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Study on Corrosion Characteristics and Stress Corrosion Cracking of the Weldment for HT-60 Steel in Synthetic Seawater

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The contents of this paper include the evaluation of corrosion characteristics and the behaviour of stress corrosion cracking(SCC) for the weldment and post weld heat treatment (PWHT) specimen and parent of HT-60 steel using a slow strain rate test(SSRT) in synthetic seawater. Corrosion characteristics were obtained from the polarization curves by potentiostat, and SCC phenomena were evaluated through the parameters such as reduction of area and time to failure by comparing the experimental results in corrosive environment with those obtained in air. Corrosion rate of the weldment was the fastest, followed by parent and PWHT specimen. SCC phenomena between the weldment of HT-60 steel and synthetic seawater were shown. Besides, SCC was dependent upon the pulling speed greatly. Maximum severity of SCC was obtained at a speed of 10^{-6}mm/min, whereas SCC could not be seen almost at 10^{-4}mm/min. The resistance to SCC for PWHT specimen was improved considerably compared that of the weldment at 10^{-6}mm/min. In case of SCC failure, it was verified from SEM examination that brittle mode and lots of pits could be seen at the fractured region near the surface of the specimen.

Key Words : Stress Corrosion Cracking(SCC), Post Weld Heat Treatment(PWHT), Slow Strain Rate Test(SSRT), Corrosion, Time to Failure

1. Introduction

The phenomena of SCC have been the subject of extensive investigation over the past decade because the catastrophic failure of metals caused by SCC has been produced in various industrial fields. It has been well known that SCC is influenced by the combination of mechanical, electrochemical and metallurgical parameters in specific environment, and most of failures in corrosive environment occurred by SCC. For examples, SCC phenomena are found in the various pipes, offshore structures, gas and petrochemical fields, boiler water reactor and heat exchanger etc. (Shreir, L. L., 1979, and Lee, J. I., 1988). Characteristics of SCC are as followings(Ann Y. T., 1998): ① long time is needed to initiate the cracks on the specimen surface in specific environment. ② local electric cell is formed around the pits which are produced on the specimen surface. ③ after pits are formed, crack propagates into the materials more faster so that time to final fracture gets shorter. Besides, SCC phenomena depend on the metal-solution system, potential, and temperature. Accordingly, study on SCC phenomena must be determined for each instance, and SCC behaviour between materials and specific environment should be conducted to establish the data related to the design of the offshore structures, as well as the selection of the appropriate material, and minimize the failure and damage by SCC in aggressive environment.

The purposes of this study are to investigate the susceptibility of SCC using SSRT test method and evaluate the corrosion characteristics against

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the weldment of HT-60 steel to provide the data like mentioned above for the offshore structures in marine environment. In addition, mechanisms of SCC fracture were examined through SEM.

2. Experimental Procedure

2.1 Specimen and welding

The material used in this study is HT-60 steel. Table 1 shows the chemical compositions and mechanical properties in air. Submerged arc welding was done under the conditions like Table 2 perpendicular to the rolling direction of the plate. Figures 1～2 represent the shape of the specimen extracted from the welded plate and the dimension, which heat affected zone(HAZ) was centered on the specimen. PWHT against the welded block was conducted as following conditions: heat temperature of 780℃, holding time of 1 hr and cooling in furnace.

Table 1 Chemical compositions and mechanical properties

(a) Chemical compositions (wt.%)

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.16	0.55	1.35	0.035	0.04	0.6	0.4	0.3	0.15

(b) Mechanical properties

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
450	588	26

Table 2 Welding conditions

Voltage (V)	Current (A)	Welding speed (cm/min)	Diameter of welding rod (mm)
24	350	24	3.2

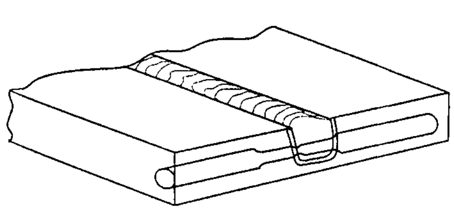


Fig. 1 Extraction of specimens from the welded plate

2.2 Experiment

2.2.1 Corrosion characteristic test

Corrosion characteristics were evaluated by analyzing the polarization curves obtained by means of the potentiostat(Model: EG&G 273-A). Synthetic seawater was made to simulate the marine environment according to ASTM standard(ASTM D1141-86, 1986) like Table 3. Figure 3 illustrates the schematic diagram for the measurement of corrosion characteristics such as corrosion rate, corrosion current density and corrosion potential etc.. Circular immersion specimens of 12mm(diameter) ×2mm(thickness) with HAZ centered were prepared at the midsection of the welded plate. Each specimen was manually abraded to a 1200 grit with dry silicon carbide paper, and then finished by polishing machine to 0.3μm of Al_2O_3 powder. The specimen(working

Table 3 Composition of synthetic seawater

(in 10 liter distilled water)

Composition	Quantity(g)
NaCl	245.34
$MgCl_26H_2O$	111.11
Na_2SO_4	40.94
$CaCl_2$	11.58
KCl	6.95
$NaHCO_3$	2.01
KBr	1.01
$SrCl_26H_2O$	0.42
H_3BO_3	0.27
NaF	0.03

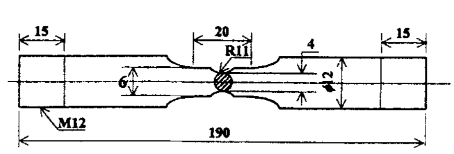


Fig. 2 Configuration and dimensions of the specimen

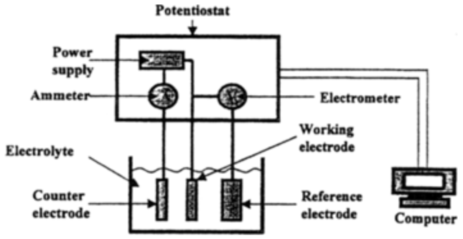


Fig. 3 Schematic diagram for measuring the polarization curve

electrode), a reference electrode(SCE), and a counter electrode(graphite) are immersed in synthetic seawater. The reference electrode was placed very close to the specimen, thus minimizing the distance over which the IR(uncompensated solution resistance) gradient operates. To facilitate this, a salt bridge is employed. This was a tube, filled with electrolyte, open at one end to a test cell containing the reference electrode and at the other end to the electrode near the specimen. After a steady state between the specimen and synthetic seawater was achieved, the specimen of interest was polarized either anodically or cathodically −0.25V to 0.25V at a scan rate of 0.5mV/sec according to the standard test method (ASTM G5-72, 1984). Corrosion potential and current density were monitored by computer in real time, and polarization curves were obtained. From the polarization curves for the all specimens, the values of corrosion characteristics such as corrosion rate, corrosion current density and corrosion potential etc. were acquired.

2.2.2 SCC test

SCC test was conducted using SSRT apparatus as shown in Fig. 4. It has been well known that SSRT method provides a useful tool to investigate the effects of chemical composition and metallurgical structure on severity of SCC(Theus, G. J. and Cels, J. R., 1975). Tensile load was applied to the specimen coated with teflon tape except for the region of interest(HAZ) at a constantly pulling speed in synthetic seawater at 25°C. The specimen was fixed between the bar connected to the load cell and the bottom of the test machine. A container made of the acrylic acid resin holds the solution. Elapsed time and applied load were

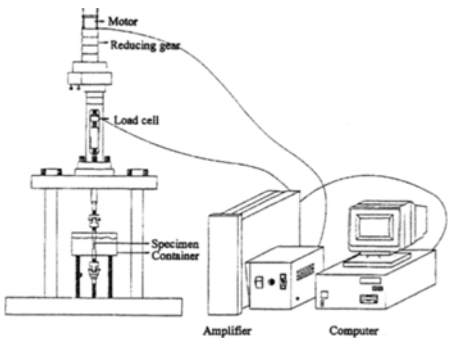


Fig. 4 Schematic drawing of slow strain rate test apparatus

recorded by a computer equipped with the data acquisition system(DAS). A pulling speed was selected by engaging the appropriate set of gears. In general, the severity of SCC is a function of the pulling speed. The most severe speed depends on the metal-solution system, potential, and temperature and must be determined for each instance. Pulling speed in this experiment ranged from 10^{-4} mm/min to 10^{-6}mm/min.

In this study, pulling speed instead of the strain rate was chosen because of the following two reasons: (a) configuration of the concave specimen is needed because the matrix of welded region is stronger than that of the parent, so region of the parent can be fractured firstly in corrosive environment; (b) it is difficult to calculate the strain rate quantitatively at the concave welded region.

3. Results and Discussion

3.1 Corrosion characteristic results

It is presumed that corrosion characteristics for the weldment have close relations with the behaviour of SCC, as SCC is believed to be influenced by the electrochemical parameters such as corrosion rate, corrosion current density and corrosion potential in a specific environment.

Table 4 presents the electrochemical parameters obtained through the Tafel calculation method (Stephen Tait, W. 1994) from the polarization curves for the weldment, PWHT specimens and parent which were shown in Fig. 5. In this study, corrosion rate was chosen as a corrosive characteristic value among parameters such as corrosion rate, E_{corr} and I_{corr}, OCV etc., where E_{corr} is corrosion potential and I_{corr} is corrosion current density and OCV means the open-circuit potential before the scan is performed. Corrosion rate of the weldment was the fastest, followed by parent and PWHT specimen as shown in Fig. 6 which was drawn based on Table 4. From these results, it can be concluded that weld HAZ is the most susceptible to the synthetic seawater, and the susceptibility becomes lower by PWHT. The reason for a little decreasing corrosion rate of the PWHT specimen compared with the parent is presumed to be change in electrochemical properties at HAZ due to PWHT. More data are needed for verifing the reason in the future.

Table 4 Corrosive parameters from Tafel calculation

	Corrosion rate(mmpy)	E_{corr} (mV)	I_{corr} (A/cm^2)	OCV (mV)
Weldment	29.13	−696.6	65.4	−666
PWHT	18.64	−682.5	41.85	−604
Parent	19.45	−684.8	43.67	−605

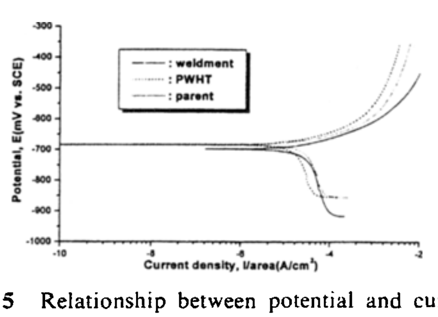


Fig. 5 Relationship between potential and current density for the weldment, PWHT and parent in synthetic seawater

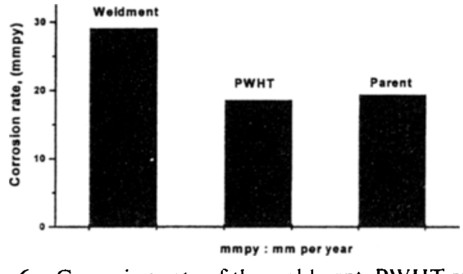


Fig. 6 Corrosion rate of the weldment, PWHT specimen and parent

These contents will be reconsidered again in connection with the discussion on SCC behavior.

3.2 SCC behaviour for the parent, weldment and PWHT specimens

Several properties are used to define and compare the severity of SCC of materials and aggressiveness of environments. Generally, a measure of the reduction of area, time to failure, elongation, or maximum load in a test solution is compared to the behaviour in an environment which does not promote SCC, for example, oil or air (Brown, B. F., 1972). In this study, reduction of area and time to failure for the evaluation of SCC severity were chosen by comparing the data in synthetic seawater with those in air. Reduction of area was obtained by measuring the diameter of the fractured part using a optical microscope with magnification of 150.

Figure 7 represents the relationship between the pulling speeds and reduction of area for the parent in synthetic seawater, including the data in air. The values of reduction of area in synthetic seawater were 41.7%, 38.10% and 21.6%, whereas those in air were 42.5%, 43% and 41.7% at the pulling speeds of 10^{-4}mm/min, 10^{-5}mm/min and 10^{-6}mm/min respectively. From these results, increased severity of SCC was indicated by less reduction of area. Maximum severity of SCC was observed at a pulling speed of 10^{-6}mm/min in this study. SCC severity could not be found almost at a comparatively rapid speed like 10^{-4} mm/min, while more significant SCC severity occurred at 10^{-5}mm/min and 10^{-6}mm/min. Dependence on the pulling speed to SCC can be

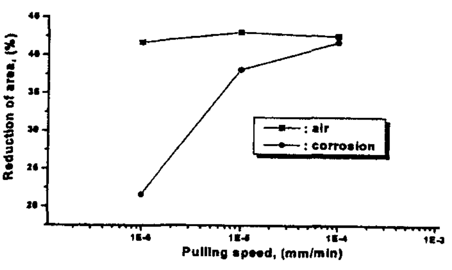


Fig. 7 Relationship between the pulling speeds and reduction of area for the parent in synthetic seawater, including the data in air

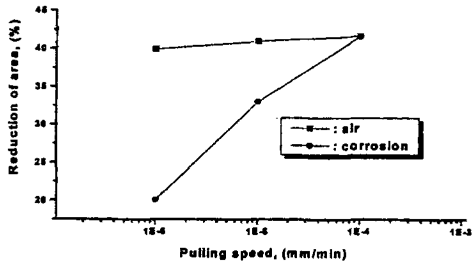


Fig. 8 Relations of the pulling speeds and reduction of area for the weldment in synthetic seawater with the data in air

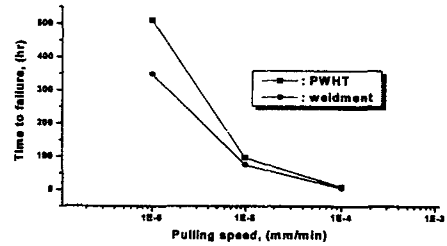


Fig. 9 Relations of the pulling speeds and time to failure for the weldment and PWHT specimen in synthetic seawater

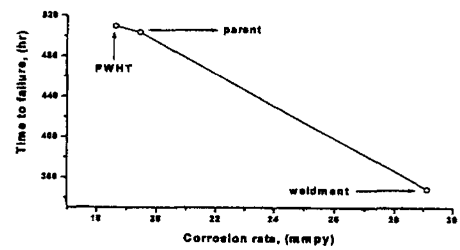


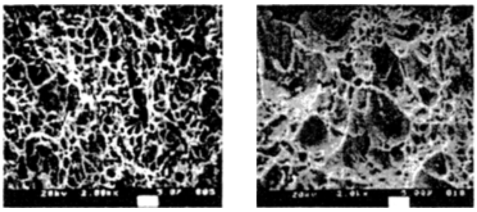
Fig. 10 Relationship between corrosion rate and time to failure in synthetic seawater at 10^{-6} mm/min of pulling speed

explained from the facts that electrochemical reaction time between the specimen and electrolyte at a pulling speed like 10^{-6}mm/min is enough so that hydrogen etc. formed during corrosion process can be absorbed on the specimen surface more easily. As a result, absorbed hydrogen causes to embrittle the specimen as will be discussed on later.

Figure 8 shows the relations of the pulling speeds and reduction of area for the weldment in synthetic seawater with the data in air. As the pulling speeds changed from 10^{-4}mm/min to 10^{-5} mm/min, 10^{-6}mm/min, the values of the reduction of area in synthetic seawater were 41.64%, 33% and 20.1% compared with the data in air which were 41.7%, 41.0% and 39.95% respectively. Except for a pulling speed like 10^{-4}mm/min, it was verified that SCC phenomena of the weldment occurred like the parent because the values of the reduction of area in synthetic seawater decreased compared with those in air. Effect of the pulling speeds on SCC was almost the same regardless of the weldment and parent. From these results, it can be concluded that failure at a pulling speed like 10^{-4}mm/min occurs due to the mechanical fracture mainly, whereas environmental failure at 10^{-6}mm/min predominates the fracture process of SCC rather than the mechanical fracture.

Figure 9 represents the relationship between the pulling speeds and time to failure for the weldment and PWHT specimens. As the pulling speeds became slower from 10^{-4}mm/min to 10^{-5} mm/min, 10^{-6}mm/min, time to failure of the weldment in synthetic seawater was 5hr, 75.50hr and 348.6hr, whereas that of PWHT specimen was 8.7hr, 97hr and 509.6hr respectively. Especially, time to failure of PWHT specimen in synthetic seawater was much longer than that of the weldment at a pulling speed of 10^{-6}mm/min. This means that the resistance to SCC was improved about 43% compared that of the weldment at 10^{-6}mm/min due to PWHT process. The reason for this result is attributed to the softening effect of weld HAZ by PWHT (Na, 1987). Consequently, it was verified that PWHT was effective for reducing the SCC susceptibility of the weldment for the offshore structures using HT-60 steel.

Figure 10 shows the relationship between corrosion rate and time to failure for the weldment, PWHT specimen and parent in synthetic seawater at a pulling speed of 10^{-6}mm/min. As corrosion rate gets higher, time to failure becomes shorter. This suggests that corrosion characteristics which were obtained from the electrochemical polarization curves have close relations with the behaviour of SCC. Future works are required in this field.



(a) 10^{-4}mm/min (b) 10^{-6}mm/min

Fig. 11 Scanning electron micrographs of fractured surfaces of the weldment in synthetic seawater at 10^{-4}mm/sec and 10^{-6}mm/min

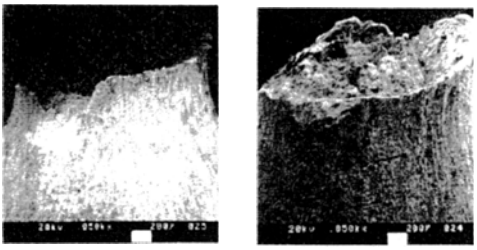
3.3 Fracture mechanisms

As mentioned above, SCC behaviour of the weldment for HT-60 steel in synthetic seawater was dependent upon the pulling speeds. Besides, it was verified that corrosion characteristics had close relations with SCC results for the weldment, PWHT specimen and parent. Fractographic examination of the fractured specimen is necessary to determine unequivocally the presence or absence of SCC. The region of interest on the fractured surface must be selected carefully. It is meaningless to select the center region of the fractured surfaces because SCC phenomenon between specimen and corrosive environment is initiated on the surface of the specimen firstly, and then cracks penetrate into the center region of the specimen. As a result, probability of ductile fracture at the center region of the specimen is considered to be much high. Accordingly, the fractured region near the surface of the specimen was selected first of all in this fractographic examination.

Figure 11 shows the fractured surfaces of the weldment in synthetic seawater at the pulling speeds of 10^{-4}mm/min and 10^{-6}mm/min by SEM observation. Firstly, in case of 10^{-6}mm/min which showed the most severe SCC behaviour, it was found that fracture mode was brittle with a little dimple, and lots of cracks were presented on the fractured region. The fractured region near the specimen surface is embrittled in the electrochemical process like a following reaction (Son, U. T., 1980):

Oxidation process: $M \rightarrow M^{+} + e^{-}$

Reduction process: $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$



(a) 10^{-4}mm/min (b) 10^{-6}mm/min

Fig. 12 Morphologies of the necked region for the weldment in synthetic seawater

$$H^{-} + e^{-} \rightarrow H$$

Hydrogen produced in the process above is absorbed on the surface of the specimen during SCC test period which takes about fifteen days for the weldment at 10^{-6}mm/min. Accordingly, brittle fracture mode is produced due to hydrogen embrittlement by H_2 gas absorption in the course of SCC test.

In case of 10^{-4}mm/min for the weldment, there are lots of voids and dimples on the fractured region which can be seen typically in ductile fracture. It was certain that SCC phenomenon between the weldment and synthetic seawater was not found almost at a pulling speed like 10^{-4}mm/min due to the predominance of the mechanical fracture.

Figure 12 represents the macroscopic fracture appearance of the fractured parts for the weldment at 10^{-6}mm/min and 10^{-4}mm/min. A large number of cracks and pits at failure are evident for the stress corroded specimen at a pulling speed like 10^{-6}mm/min, while cup shape representing the ductile fracture without pits can be seen at 10^{-4}mm/min.

4. Conclusion

This study was conducted to evaluate the corrosion characteristics and SCC behaviour for the weldment of HT-60 steel in synthetic seawater using SSRT method. The evaluation on SCC was made through the parameters like reduction of area and time to failure by comparing the experimental results in corrosive environment with those obtained in air. Corrosion rate of the weldment was the fastest, followed by parent and PWHT specimen. Besides, as the pulling speeds became slower from 10^{-4}mm/min to 10^{-5}mm/min and 10^{-6}mm/min, reduction of area in synthetic seawater decreased compared with that in air. PWHT process was effective for reducing the SCC susceptibility of the weldment for the off-shore structures using HT-60 steel. As the susceptibility to SCC is higher, time to failure becomes shorter. At 10^{-6}mm/min, it was found out that specimens were fractured in a brittle manner, and lots of cracks as well as pits were formed at the region near the surface of the specimens. However, ductile fracture was shown at a pulling speed of 10^{-4}mm/min, which SCC behaviour could not be seen almost.

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