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Effect of cooling rate on microstructure, inclusions and mechanical properties of weld metal in simulated local dry underwater welding

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ABSTRACT

Quenched and tempered E550 steel was joined using flux-cored arc welding. The effect of cooling rate on microstructure, inclusions and mechanical properties of the weld metal was investigated by optical microscope, scanning electron microscope, transmission electron microscope and mechanical testing. Results show that weld metal microstructures consist of proeutectoid ferrite, ferrite side plate and acicular ferrite. As the cooling rate increased, the volume fraction of proeutectoid ferrite and ferrite side plate decreased, acicular ferrite increased accompanied with refined grain. Furthermore, inclusions of Ti, Mn oxide with diameter below 2.0 μm were found in the weld metal and rapid cooling rate causes distinct Mn-depleted zone between inclusions and matrix. Excellent balance of high strength and toughness is obtained as more acicular ferrite in weld metal with rapid cooling rate. This can attribute to the increased of acicular ferrite with its refined grain and high density dislocation. These findings suggest that the rapid cooling rate can improve the impact toughness and tensile strength of weld metal in local dry underwater welding.

1. Introduction

Low carbon quenched and tempered (Q&T) E550 steel is mainly used for ships and offshore engineering high strength structure. Its excellent strength and toughness enable the structures to become lightweight and have longer service life [1–3]. However, it is prone to structure damage due to its special service environment such as offshore platform withstand the erosion of sea water, impact fatigue of tide, etc. Sometimes, these damages are required for underwater welding repair. So, obtaining excellent balance of high strength and toughness is urgent need for weld metal in offshore repair using local dry underwater welding. And the quality of weld metal is closely related to the welding thermal cycle, especially the cooling rate [4]. The microstructure of weld metal of high strength low alloy (HSLA) steel usually contains acicular ferrite, proeutectoid ferrite and ferrite side plate [5]. Generally, the phase transformation sequences of HSLA steel carbon content below 0.09% may be described as follows [6–9] (see Fig. 1): as the weld pool region is heated to temperatures as high as 1900–1600 °C (Fig. 1a), the dissolved oxygen and deoxidizing elements in liquid steel react to form complex oxide inclusions. In the temperature range 1530–1400 °C (Fig. 1b), solidification to δ-ferrite starts and envelops these oxide inclusions; and this δ-ferrite transforms to austenite. In the temperature range from 1400 to 850 °C (Fig. 1c), austenite grain growth occurs. In the temperature range 850–680 °C (Fig. 1d and e), proeutectoid ferrite nucleates at the prior γ–γ boundaries and grows by a diffusional mechanism and eventual coverage of these boundaries. With continued cooling to the temperature range 700–550 °C (Fig. 1f), ferrite side plate nucleates at the proeutectoid ferrite or austenite boundaries and extends into the untransformed austenite grain interiors. Further cooling to around 500 °C (Fig. 1g), the acicular ferrite would nucleate on the inclusions located in the austenite grain interiors and grow in needle form. On further cooling to room temperature, any remaining austenite may completely or partially transform to martensite. This mixture of martensite–austenite phases is referred to as M–A constituent. Generally, the acicular ferrite microstructure with excellent combination of strength and toughness is becoming a favorable microstructure [10]. Fine acicular ferrite containing high density of dislocations is the expected microstructure in weld metal. High-angle boundaries among ferrite laths act as obstacles to resistant the propagation of weld cracks, forcing cleavage crack to change the microscopic path of propagation [6]. Zhang et al. [11] studied weld metal microstructure and properties of HSLA S690QL steels at various cooling rate and found that excellent Charpy toughness was obtained with acicular ferrite as predominantly microstructure. Sarma et al. [12] analyzed acicular ferrite from the point view of inclusions characteristics and concluded that complex inclusions (oxy-sulfides and multi-phases inclusions) are more active nucleation sites for acicular ferrite. Four kinds of mechanisms for acicular ferrite nucleation have been summarized as follows

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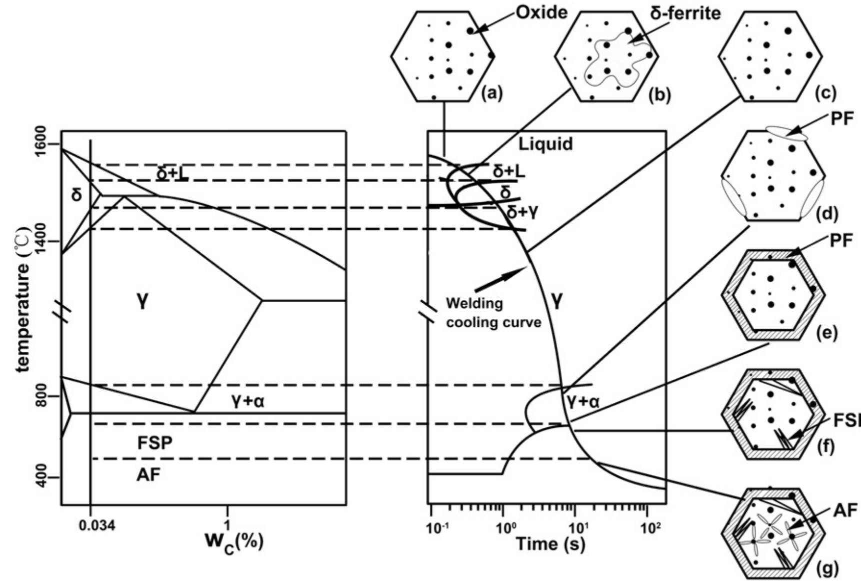

Fig. 1. Schematic illustration of HSAL weld metal phase transformation at continuing cooling condition. Note: AF: acicular ferrite; PF: proeutectoid ferrite; FSP: ferrite side plate.

Table 1
Chemical composition (wt.%) of Q&T E550 steel and deposited metal.

Element	C	Mn	Si	P	S	V	Ni	Cr	Mo	Cu	Fe
Q&T E550	0.11	1.30	0.18	0.013	0.003	0.04	0.37	0.32	0.31	0.19	Bal.
Deposited metal	0.034	1.24	0.37	0.011	0.005	0.01	0.45	0.03	0.01	/	Bal.

[9,12,13]: (1) inclusions act as inert surfaces leading to a reduction of activation energy; (2) a low mismatch strain between the inclusion and ferrite; (3) a depletion of alloying elements Mn and Si; and (4) thermal strains between the inclusion and the matrix.

During local dry underwater welding, a drainage device is used to make a dry area in the surface of workpiece for welding. This method ensures the flexibility of operation and higher quality of welding joints compared to wet underwater welding. In local dry underwater welding, its cooling rate is neither different with wet underwater welding, nor different with land welding. However, there are few systematic and in-depth studies on weld metal microstructure and mechanical properties under this condition.

In this research, efforts have been put out to investigate the effect of cooling rate on microstructure and mechanical properties of E550 steel weld metal. The results will be available for determining welding procedure and as a reference for E550 steel in local dry underwater welding.

2. Experimental procedures

The chemical compositions and mechanical properties of the used E550 steel and deposited metal of E71T-1C-J flux-cored wire are listed in Tables 1 and 2, respectively. The microstructure of E550 steel shown in Fig. 2 is tempered sorbite at room temperature. It composes of equiaxed ferrite and fine granular carbide particles distributed in the ferrite. The dimensions of the test plates used in this investigation are 1000.0 × 500.0 × 26.0 mm. Details of the weld joint are given in Fig. 3. Considering the rapid cooling will increase weld metal strength, low strength matching scheme was adopted in the E550 steel welding.

As shown in Fig. 4, a sink full of water have been manufactured and test plates were located under the water 100 mm. A dry area (500 × 300 mm) was surrounded by baffles for welding. During welding, the water in the sink is cycling in order to simulate the flow state of seawater. After that, three test plates were welded on land in order to evaluate the effect of water cooling. A shielding gas of pure CO_2 with the gas flow rate 15–20 L/min was used. Thermocouples are inserted into weld pool to record the thermal cycle, and $t_{8/5}$ time is measured to represent the cooling rate. Heat input can be calculated using

Table 2
Mechanical properties of Q&T E550 steel and deposited metal.

	Yield strength/MPa	Tensile strength/MPa	Elongation/%	A_{KV}(−40 °C)/J
Q&T E550	605	670	22	≥220
Deposited metal	505	560	28	118

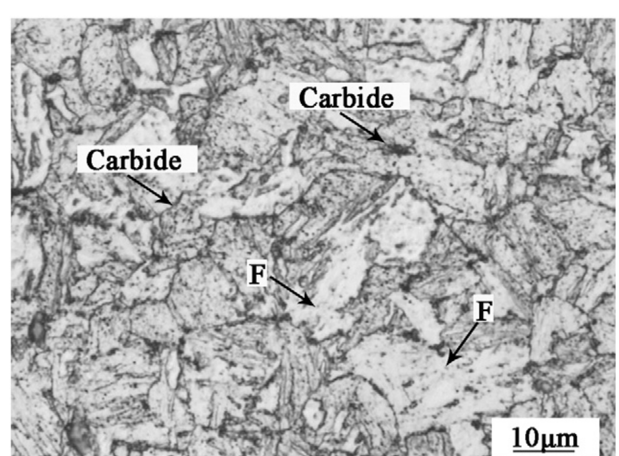

Fig. 2. Microstructure of E550 steel under optical microscope.