Welding Thermal Simulation and Corrosion Study of X-70 Deep Sea Pipeline Steel

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Abstract: Gleeble thermomechanical processing machine was used to simulate coarse grain heat affected zone (CGHAZ) of API X-70 thick wall pipeline steel used in deep sea. Microstructures and corresponding corrosion behavior of the simulated CGHAZs using different cooling rate were investigated and compared to the as-received material by scanning electron microscope and electrochemical experiments carried out in 3.5 wt. % NaCl solution. Results of this study show that the as-received samples exhibited a little bit higher corrosion resistance than the simulated CGHAZs. Among 3 sets of simulation experiments, the maximum corrosion tendency was exhibited at the $t_{8/5} = 20$ s with the most martensite-austenite (M-A) microstructure and highest corrosion potential was shown at the $t_{8/5} = 60$ s.

1. Introduction

Pipelines are widely used in oil and gas industry as it is the most economical and feasible way to transport fluids such as oil and gas, seawater and other materials associated with the process of exploitation, transportation, refining and storage in oil and gas industry.[1] Demand for energy all over the world is promoting non-conventional oil discoveries such as deep underwater extraction which bring many challenges so that engineering innovation, design adaptation, and selection of alternative materials and systems are needed.[2-4] The major issues in deep water production are corrosion and extreme conditions of high pressure.[5] Higher thickness to diameter ratio is the trend for pipeline steel used in deep ocean and multiple-wire submerged-arc welding which have high heat input is the most economic and effective way to connect thick wall pipeline.

Ren et al. [6] found that segregation and coarse grains lead to the high corrosion sensitivity of heat affected zone (HAZ). It is very difficult to analyze the effect of microstructure on corrosion behavior using the true weldment due to the narrow zone of HAZ in a welded joint. Usually different heat treatments procedures were used to simulate the microstructures of HAZ. With the development and application of thermal simulation technique in welding field nowadays, research on the relation between microstructures and properties for the welded joint becomes possible. [7-9]

A lot of researches has been done on the microstructure and corrosion of heat affected zone of pipeline steel [10,11], but few studied the relationship between the CGHAZ and the corrosion performance of deep sea pipeline under high input welding so far. The object of this study is to investigate the relationship between microstructure and corrosion behavior of CGHAZ of deep sea X-70 pipeline by using Gleeble thermomechanical simulator.
2. Experimental

2.1. Materials
The test material is X-70 pipeline steel plate with a thickness of 40.5 mm. Chemical composition of the steel is shown in Table 1. The test material has high strength that yield strength and tensile strength was ~530 MPa and ~640 MPa, respectively. It also has an excellent Charpy v-notch impact toughness of 355 J at -30 °C.

Table 1. Chemical composition of X-70 pipeline steel, in wt. %

| C   | Si | Mn | Ni | Cr | Mo | S   | P   | Co | V | Ti |
|-----|----|----|----|----|----|-----|-----|----|---|----|
| 0.04| 0.21| 1.27| 0.28| 0.25| 0.17| 0.002| 0.01| 0.14| 0.003| 0.01|

2.2. Gleeble Thermomechanical Simulation
A thermal simulation test was carried out using Gleeble-3800 thermomechanical processing machine to simulate different welding heat input. The standard sample is 10 mm×10 mm×60 mm in size. Figure 1 shows the welding thermal cycle of the sample heated up to 1300 °C by the rate of 130 °C/s, then, cooled down at 3 different cooling rate of $t_{8/5} = 20$ s, 60 s and 100 s.

![Figure 1. Schematic diagram of welding thermal cycle with different $t_{8/5}$](image)

2.3. Electrochemical Tests
Before each single experiment, samples were ground by a wet 1500 grit SiC paper. All electrochemical experiments were carried out in 3.5 wt.% NaCl solution (100 mL) using a standard three-electrode cell (PAR), involving a saturated calomel electrode (SCE) and a platinum counter electrode. Electrochemical corrosion potential ($E_{corr}$) was collected by a potentiostat (IVIUM VERTEX). Potentiodynamic polarization scans (PD) were conducted with a starting potential 250 mV below the open circuit potential (OCP) under a scan rate of 0.2 mVs$^{-1}$. The OCP was recorded for 3600 s to reach a steady corroding condition from an open circuit setup. Values of corrosion current density ($I_{corr}$) were determined from Tafel plots of the polarization data. The experiments were carried out in air at room temperature. The reported values are averages from three individual measurements.

2.4. Material Characterization
Microstructure of the samples was characterized using scanning electron microscopy (SEM). All samples were prepared by standard metallographic techniques. The samples were mounted in epoxy resin at room temperature before grinding and polishing.
3. Results and Discussion

Figure 2 shows SEM microstructure of the as-received sample and CGHAZ under different thermal cycles. Microstructure of the as-received sample is mainly composed of polygonal ferrite (PF) and acicular ferrite (AF). As shown in Figure 2(b), the CGHAZ is mainly composed of bainite ferrite (BF) and few M-A island when \( t_{8/5} = 20 \) s. Granular bainite is the main component of BF, in which a small amount of ferrite co-existing with lath bainite. The M-A island is bulk and disperses in the matrix. The granular bainite gradually enlarge, and quasi-polygonal ferrite appears with increasing \( t_{8/5} \). When \( t_{8/5} = 60 \) s, as shown in Figure 2(c), granular bainite is the major phase and little polygonal ferrite can be clearly seen. The number of M-A island decreased significantly compared with the sample obtained by \( t_{8/5} = 20 \) s. The M-A island gradually disappear when \( t_{8/5} = 100 \) s and it composed of polygonal ferrite and bainite which is larger in size.

![SEM micrographs of X-70 pipeline steel](image)

(a) as received (b) \( t_{8/5} = 20 \) s (c) \( t_{8/5} = 60 \) s (d) \( t_{8/5} = 100 \) s

Figure 2. SEM micrographs of X-70 pipeline steel; (a) as received; and heat-treated (b) \( t_{8/5} = 20 \) s (c) \( t_{8/5} = 60 \) s (d) \( t_{8/5} = 100 \) s

Figure 3 depicts potentiodynamic polarization scans of the as-received sample and 3 sets of thermal simulated samples in NaCl solution. The potential E in V vs. a saturated calomel electrode (SCE) as a function of current density (i) was shown. The electrochemical corrosion experiment results are summarized in Table 2. As demonstrated in Table 2 and Figure 3, the heat affected samples showed a drop of 0.06-0.14 V compared to the \( E_{	ext{corr}} \) of the as-received sample. That means the thermal simulated samples have higher tendency to corrode.
Among the 3 sets of thermal simulation experiments, the CGHAZs has the lowest corrosion potential at the $t_{8/5}=20$ s, which shows the maximum corrosion tendency and the least corrosion tendency appeared at $t_{8/5}=60$ s. The reason of the higher corrosion tendency of heat simulated samples compare to as-received sample is the changes of microstructure that uneven distribution of bainite and M-A island appeared which led to the decrease of corrosion resistance. All samples have a similar corrosion rate that their corrosion current densities are in the same order.

![Figure 3. Potentiodynamic polarization scans of the samples in 3.5wt. % NaCl solution](image)

**Table 2.** Electrochemical test results (in 3.5 wt. % NaCl) of the samples

|                  | As received | $t_{8/5}=20$ s | $t_{8/5}=60$ s | $t_{8/5}=100$ s |
|------------------|-------------|----------------|----------------|-----------------|
| OCP(V)           | -0.6770±0.02| -0.7183±0.02   | -0.6744±0.03   | -0.6915±0.04    |
| $E_{corr}$(V)    | -0.6433±0.03| -0.7874±0.01   | -0.7051±0.02   | -0.7630±0.02    |
| $i_{corr}(\times 10^4 A/cm^2)$ | 1.774±0.74   | 1.893±1.01     | 3.428±1.21     | 1.778±0.96      |

4. Conclusion
(1) The microstructure of the as-received sample composed of acicular ferrite and polygonal ferrite. While, the microstructure of the heat-treated sample with the shortest $t_{8/5}$ ($t_{8/5}=20$ s) results in the highest amount of M-A island. With the increase in $t_{8/5}$, M-A island began to disappear, microstructure transformed from bainite with fine grain to bainite and ferrite with coarse grain.
(2) As-received samples exhibited a little bit higher corrosion resistance compared to that of the simulated CGHAZs.
(3) Among 3 sets of thermal simulation experiments, microstructure of CGHAZ containing M-A island has the worst corrosion performance and should be avoided during welding to ensure good corrosion resistance.

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