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# Study of underwater wet welding stability using an X-ray transmission method

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ABSTRACT

The effects of arc voltage on the stability of the underwater wet flux-cored arc welding (FCAW-S 114) process are explained based on studying the droplet transfer process using the X-ray transmission method. The mode of metal transfer and the protective bubble effect, which vary with voltage, affect the stability of the welding process. The results indicate that there is a critical arc voltage (32 V). When the arc voltage is less than 32 V, an unstable welding process occurs because of the high proportion of short-circuit transfer and limited bubble size. Increase in the arc burning zone must be protected, and the proportion of repelled metal transfer caused by the high arc voltage decreases the stability of the welding process. In this study, stable welding process is acquired when the proportion of repelled metal transfer is less than 20%, the short circuit frequency is lower than 1 Hz and the bubble diameter is larger than 24 mm.


## 1. Introduction

The wet welding process, which is a widely used underwater welding technology, is conducted directly in water without the use of any additional engineering vessels, complex chambers or shielding gases. The simplicity of the wet welding process allows even the most geometrically complex structures to be welded. According to Richardson et al. (2002), underwater wet flux-cored wire welding process, which is suitable for automatic welding processes conducted in deep water, has considerably higher production efficiency than that of underwater manual metal arc welding. The special operating environment is hypothesized to have a significant effect on the arc behavior, metal transfer, welding metallurgy and welding stability. Therefore, it is necessary to develop an effective method and statistical model for quantitatively estimating arc stability during the underwater wet flux-cored wire welding process. Until recently, substantial efforts have been devoted to studying the welding stability of various welding technologies. The research methods applied in these studies include welding spatter evaluation, acoustic emission signal, electric signal analyses and the visual sensing method.

Modenesi and De Avelar (1999) demonstrated that welding stability and the weight of the spatter generated during welding exhibit similar behavior. An estimation model that can accurately represent arc stability by calculating the amount of spatter was developed by Kang and Rhee (2001). Wagner et al. (2013) studied the gas metal arc welding (GMAW) process using controlled short-circuiting to control the amount of spatter. Roca et al. (2007) analyzed the stability of GMAW processes based on the acoustic emission generated by the arc. Chu et al. (2004) investigated the relationship between short-circuiting frequency and process stability by analyzing the arc voltage and current. Luksa (2006) studied the stability of welding arcs by monitoring the GMAW process. Based on measurements of the time-varying welding current and arc voltage, Suban and Tušek (2003) described several methods for determining arc stability in GMAW. Ghosh et al. (2009) used the optical method to study the behavior of metal transfer. Modenesi and Reis (2007) acquired droplet images using high-speed video photography.

The spatter evaluation method can only be performed after the welding process and is not suitable for real-time monitoring. Recording the instantaneous values of acoustic emission signals during the welding process can be used to estimate arc stability in real time. However, the acoustical method requires an extremely quiet work environment. Given the conditions under which underwater wet flux-cored wire welding process is performed, it may be difficult to monitor the acoustic emission signals generated in

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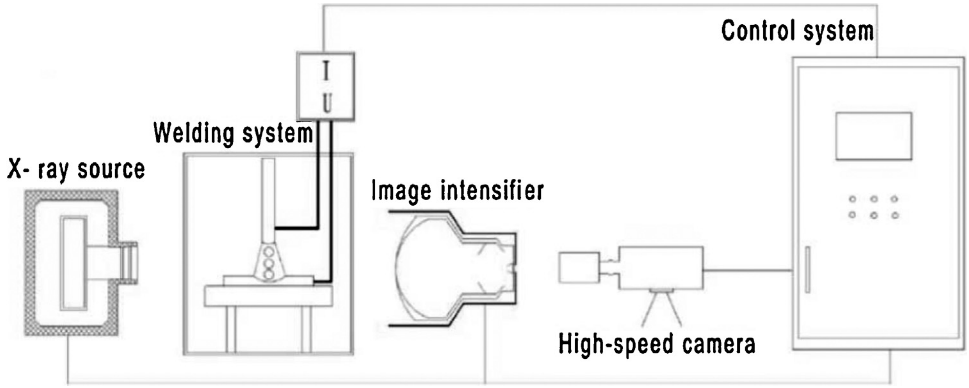


**Fig. 1.** Schematic of X-ray imaging system.

water. Metal transfer and welding stability can also be analyzed using high-speed videography via the laser back-lit shadowgraph method. Vision-based sensing can provide direct information on the frequency and size of droplets. However, due to the presence of water, Liu et al. (2000) demonstrated that acquiring images of the welding arc and metal transfer can be influenced by weld fumes, light absorption, refraction and reflection. During an underwater wet flux-cored wire welding process, the shape of the bubbles is always irregular and globular with rippled walls, as determined using the laser-back-lit shadowgraph technique, and the shape of the arc is blurred and rarely observed. Consequently, the traditional optical method is difficult to apply when investigating arc physics.

Thus, most studies on underwater welding stability have focused on the analysis of electric signals. The coefficient of voltage variation was used as an index of stability by Gretsky and Maksimov (2004) to investigate the efficiency of introducing activating additives into the composition of underwater flux-cored arc wet welding flux wire. Vilarinho et al. (2013) calculated the welding stability index using information obtained by analyzing the arc voltage during an underwater wet flux-cored wire welding process. In a study on underwater shielded arc welding, the mean values of current (I) and voltage (V) and their respective standard deviations ($\sigma$I and $\sigma$V) were used by Mazzaferro and Machado (2009) to calculate the inverse of their relative standard deviations and thereby assess arc stability.

However, information obtained from electrical signals is inadequate for characterizing the stability of the welding process. It is necessary to analyze the welding process using a vision-based sensing method. Because X-rays traverse relatively thick objects without being absorbed or scattered, they can overcome the adverse effect of the surrounding water and can thus be used to capture clear images of metal transfer in underwater welding processes.

In this study, the welding stability, which is represented by the variation coefficient of electrical signals, is investigated. Using an X-ray-based optical method, the stability trend is explained by a metal transfer model and bubble characteristics. The optimal welding parameters are determined for the filler material used in the experiment.

## 2. Experimental procedure

A schematic of the X-ray imaging system used in this study is shown in Fig. 1, which consists of a micro-focused X-ray tube, an image intensifier, which converts the X-ray transmission image to a visible image, and a high-speed camera. X-ray transmission images were captured by the camera (i-Speed) at a frame rate of 2000 f/s. The welding power source was SAF-FRO DIGI@WAVE500, which was operated with a constant wire feed speed and in constant-voltage mode. The filler material was a $TiO_2$-$CaF_2$-CaO-$SiO_2$ slag system self-shielded flux-cored wire with a diameter of 1.6 mm. Low-alloy steel plates (Q235) with dimensions of 200 mm × 60 mm × 16 mm were used as the base metal. Welding with DCEP polarity was conducted in a water box at a water depth of 0.5 m. The welding current and voltage signals were acquired in real time by Hall sensors and data acquisition cards at a frequency of 10 kHz/s. All of the welding parameters are shown in Table 1.

**Table 1**
Welding parameters.

| Processing parameters | Details |
|---|---|
| Polarity | DCEP |
| Welding process | FCAW-S(114) |
| Contact tip-to-work distance | 20 mm |
| Welding position | 1G |
| Arc voltage | 24,26,30,32,34,38,40,42V |
| Wire feed speed | 5 m/min |
| Travel speed | 1.5 mm/s |
| Water type | Fresh water |
| Water depth | 0.5 m |

The surfaces of the samples were cleaned with acetone prior to welding. Eight sets of experiments were designed to explore the effect of the arc voltage using high-speed video photography during the flux-cored wire welding process. The droplet behavior was evaluated by analyzing consecutive frames of the video during the welding process.

## 3. Results

The mean voltage and standard deviation thereof during the welding process at different preset arc voltages were calculated. Therefore, the coefficient of voltage variation, which was used to characterize arc stability, could be defined as the quotient of the standard deviation and the mean. The current signal was processed in the same way to obtain the coefficient of current variation.

Fig. 2 presents the evolution of the coefficient of voltage variation and the coefficient of current variation at different values of arc voltages. The results indicate that the coefficient of current variation increases with increasing voltage when the preset value is greater than 32 V. When the arc voltage is less than 32 V, the coefficient of current variation decreases with the increasing of arc voltage. Notably, the behavior of the coefficient of voltage variation is extremely similar to that of the current. Furthermore, the figure shows that the change in the coefficient of voltage variation is more pronounced than that of the coefficient of current variation.

A decrease in the coefficient of variation indicates an increase in the stability of the welding process. The welding quality is affected by the stability of the welding process, which can be ver-