EFFECT OF POST-WELD HEAT TREATMENT OF MARINE STRUCTURE STEEL DURING CATHODIC PROTECTION

By Seong-Jong Kim [1]*, Masazumi Okido[1], Jin-Gyeong Kim [2] and Kyung-Man Moon [3]

[1]Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan, kmue43aksj@hanmail.net
[2]Korea Institute of Maritime and Fisheries Technology, Busan, 608-080 Korea
[3] Korea Maritime University, Busan 606-791, Korea, lab@hanara.kmaritime.ac.kr

ABSTRACT

The effect of post-weld heat treatment (PWHT) of marine structures steel was investigated at electrochemical viewpoint. In addition, slow strain rate test (SSRT) was carried out to investigate both electrochemical and mechanical properties by PWHT effect during impressed current cathodic protection. The optimum cathodic protection potential by SSRT was –770 mV(SCE). At the applied cathodic protection potential of –770 mV～ -850 mV(SCE), the fracture morphology was dimple pattern with ductile fracture, while it was transgranular pattern (Q.C : quasi cleavage) under –875 mV(SCE).

KEYWORDS : Impressed current cathodic protection, Hydrogen embrittlement, Post-weld heat treatment, Slow strain rate test, Electrochemical properties

1. Introduction

The cathodic protection method is being widely used in marine structural steel, however high strength steel for marine structural is easy to get hydrogen embrittlement due to over-protected during impressed current cathodic protection. On the other hand, it was reported that most of the accidents probably were associated with corrosion of welding part and hydrogen embrittlement of marine structures under cathodic protection [1]. Variation of hardness and microstructure it can be attributed to enhance the galvanic corrosion by shifting to more active HAZ part [2]. Therefore it appears to be several cases that PWHT was performed in order to reduce galvanic corrosion of welding part [3]. And mechanical properties were investigated at notched BM part of test specimen by SSRT method. SSRT as a function of cathodic potential was examined closely a limiting potential not causing hydrogen embrittlement and an optimum cathodic protection potential [4]. Therefore it is considered that the results of this study may be provided to a good reference not only to prevent hydrogen embrittlement but also to know the mechanical property of BM in case of design for marine structures or vessels.

2. Experiment

High strength steel was used as SSRT and PWHT test specimen. The length, width, gauge length, and thickness of test specimen were 358 mm, 4 mm, 59 mm, and 23.6 mm respectively. It was made according to proportion No. 14B of JIS Z2201. And welding part is located on center of test specimen and groove angle of welding parts is $35\pm5^{\circ}$, and notches were made width of 0.5 mm, depth of 4.8 mm on both sides of BM in order to lead fracture in the BM. Table 1 shows the chemical composition, mechanical properties of high strength steel and chemical composition of filler metal. And welding method is adopted with flux cored arc welding. And then PWHT condition was heated at 80℃ per hour and heated until 550℃, 600℃, 650℃ and kept for 1.5 hours, after that, it carried out furnace cooling.

Table 1 Chemical composition and mechanical properties of used steel specimen and chemical composition of filler metals

(a) Chemical composition of used steel (%)

C	Si	Mn	P	S	Fe
0.17	0.45	1.26	<0.0027	<0.0008	Balance

(b) Mechanical properties of used steel

T·S (MPa)	Y·S (MPa)	Elongation (%)
597	360	26.6

(c) Chemical composition of filler metals (%)

C	Si	Mn	P	S	Ni
0.04	0.40	1.20	0.012	0.008	1.50

The surface area of test specimen for measuring cathodic and anodic polarization trend to investigate corrosion current density was 6.45 cm^2 involving BM, HAZ, WM part, polished until emery paper No. 600. On the other hand, the surface area to measure cathodic polarization curves was 1 cm^2, measured in scan rate 1 mV/s used SCE as a reference electrode and Pt as a counter electrode. Surface of SSRT specimen is directly exposed to in natural sea water cell. And sea water of the cell flows continuously from upper tank to bottom tank by circulation pump. And SSRT was carried out at strain rate 3 x 10^{-7} /s during constant potential was maintained.

3. Results and discussion

3.1 Electrochemical test

At cathodic and anodic polarization curves, activation reaction due to dissolution reaction of Fe($Fe \rightarrow Fe^{+2} + 2e^-$) occurred at anodic polarization curves. While concentration polarization due to dissolved oxygen reduction reaction($O_2 + 2H_2O + 4e \rightarrow 4OH^-$) was happened at cathodic polarization curves. And polarization trend, corrosion current density and Tafel slope were obtained through the cathodic and anodic polarization curves. And corrosion current density is calculated by Stern-Geary formula and diffusion limiting current density in anodic and cathodic polarization curves. that is, Stern-Geary formula is

$$i_{corr} = \frac{1}{2.3} \frac{i_{(applied)}}{\Delta\phi} \left(\frac{\beta_c \beta_a}{\beta_c + \beta_a} \right) \qquad (1)$$

At above formula, $i_{(applied)}$ is applied current density, $\Delta\phi$ is polarization potential value, βc and βa are Tafel slope of cathodic and anodic respectively. And (1) formula is used both anodic and cathodic Tafel slope. On the other hand, next (2) formula is used only anodic Tafel slope because of diffusion limiting current density regard as corrosion current density in case of corroded by dissolved oxygen reduction reaction in natural sea water solution. In that case, cathodic Tafel slope becomes infinity. that is,

$$i_{corr} = \frac{\beta_a}{2.3} \frac{i_{(applied)}}{\Delta\phi} \qquad (2)$$

Corrosion current density value in As-welded is biggest compared to PWHT specimen both (1) and (2) formulas. Among post-weld heat treated condition, the smallest corrosion current density value was 550℃. Moreover corrosion current density value by (1) formula is smaller than that by (2) formula. Till now, optimum PWHT temperature condition obtained by electrochemical method represented at 550℃. Accordingly, we will treated As-welded and only post-weld heat treated at 550℃ in case of SSRT method.

3.2 Mechanical property evaluation by SSRT method

SSRT with constant cathodic potential was carried out at notched-BM part of test specimen in case of As-welded and PWHT specimen. Cathodic polarization curves of BM were measured in natural sea water solution as with and without PWHT. Two cathodic polarization curves trend are simillar but corrosion potential in post-weld heat treated at 550℃ shows more or less noble than that of As-welded specimen. And difference of polarization curves is not appear largely from open circuit potential to –800 mV(SCE). On the other hand, current density in post-weld heat treated specimen is smaller than that in As-welded specimen under –800 mV, Therefore it is suggested that hydrogen generation overpotential is increased by PWHT. And turning point between concentration polarization due to dissolved oxygen reduction reaction and activation polarization due to hydrogen gas generation ($2H_2O + 2e \rightarrow H_2 + 2OH^-$) is approximately –1000 mV regardless of As-welded and PWHT condition. However hydrogen embrittlement limiting potential can not decided with only cathodic polarization curves. Therefore we carried out SSRT according to constant cathodic potential in order to investigate hydrogen embrittlement limiting potential.

Table 2 shows the data obtained by SSRT method as a function of cathodic potential in As-welded and PWHT specimen. The largest maximum tensile strength both As-welded and post-weld heat treated were observed to be 643.4 MPa and 624.2 MPa at air respectively. And the maximum tensile strength at -770mV in case of As-welded and post-weld heat treated specimen as a function of cathodic potential indicated the highest value among other cathodic potentials. Elongation is being decreased by shifting to negative cathodic potential which is easy to get hydrogen evolution reaction. However elongation values in post-weld heat treated at 550℃ are bigger more or less than those of As-welded condition through all potentials range. Therefore it is suggested that hydrogen embrittlement is easy to occur with increasing negative potential gradually. Time to fracture was the highest value among all cathodic potential regardless of PWHT condition. And then time to fracture decreased with shifting to negative cathodic potential. And the strain to failure ratio is mean the ratio of % elongation in sea water to % elongation in air. So that it is mean that the larger hydrogen embrittlement ratio (strain to failure ratio) has, the less hydrogen embrittlement happen. And hydrogen embrittlement ratio of -770mV in As-welded and PWHT condition are the largest compare to those of the others potential. On the whole, hydrogen embrittlement ratio in post-weld heat treated are increased compare to those in As-welded.

Table 2 The data obtained by SSRT as a function of applied cathodic potential in As-welded and PWHT

		Maximum Tensile Strength (MPa)		Elongation (%)		Time to Fracture (Hrs)		Strain to Failure Ratio	
		As-welded	PWHT	As-welded	PWHT	As-welded	PWHT	As-welded	PWHT
at Air		643.4	624.2	5.43	6.06	44.61	49.19		
at Sea Water	Ecorr	600.4	554.3	4.12	4.77	34.44	38.96	0.7716	0.7873
	-770mV	614.5	609.1	4.40	5.32	36.25	44.23	0.8112	0.8780
	-850mV	561.8	596.7	3.50	4.04	28.30	32.72	0.6439	0.6676
	-875mV	542.6	496.3	3.10	3.60	26.19	29.56	0.5717	0.5948
	-900mV	534.2	586.4	3.08	3.51	25.28	28.39	0.5679	0.5796
	-1000mV	550.6	503.5	3.05	3.29	23.93	26.67	0.5614	0.5438

From results obtained by SSRT as a function of cathodic potential, it is considered that there is no special correlation between maximum tensile strength and hydrogen embrittlement. On the other hand, it is suggested that there is special correlation between elongation, time to fracture, strain to failure ratio and hydrogen embrittlement. And optimum cathodic protection potential in As-welded and PWHT specimen are –770 mV because of elongation, time to fracture, strain to failure ratio at –770 mV are the largest among all applied cathodic potential. According to the Y. Tamaguchi et al study, it is reported that the hydrogen input activity has been shown to increase with increasing negative potential or with increasing current density up to a certain level reaching a plateau [5]. At fractography analysis dimple was indicated wholly at air, E_{corr}, -770 mV, -850 mV regardless of As-welded and PWHT condition. However fractographies at under –875 mV regardless of As-welded and PWHT condition shown the mixed phenomena with dimple and Q.C. It seems to be mixed phenomena with a little dimple and Q.C at –875 mV, -900 mV, and –1000 mV. Fracture mode of –1000 mV including a lot of Q.C especially As-welded is to be observed in the range of hydrogen embrittlement [6]. From these results, it seems that the susceptibility of hydrogen embrittlement is predominantly decreased with increasing elongation, time to fracture, strain to failure ratio and a amount of dimple by PWHT. On the other hand, although the cathodic potential of –875 mV is the range of concentration polarization due to dissolved oxygen reduction reaction, the influence of a little hydrogen embrittlement appeared both As-welded and PWHT condition. So it is considered that this is atomic hydrogen with decreasing of pH by hydrolysis reaction (Fe^{+2}+2e →$FeCl_2$, $FeCl_2+2H_2O \rightarrow Fe(OH)_2+2HCl$) inside of notch can be entered to interior of metal [7]. And generally, shear lips in PWHT specimen are by far increased compare to those in As-welded specimen. Therefore it is suggested that elongation, time to fracture, and strain to failure ratio were increased with increasing shear lip in PWHT. Consequently it is suggested that an optimum cathodic protection potential range not causing hydrogen embrittlement is from –770 mV to –850 mV in As-welded and PWHT condition.

4. Conclusion

Corrosion resistance was increased with PWHT. And it seems that there is no correlation between maximum tensile strength and hydrogen embrittlement. However the value of elongation, time to fracture and strain to failure ratio were decreased with shifting to lower potential direction. Those reason are caused by hydrogen evolution and Q.C fracture mode was also observed at the lower potential range, and susceptibility of hydrogen embrittlement was significantly increased with decreasing the value of elongation, time to fracture by shifting to lower potential. The susceptibility of hydrogen embrittlement in case of post-weld heat treated at 550℃ was also decreased with increasing elongation, time to fracture and a large amount of dimple. At the applied cathodic potential between –770 mV and –850 mV, the fracture morphology was dimple pattern with ductile fracture, when it changed transgranular pattern under –875 mV.

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