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Effect of Heat Treatment on the Corrosion Behavior of AISI 4135 Steel under Natural Seawater Film at Different Temperatures

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High strength steel has a prosperous future in catering the needs of marine applications especially the tapping of deep sea resources. The use of high strength steel will reduce the weight of steel structures and reduce the environment burden for the production of materials. Thus it is necessary to study the problems concerning the safety of high strength steel applications in marine environment. In this paper the corrosion behavior of heat treated AISI 4135 steel was studied by means of electrochemical techniques at different temperatures when it is covered by natural seawater film. The results showed that the corrosion rate of the steel increases with the elevation of temperature but the heat treatment processes have no profound effect on the corrosion. The expected mitigation of corrosion by tempering of quenched specimens could not be concluded based on the data of this research.

Keywords: Heat treatment, high strength steel, seawater, temperature, electrochemistry

1. INTRODUCTION

The 21st century is the ocean's century, the era into which the mankind will step with the full development of ocean. With the development and utilization of marine resources, marine infrastructures such as port terminals, sea-crossing bridges, offshore oil platforms and so on, are in enormous building with the development of deep-sea engineering. A great deal of metal materials has been put into use for these constructions. For harsh corrosion conditions [1,2], marine corrosion is the

one of the problem which ocean exploitation must face and resolve. In the marine environment, corrosion is one of the major factors for failure and damage of steel structures. Corrosion behavior of materials in seawater environment is determined by material states and seawater conditions. Material state includes chemical components, structures and surface states. Seawater conditions consist of temperature, dissolved oxygen, pH and biological fouling etc.

In 50s of last century, U.S. Steel Corporation promoted famous Mariner steel, which contains main elements, such as Ni, Cu and P. Researchers in Japan took into Mariner's technology and substituted Cr for Ni. They developed a series of seawater corrosion resistant steel that are suitable for different marine corrosion zones [3,4]. At present, the enhancement in material strength is desired to reduce the impact of industrial development on the environment. High strength low alloy steel can reduce weights of frame elements and wastages of steel. In addition, it can improve the service reliability and get better mechanical properties than that of common carbon steel. Thus, there is an increasing trend to replace the ordinary carbon structural steels by high strength steels. AISI 4135 steel belongs to CrMo steel series with high strength, high plasticity, high toughness and fair abrasion resistance. For its excellent properties and environmental corrosion resistant ability, it is expected to find a wider range of application. In the machinery manufacturing industry, AISI 4135 steel is commonly used in the manufacture of various parts, while it is the main material of oil drilling joints in the petrochemical industry [5].

AISI 4135 steel is a low alloy steel with its properties achieved through heat treatment. After heat treatment, it can have good strength and toughness combinations. This steel has a lower tendency to temper brittleness with less use of Ni elements, and can be used to produce parts which are large cross-section and subject to high loads on petroleum equipment, such as shafts, gears, fasteners, etc [6,7,8]. The prior study of heat treatment on the corrosion behavior of the steel in the marine environment is of very important significance for the field application of the steel. The research will help to select proper heat treatment processes to meet the needs of material applications. The marine splash zone is the most severe corrosion environment. Further understanding of the corrosion behavior of AISI 4135 steel, especially the localized corrosion will be beneficial in promoting the safety applications of it.

In the real spray splash zone conditions, the splashed seawater temperature changes with different geographic locations, the seasonal variation, the irradiation of sunlight and the alteration of day and night. As a result, AISI 4135 steel are often covered with corrosive seawater film at different temperatures. Seawater temperature is one of important factors in the corrosion development process. Therefore, it is necessary to study the influence of heat treatment as well as the effect of seawater temperature on the corrosion behavior of AISI 4135 steel. .

The effects of heat treatment and seawater temperature on the corrosion behavior of AISI 4135 steel were studied by electrochemical techniques in this paper. Because of large relative humidity in splash zone, the splash of seawater can form a stable layer of seawater film on the surface of steel. Therefore, the study on the corrosion behavior of AISI 4135 steel under natural seawater film provides a basis for the evaluation of AISI 4135 steel in service at splashed zone.

2. EXPERIMENTAL

The experimental material is AISI 4135 steel with the chemical composition of 0.399C, 0.903 Cr, 0.204 Mo, 0.509 Mn, 0.293 Si, 0.080 Ni, 0.015 P, and 0.014 S in wt%. Samples of the size Φ 10mm × 10mm were cut with electric discharge line saw cutting machine.

Heat treatments were done by using SG2-7.5-12 high temperature resistance furnace with temperature controlled by specialized XMT-90000 digital controller. Four different kinds of heat treatment schemes were used in this study. The heat treatment processes are as follows:

Heat treatment A: samples were heated at 860C^o for 50min, quenched at 370 C^o for 30min and then air-cooled;

Heat treatment B: samples were heated at 860 C^o for 50min, oil quenched, tempered at 200 C^o for 1h and then air-cooled;

Heat treatment C: samples were heated at 860 C^o for 50min, oil quenched, tempered at 550 C^o for 1h and then air-cooled;

Heat treatment D: the samples were heated at 1120 C^o for 20min, at 860 C^o for 10min, oil quenched, tempered at 200 C^o for 1h and then air-cooled;

The samples were sealed with epoxy resin leaving the cross section with a surface area of 0.785cm^2 as working surface. All the samples were abraded to $^{\#}$600 grit SiC paper before use.

Potentiodynamic polarization experiments were carried out with samples under seawater film at 10 C^o, 20 C^o, 30 C^o, 40 C^o, 50 C^o respectively. The electrochemical cell was conventional 3 electrode system with saturated calomel electrode (SCE) as reference electrode and Pt as counter electrode. The potential was controlled potentiodynamicaly at a scan rate of 10mV/min. All the electrode potentials are reported vs. SCE. Open circuit potential was measured before potentiadynamic scan. All measurements were repeated to verify the reproducibility with the average value or the most typical results being reported. The number of repeated times was denoted as sampling size in results and discussion section.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties and microstructure of AISI 4135 steel after heat treatments

Different heat treatments resulted in different microstructures. The microstructure of the specimens after heat treatment A is mainly bainite with small amount of martensite and retained austenite. The microstructure after heat treatment B is mainly martensite, after heat treatment C is mainly tempered martensite. The microstructure after heat treatment D is also martensite but with coarse prior austenite grain. The strength of specimens after heat treatment B and D is high with no significant difference in plastic strength, tensile strength and plasticity. The specimens after heat treatment A have moderate strength and plasticity combination. While the specimens after heat treatment C has a low strength but high plasticity. The mechanical properties after heat treatments are listed in table 1.

Table 1. Mechanical properties of AISI 4135 steel after heat treatments

Heat Treatment	A	B	C	D
Plastic Strength/MPa	666	1635	417	1648
Tensile Strength/MPa	871	1757	680	1720
Elongation/%	15.5	12.5	22.8	12.7

3.2 Potentiodynamic polarization behavior of AISI 4135 steel after heat treatments under seawater film at different temperatures

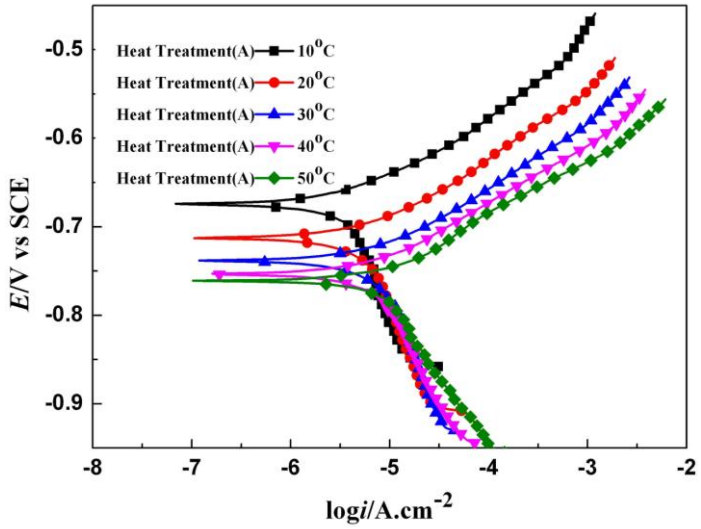

Figure 1(a). Potentiodynamic polarization of AISI 4135 steel after heat treatment (A) under seawater film at different temperatures

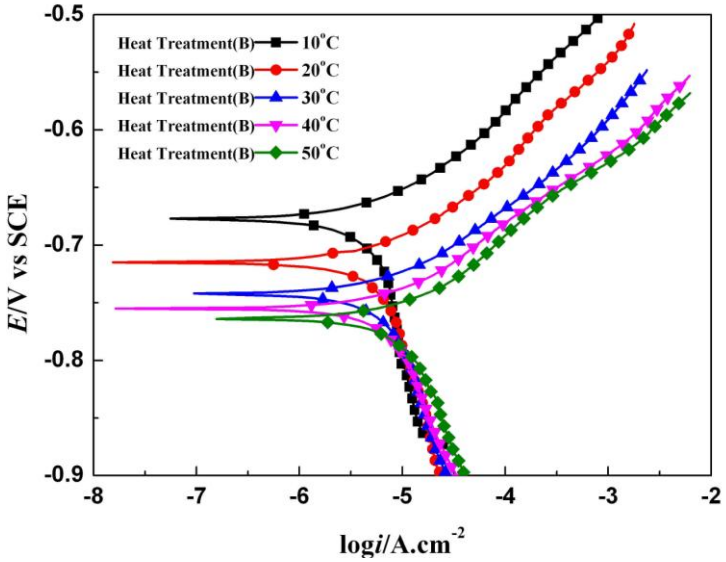

Figure 1(b). Potentiodynamic polarization of AISI 4135 steel after heat treatment (B) under seawater film at different temperatures

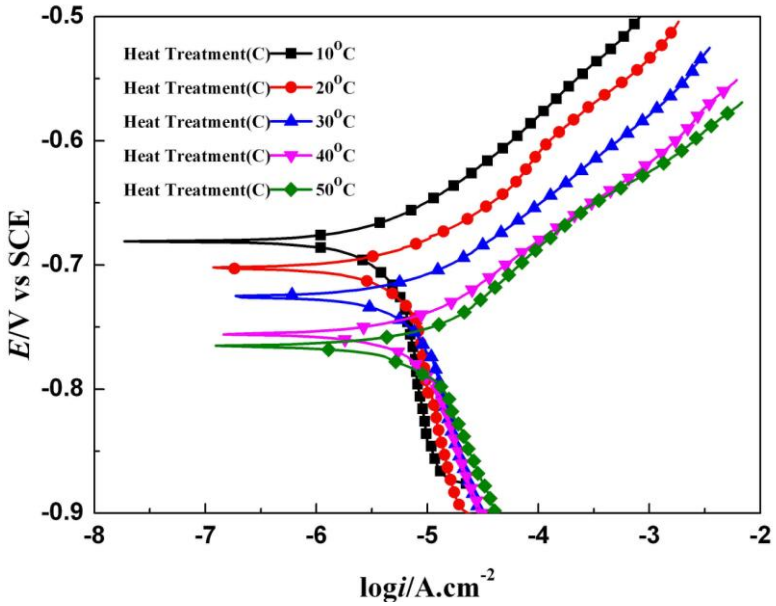

Figure 1(c). Potentiodynamic polarization of AISI 4135 steel after heat treatment (C) under seawater film at different temperatures

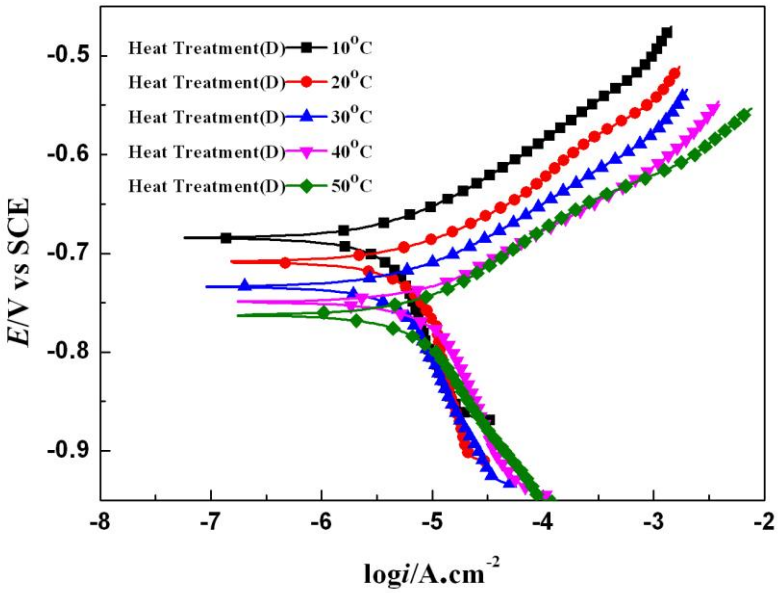

Figure 1(d). Potentiodynamic polarization of AISI 4135 steel after heat treatment (D) under seawater film at different temperatures

Figure 1(a), (b), (c) and (d) show the typical polarization curves of AISI 4135 steel after heat treatment A, B, C and D under seawater film at different temperatures. It is shown that the open corrosion potential shifts negatively with the increase of temperature. This reveals that the corrosion of AISI 4135 steel is sensitive to temperature in the marine splashed zone environment.

The open corrosion potential is a thermodynamic concept. It is a measure of the corrosion reaction trend. More negative open circuit potential indicates that the specimen is more prone to severer corrosion. The higher temperature helps both anodic and cathodic reactions to overcome

reactivation energy by providing additional energy making the open circuit potential to decrease and the corrosion reaction rate to increase.

The polarization measurements were repeated and then the obtained curves were analyzed by curve fitting according to Tafel law. The measured open circuit potentials and estimated values of corrosion current densities are listed in table 2. The number of repeated times was denoted as sampling size and listed in table 3.

Table 2. The estimated values of open circuit potential E_c and corrosion current density I_c by Tafel curve fitting

T/ C^o	Heat treatment A		Heat treatment B		Heat treatment C		Heat treatment D	
	E_c/V	I_c/A.cm^{-2}	E_c/V	I_c/A.cm^{-2}	E_c/V	I_c/A.cm^{-2}	E_c/V	I_c/A.cm^{-2}
10℃	-0.674	5.85×10^{-6}	-0.681	6.75×10^{-6}	0.677	9.205×10^{-6}	0.684	5.649×10^{-6}
	-0.676	6.51×10^{-6}	-0.63	3.90×10^{-6}	0.666	8.258×10^{-6}	0.672	5.701×10^{-6}
	-0.636	2.76×10^{-6}	-0.67	3.22×10^{-6}	0.615	6.567×10^{-6}	0.662	4.89×10^{-6}
	/	/	/	/	/	/	0.680	5.937×10^{-6}
20℃	-0.713	7.89×10^{-6}	-0.702	1.12×10^{-6}	0.715	8.675×10^{-6}	-0.708	1.136×10^{-5}
	-0.693	6.23×10^{-6}	-0.695	5.18×10^{-6}	0.703	5.115×10^{-6}	-0.704	8.324×10^{-6}
	-0.702	4.86×10^{-6}	/	/	0.704	5.619×10^{-6}	-0.723	6.234×10^{-6}
	-0.716	4.72×10^{-6}	/	/	0.718	4.045×10^{-6}	-0.710	7.928×10^{-6}
	-0.710	8.64×10^{-6}	/	/	0.710	3.573×10^{-6}	/	/
30℃	-0.738	9.33×10^{-6}	-0.725	1.08×10^{-5}	0.742	9.293×10^{-6}	-0.734	6.773×10^{-6}
	-0.724	1.34×10^{-5}	-0.719	1.33×10^{-5}	0.713	1.354×10^{-6}	-0.741	9.815×10^{-6}
	/	/	/	/	/	/	-0.732	7.859×10^{-6}
40℃	-0.753	8.58×10^{-6}	-0.756	9.85×10^{-6}	0.755	9.088×10^{-6}	-0.749	1.133×10^{-5}
	-0.724	1.51×10^{-5}	-0.752	1.06×10^{-5}	0.751	1.008×10^{-6}	-0.746	1.172×10^{-5}
	-0.737	1.34×10^{-5}	/	/	/	/	-0.760	7.003×10^{-6}
	/	/	/	/	/	/	-0.741	1.42×10^{-5}
	/	/	/	/	/	/	-0.746	1.305×10^{-5}
	/	/	/	/	/	/	-0.752	8.881×10^{-6}
50℃	-0.761	1.07×10^{-5}	-0.765	1.32×10^{-5}	0.764	1.437×10^{-6}	-0.763	8.412×10^{-6}
	-0.753	7.25×10^{-6}	-0.755	1.32×10^{-5}	0.756	9.645×10^{-6}	-0.761	1.007×10^{-5}
	-0.750	1.07×10^{-5}	-0.774	1.16×10^{-5}	0.741	1.5×10^{-5}	-0.746	6.83×10^{-6}
	/	/	/	/	/	/	-0.765	1.092×10^{-5}
	/	/	/	/	/	/	-0.746	1.7×10^{-5}
	/	/	/	/	/	/	-0.741	9.813×10^{-6}
	/	/	/	/	/	/	-0.759	7.141×10^{-6}

Because of the scattering of obtained data, *t*-test of mathematical statistics [9] is used here to compare the differences of significance in corrosion behavior among the specimens after four kinds of heat treatments.

We suppose the estimated data of E_c and I_c follow the normal distribution. The *t*-test requires the equal variances of two normal populations. *F*-test is used here to verify the equal variances of the two populations for comparison.

F-test requires the parameters of variance. *t*-test requires sample size, sample average and variance. The parameters of sample size *n*, sample average $\bar{x}$ ($\bar{x}_{Ec}$ for open circuit potential, $\bar{x}_{Ic}$ for corrosion current) and variance s^{*2} (s^{*2}_{Ec} for open circuit potential, s^{*2}_{Ic} for corrosion current density) calculated from data of table 2 are listed in table 3-7.

Assume population X_1 and X_2 obey normal distribution, sample sizes and sample variances are n_1, S_1^{*2} and n_2, S_2^{*2} respectively, then

$$F = \frac{S_1^{*2}}{S_2^{*2}} \qquad (1)$$

obeys *F* distribution with degree of freedom (n_1-1, n_2-1).

Given significant level α, if

$$F_{1-\frac{\alpha}{2}}(n_1-1, n_2-1) < F < F_{\frac{\alpha}{2}}(n_1-1, n_2-1) \qquad (2)$$

then, the variances of the two populations can be regarded as having no significant differences.

Set the significant level α as 0.05, the values of $F_{1-\frac{\alpha}{2}}(n_1-1, n_2-1)$, $F_{\frac{\alpha}{2}}(n_1-1, n_2-1)$ and calculated *F* between heat treatment A and B, heat treatment A and C, heat treatment A and D are shown in table 8-10.

Table 3. Sample size *n* of estimated E_c and I_c at different temperatures

Heat treatment \ *T*	10℃	20℃	30℃	40℃	50℃
A	3	5	2	3	3
B	3	2	2	2	3
C	3	5	2	2	3
D	4	4	3	6	7

Table 4. Open circuit potential average $\bar{x}_{Ec}$ (V) at different temperatures

Heat treatment \ *T*	10℃	20℃	30℃	40℃	50℃
A	-0.662	-0.707	-0.731	-0.738	-0.755
B	-0.660	-0.699	-0.722	-0.754	-0.765
C	-0.653	-0.710	-0.728	-0.753	-0.754
D	-0.674	-0.711	-0.736	-0.749	-0.754

Table 5. Corrosion current density average $\bar{x}_{Ic}$ at different temperatures

Heat treatment \ T	10℃	20℃	30℃	40℃	50℃
A	5.04×10^{-6}	6.47×10^{-6}	9.33×10^{-6}	1.1×10^{-5}	9.57×10^{-6}
B	4.62×10^{-6}	8.18×10^{-6}	1.2×10^{-5}	1.02×10^{-5}	1.27×10^{-5}
C	8.01×10^{-6}	5.41×10^{-6}	1.14×10^{-5}	9.58×10^{-6}	1.30×10^{-5}
D	5.54×10^{-6}	8.46×10^{-6}	8.15×10^{-6}	1.10×10^{-5}	1.00×10^{-5}

Table 6. Open circuit potential variance s^{*2}_{Ec} at different temperatures

Heat treatment \ T	10℃	20℃	30℃	40℃	50℃
A	3.39×10^{-4}	6.94×10^{-5}	4.9×10^{-5}	1.41×10^{-4}	2.16×10^{-5}
B	4.8×10^{-4}	1.23×10^{-5}	9×10^{-6}	4×10^{-6}	6.02×10^{-5}
C	7.3×10^{-4}	3.48×10^{-5}	2.1×10^{-4}	4×10^{-6}	9.09×10^{-5}
D	7.07×10^{-5}	1.22×10^{-4}	0.126	3.53×10^{-5}	8.17×10^{-5}

Table 7. Corrosion current density variance s^{*2}_{Ic} at different temperatures

Heat treatment \ T	10℃	20℃	30℃	40℃	50℃
A	2.67×10^{-12}	2.48×10^{-12}	4.14×10^{-12}	7.61×10^{-12}	2.68×10^{-12}
B	2.34×10^{-12}	9×10^{-12}	1.45×10^{-12}	1.56×10^{-12}	5.73×10^{-12}
C	1.19×10^{-12}	3.21×10^{-12}	4.51×10^{-12}	2.46×10^{-13}	5.71×10^{-12}
D	1.54×10^{-13}	3.54×10^{-12}	2.08×10^{-11}	5.92×10^{-12}	1.01×10^{-11}

Table 8. *F*-test of heat treatment A and B

T		10℃	20℃	30℃	40℃	50℃
E_c	F	0.7052	5.6620	5.4444	35.1667	0.3579
	$F_{1-\alpha/2}$	0.0256	0.0818	0.0015	0.0260	0.0256
	$F_{\alpha/2}$	39	899.6	647.8	799.5	39
I_c	F	1.1446	0.2758	2.8520	48.9113	4.6786
	$F_{1-\alpha/2}$	0.0256	0.0818	0.0015	0.0260	0.0256
	$F_{\alpha/2}$	39	899.6	647.8	799.5	39

Table 9. *F*-test of heat treatment A and C

T		10℃	20℃	30℃	40℃	50℃
E_c	*F*	0.4642	1.9931	0.2331	35.1667	0.2372
	$F_{1-\alpha/2}$	0.0256	0.1042	0.0015	0.0013	0.0256
	$F_{\alpha/2}$	39	9.6	647.8	799.5	39
I_c	*F*	2.2448	0.7742	0.9183	30.9414	0.4696
	$F_{1-\alpha/2}$	0.0256	0.1042	0.0015	0.0260	0.0256
	$F_{\alpha/2}$	39	9.6	647.8	799.5	39

From table 8-10, it is shown that only the *F* value for open circuit potential variance comparison between heat treatment A and D at 30℃ slightly falls beyond the interval of $F_{1-\frac{\alpha}{2}}(n_1-1,n_2-1)$ and $F_{\frac{\alpha}{2}}(n_1-1,n_2-1)$. The variances of open circuit potential, corrosion current density for heat treatment A, B, C and D at same temperature can be regarded as having no significant differences. Then the *t*-test can be used to compare the average values of open circuit potential, corrosion current density at the same temperature.

Table 10. *F*-test of heat treatment A and D

T		10℃	20℃	30℃	40℃	50℃
E_c	*F*	4.79	0.5698	0.0004	3.9811	0.2639
	$F_{1-\alpha/2}$	0.0255	0.1002	0.0013	0.0254	0.0254
	$F_{\alpha/2}$	16.04	15.1	38.51	8.43	7.26
I_c	*F*	17.4	0.7004	0.1987	1.2855	0.2658
	$F_{1-\alpha/2}$	0.0255	0.1002	0.0013	0.0254	0.0254
	$F_{\alpha/2}$	16.04	15.1	38.51	8.43	7.26

If the average values of two normal population are identical, then

$$T=\frac{\overline{X}_1-\overline{X}_2}{\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}S^*} \qquad (3)$$

obeys the *t*-distribution with degree of freedom (n_1+n_2-2). Where,

$$S^*=\sqrt{\frac{(n_1-1)S_1^{*2}+(n_2-1)S_2^{*2}}{n_1+n_2-2}}$$

Given significant level α, if

$$|\bar{x}_1-\bar{x}_2|<t_{\frac{\alpha}{2}}(n_1+n_2-2)\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}S^* \qquad (4)$$

then the average values of the two normal populations can be regarded as having no significant differences. For simplicity, set $X=t_{\frac{\alpha}{2}}(n_1+n_2-2)\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}S^*$.

Set the significant level α as 0.05, the values of $X=t_{\frac{\alpha}{2}}(n_1+n_2-2)\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}S^*$ and the calculated $|\bar{x}_1-\bar{x}_2|$ between heat treatment A and B, heat treatment A and C, heat treatment A and D are shown in table 11-13.

Table 11. *t*-test of heat treatment A and B

T		10℃	20℃	30℃	40℃	50℃
E_c	$\lvert \bar{x}_{Ec1}- \bar{x}_{Ec2}\rvert$	0.0017	0.0083	0.0090	0.0160	0.0100
	X_{Ec}	0.0459	0.0164	0.0232	0.0283	0.0145
I_c	$\lvert \bar{x}_{Ic1}- \bar{x}_{Ic2}\rvert$	4.19×10^{-7}	1.71×10^{-6}	2.72×10^{-6}	7.35×10^{-7}	3.1×10^{-6}
	X_{Ic}	3.59×10^{-6}	4.18×10^{-6}	7.2×10^{-6}	6.58×10^{-6}	2.89×10^{-6}

Table 12. *t*-test of heat treatment A and C

T		10℃	20℃	30℃	40℃	50℃
E_c	$\lvert \bar{x}_{Ec1}- \bar{x}_{Ec2}\rvert$	0.0093	0.0032	0.0035	0.0150	0.0010
	X_{Ec}	0.0524	0.0105	0.0490	0.0283	0.0170
I_c	$\lvert \bar{x}_{Ic1}- \bar{x}_{Ic2}\rvert$	2.97×10^{-6}	1.06×10^{-6}	2.09×10^{-6}	1.4×10^{-6}	3.44×10^{-6}
	X_{Ic}	3.15×10^{-6}	2.46×10^{-6}	8.95×10^{-6}	6.6×10^{-6}	4.64×10^{-6}

Table 13. *t*-test of heat treatment A and D

T		10℃	20℃	30℃	40℃	50℃
E_c	$\lvert \bar{x}_{Ec1}- \bar{x}_{Ec2}\rvert$	0.0120	0.0045	0.0047	0.0110	0.0002
	X_{Ec}	0.0262	0.0152	0.8426	0.0135	0.0130
I_c	$\lvert \bar{x}_{Ic1}- \bar{x}_{Ic2}\rvert$	4.99×10^{-7}	1.99×10^{-6}	1.18×10^{-6}	5.07×10^{-8}	4.6×10^{-7}
	X_{Ic}	2.12×10^{-6}	2.72×10^{-6}	1.14×10^{-5}	4.23×10^{-6}	4.57×10^{-6}

From table 11-13, it is shown that only the average value's difference $|\bar{x}_{Ic1}- \bar{x}_{Ic2}|$ for corrosion current comparison between heat treatment A and B at 50 C^o is slightly larger

than $t_{\frac{\alpha}{2}}(n_1+n_2-2)\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}S^*$. The average value's difference $|\bar{x}_{Ic1}-\bar{x}_{Ic2}|$ of open circuit potential, corrosion current density for heat treatment A, B, C and D at same temperature can be regarded as having no significant differences. The average open circuit potential and corrosion current density's dependence on temperature for specimens after different heat treatments are shown in figure 2 and 3. Although the effect of heat treatment on the corrosion behavior was not found, the effect of temperature on open circuit potential and corrosion current density was clearly shown. The open circuit potential decreases with the increase of temperature and the corrosion current density increases

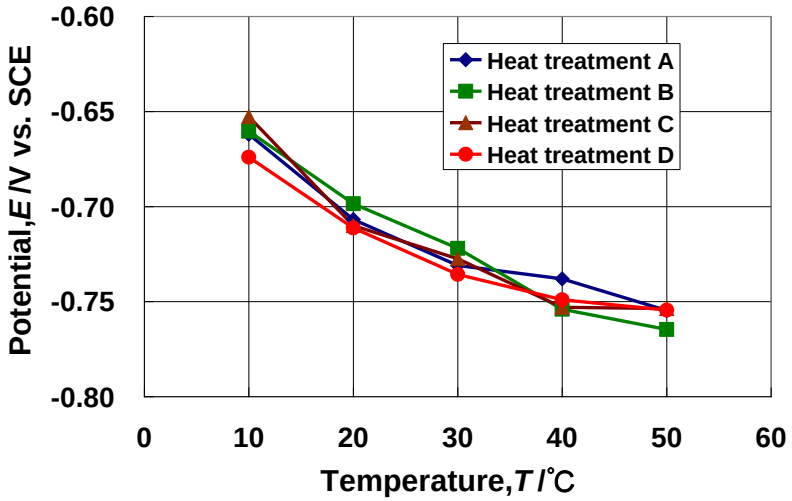

Figure 2. Open circuit potential's dependence on temperature for specimens after different heat treatments

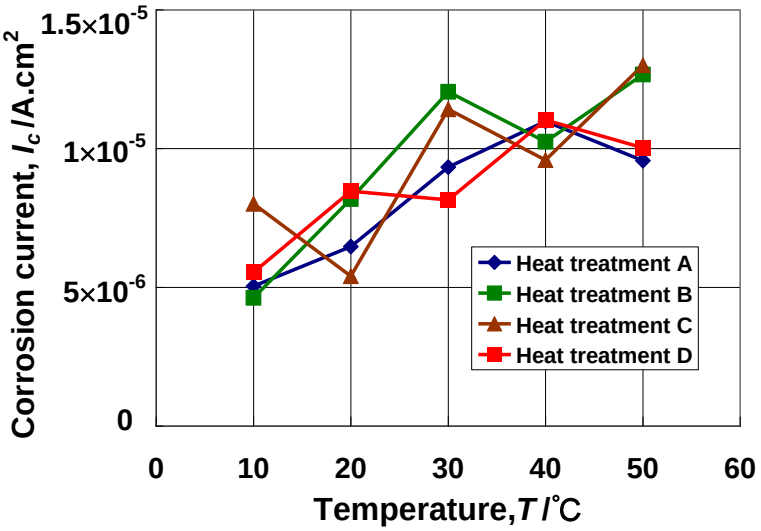

Figure 3. Corrosion current density's dependence on temperature for specimens after different heat treatments

with the increase of it. In natural splash zone corrosion conditions, the temperature changes with seasons and the alteration of day and night. The steel suffers localized corrosion at splash zone for

long exposure. The localized corrosion occurs generally while the general corrosion rate is small. The low corrosion rate at low temperatures may facilitate the initiation of localized corrosion at specific active sites which needs further investigation.

4. CONCLUSIONS

The temperature increase lowers the open circuit potential and increases the corrosion rate for all heat treated samples. Heat treatments affects the mechanical properties of the tested material but have no significant effects on corrosion electrochemical behavior under natural seawater film at same temperature.

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References

1. F.L. Laque,*Marine corrosion: causes and prevention.*Corrosion monograph series. United States: John Wiley and Sons, Inc., New York(1975)
2. F.Corvo, T.Perez, L. R.Dzib,et al.,*Corros. Sci.*, 50(2008)220
3. Matsushima I, Translated by Jin Y K. *Low Alloy Corrosion Resistant Steels——A History of Development Application and Research,*Metallurgical Industry Press, Beijing(2004)
4. R. E.Melchers,*Corros. Sci.*, 46(2004)1669
5. G. K.Zhu, *Liaoning University of Technology*, 2(2008)129
6. J. E. Lu,*Heat treatment*, 4(1999)40
7. H. Liu, Y. C. Li,*Chemical engineering and equipment*, 4(2010)92
8. M. Hong, *Structural Steel Manual*, Hebei Science and Technology Press, Hebei (1985)
9. R. X. Wang, *Mathematical Statistics*, Xi'an Jiaotong University Press, Xi'an (1987)