. The extracted location of mechanical specimens is displayed in Fig. 2(d). Transverse tensile test was conducted using a universal testing machine (Instron 5967) with the speed of 5 mm/min. Charpy V-notch impact test were carried out at room temperature. In mechanical properties tests, each data point represented an average of at least three to four specimens. Finally, the fraction surfaces of welded joints were observed using the scanning electron microscope (SEM, MERLIN Compact, Zeiss).

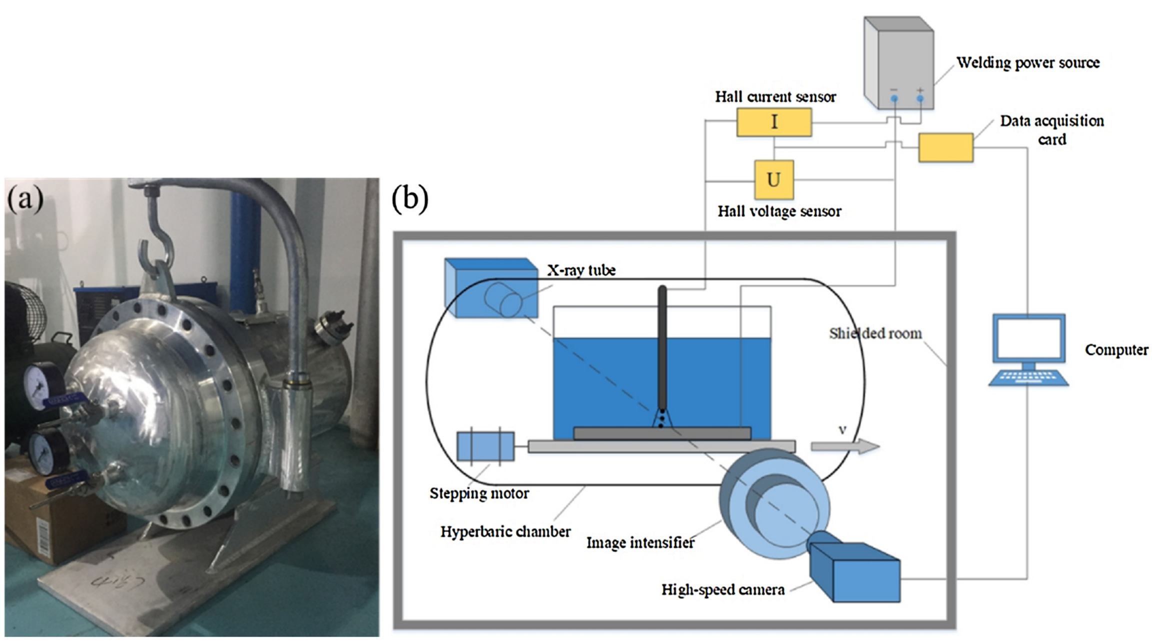


**Fig. 1.** The setup of welding system: (a) the hyperbaric chamber, (b) the schematic of the synchronous acquisition system of X-ray image and electrical signal.