Experimental and Numerical Investigation on Underwater Wet Welding Of HSLA Steel

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1. Introduction
Underwater wet shielded metal arc welding (SMAW) has been widely applied for many years in the repair of vessels and warships, offshore platforms, submarine oil and gas pipelines, etc., especially for the water depth less than 100 meters. The advantages of underwater wet welding (UWW) are the following: lower cost, higher welding speed and good maneuverability compared to open-area dry welding [1-3]. Its main drawback, however, is the decrease of the ductility and impact toughness resulting from rapid quenching of the weld, and hydrogen induced cracking resulting from dissociation of free hydrogen by some acids generated by interaction of shielding gases and high temperature vapor. It is well known that thermal cycles in the welding process significantly affect the microstructures, hardness, welding stress and strain in the welded joint [4, 5]. Therefore, investigation of the thermal cycles in UWW process is critical since the cooling condition is quite different from that of dry welding.

In the present study, underwater wet welding of typical HSLA steel was conducted using SMAW method under different water temperatures. The microstructure and hardness distribution in the welded joint was analyzed. The temperature distribution and thermal cycles in the welding process were analyzed based on finite element analysis. The effects of water temperature on the microstructure, hardness distribution and welding thermal cycles were clarified.

2. Experimental
The base metal employed is a normalized 8mm-thick S355 steel. The specimens were prepared with dimensions of 250×80×8 mm. Underwater bead-on-plate welding was conducted using shielded metal...
The specimens were examined first to detect welding defects. Subsequently, they were mechanically polished and etched with 2% natal solution. Weld geometry parameters were obtained by examination of the cross-sections of the weld beads. Microstructures of each test specimen were analyzed by means of optical microscopy. The Vickers microhardness test was conducted using a constant load of 200g and 15 seconds dwell time. The weld appearance under two water temperatures is presented in Fig. 1 and weld bead geometry parameters are summarized in Table 2. The microstructures in the welded joint are presented in Fig. 2 and Fig. 3.

From Fig. 2 and Table 2, it can be seen that the weld bead width of 5°C water temperature is narrower than that of 22°C water temperatures, while the reinforcement height increases when the water temperature decreases due to the faster cooling in the cold water. From Fig. 2 and Fig. 3, it can be seen that microstructures in the cold water is finer than that in the water of 22°C. For the 5°C water temperature, the microstructure in weld metal (WM) consists of grain boundary ferrite, ferrite side plate (FSP), polygonal ferrite (PF) and acicular ferrite (AF). The microstructure in the fusion zone (FZ) mainly consists of coarse lath martensite (LM) with different oriented packets. The microstructure in the coarse-grained heat affected zone (CGHAZ) is also characterized by lath martensite, but with fine parallel laths compared to that in the FZ. The fine-grained HAZ (FGHAZ) reveals a predominantly fine polygonal ferrite microstructure with a small amount of pearlite.

The microhardness distribution across the welded joint is shown in Fig. 4. It is observed that the highest hardness appears in the fusion zone and the HAZ. This can be explained by the predominant microstructure of coarse lath martensite. The hardness level of 5°C water temperature specimen is higher than that of 5°C water temperature, because the lower water temperature results in higher cooling rate and quenched microstructures with high hardness.

### Table 1. Chemical composition of the base metal (wt, %).

|   | C  | Si | Mn  | S  | P | Ni | Cr |
|---|----|----|-----|----|---|----|----|
|   | 0.14 | 0.4  | 1.36 | 0.003 | 0.010 | 0.010 | 0.022 |

### Table 2. Weld bead geometry parameters.

| Water temperature $T_w$(°C) | Weld bead width $B$(mm) | Weld bead penetration $H$(mm) | Reinforcement height $h$(mm) |
|-----------------------------|-------------------------|------------------------------|------------------------------|
| 5                           | 9.9                     | 4.0                          | 3.2                          |
| 22                          | 13.6                    | 3.1                          | 2.1                          |

Figure 1. Weld appearance under two water temperatures: (a) 5°C water temperature, (b) 22°C water temperature.
Figure 2. Microstructures in the welded joint with 5°C water temperature: (a) WM, (b) FZ, (c) CGHAZ, (d) FGHAZ.

Figure 3. Microstructures in the welded joint with 22°C water temperature: (a) WM, (b) FZ, (c) CGHAZ, (d) FGHAZ.
3. Numerical simulation
To investigate the thermal cycles and relative characteristics in UWW process, finite-element based (FE-based) numerical calculation was conducted to predict the temperature distribution and its evolution. Transient heat transfer analysis was carried out and temperature field under different water temperatures was analyzed using SYSWELD FE analysis software. Firstly, a three-dimensional (3D) model was created for accurate simulations with the dimension of 250 mm×80 mm×8 mm. In view of calculating precision and efficiency, the non-uniform meshing was used in modeling, with the density being higher for the weld metal and HAZ, and progressively reducing towards the edges of the plates. For 3D FE modeling and analysis, hexahedral elements were used which contains 32640 nodes and 38590 elements. Figure 5 shows the modeling of the welded joint and corresponding meshing. Goldak double ellipsoid heat source [6] was applied in the simulation to capture the heating effect of the welding arc and achieve high consistency with the practical situations in the UWW process due to the deep penetrations of the experimental welds.

The condition within heat outfluxes in the UWW process is very different than in open-area welding (OPW), because in some regions of HAZ, the vaporization of surrounding water and particularly in a region surrounding the center of arc beam is so intensive that welding pool almost has no contact with the surrounding water. Therefore, the heat exchange from weld metal and HAZ is almost the same as in the case of welding in open-air above water.

Temperature distribution in the UWW process and in open-area welding is shown in Fig. 6. It can be seen that peak temperature in 22 °C open-area welding is the highest (2585 °C), while the peak temperature (2422 °C) in 5 °C UWW is the lowest. This phenomenon can be explained by the faster cooling rate in water than in air without water, and the lower water temperature results in lower temperature level.

Comparison of thermal cycles in corresponding positions in the weld metal for UWW 22 °C and open-area welding 22 °C is shown in Fig. 7(a). The peak temperature in open-area dry welding is 2584 °C, higher than that in UWW process (2433 °C). The difference in the heating rates is slight, while difference in the cooling rates is visible. Cooling rate in UWW process is faster than that in open-area dry welding. A lower water temperature results in a faster cooling rate in the cooling process. Effect of water temperature on welding thermal cycles is shown in Fig. 7(b). It is observed that lower water temperature (5 °C) results in lower peak temperature and faster cooling rate compared to that of 22 °C UWW.

![Figure 4. Hardness distribution in the welded joint with different water temperatures.](image1)

![Figure 5. FE Meshing of the UWW welded joint.](image2)
Figure 6. Temperature distribution in the process: (a) 5°C underwater welding, (b) 22°C underwater welding, (c) 22°C open-area welding.

Figure 7. Thermal cycles in the weld metal: (a) comparison between UWW and OPW, (b) comparison between two water temperatures.

4. Conclusion

(1) The weld bead width of decreases with reduced water temperature, while the reinforcement height increases.

(2) Microstructures in water with lower temperature are finer that in the water of 22°C. The microstructure in FZ and CGHAZ are mainly lath martensite for both cases.
(3) The temperature distribution in UWW process shows a smaller weld pool contour than that of open-area welding process. The peak temperature in UWW process is lower than that in open-area welding, while the cooling rate in UWW process is faster than that in open-area welding.

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