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# A Study on the Post-Weld Heat Treatment Effect to Mechanical Properties and Hydrogen Embrittlement for Heating Affected Zone of a RE 36 Steel

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The cathodic protection method is being widely used in marine structural steel, however a high tensile steel like RE 36 steel for marine structural steel is easy to get hydrogen embrittlement due to over protection during cathodic protection as well as preferential corrosion of HAZ(Heating Affected Zone) part.
In this paper, corrosion resistance and mechanical properties such as elongation and hydrogen embrittlement were investigated with not only in terms of electrochemical view but also SSRT(Slow Strain Rate Test) method with applied constant cathodic potential, analysis of SEM fractography in case of both As-welded and PWHT(Post-Weld Heat Treatment) of 550℃.
The best effect for corrosion resistance was apparently indicated at PWHT of 550℃ and elongation was increased with PWHT of 550℃ than that of As-welded condition.
On the other hand. Elongation was decreased with applied potential shifting to low potential direction which may be caused by hydrogen embrittlement, however the susceptibility of hydrogen embrittlement was decreased with PWHT of 550℃ than that of As-welded condition and Q.C(quasi cleavage) fracture mode was also observed significantly according to increasing of susceptibility of hydrogen embrittlement.
Eventually it is suggested that an optimum cathodic protection potential range not causing hydrogen embrittlement is from -770 mV(SCE) to -850 mV(SCE) in As-welded condition while is from -770 mV(SCE) to -875 mV(SCE) in PWHT of 550℃.

***Keywords*** : *cathodic protection, hydrogen embrittlement, post-weld heat treatment, slow strain rate test, quasi cleavage, corrosion resistance*

## 1. Introduction

Recently a marine structure is getting more and more a big scale, so that both the maintenance and repairing for them due to their large scale was presented at an important factor in terms of economical and industrial view. And it is considered that corrosion resistance of material is apparently one of the important factors which keep the long life for the structures and most of the marine structures like static platform is fixed and located at under sea water, thus it may be difficult to repair and maintain their structures especially to inspect their welding part however it is thought that it would be probably taken a large amount of cost for their inspection and maintenance as well.

On the other hand, it was reported that most of the accidents which probably must be done for repairing and inspection were also associated with corrosion of welding part and hydrogen embritllement of marine structures.[1)-4)] And corrosion problem mentioned above probably might be caused by both physical parameters such as welding methods, welding design condition and residual stress as well as metallurgical parameters such as chemical composition, segregation, inclusion, and impurity,[5)] in addition to when structure is being welded continuously, variation of hardness and microstructure due to rapid heating and cooling was resulted in galvanic cell providing potential difference of each welding part, subsequently it can be attributed to enhance the galvanic corrosion on the welding parts.[6)-8)] Therefore it appears to be some several cases that PWHT(Post-Weld Heat Treatment) was performed in order to restrain galvanic corrosion of welding part.[9)-12)]

In this study RE 36 steel which is high tensile steel was performed with FCAW(Flux Cored Arc Welding), and then corrosion property on each part of welding area in case of both As-welded and with PWHT at 550℃, 600℃, 650℃ was investigated in electrochemical view however a correlation investigation of mechanical properties such as maximum tensile strength, yield strength, elongation, time to fracture and strain ratio was also carried out on the HAZ(Heat Affected Zone) part having a artificial notch in the test specimen by SSRT(Slow Strain Rate Test) method with applying constant polarization potential[13)-16)] and a limiting potential not causing Hydrogen Embrittlement and an optimum cathodic potential was also observed through the analysis of fractured surface with SEM fractography.

Therefore it is considered that the results of this study may be helpful to provide a good reference not only to prevent hydrogen embrittlement but also to know the mechanical property of HAZ in case of design and execution for marine structures or vessels.

## 2. Experiments

### 2.1 Test specimen and PWHT

In this study the test specimen used for SSRT and PWHT is RE 36 steel for marine structure, which is composed that length is 358 ㎜, width is 23.6 ㎜, and thickness is 4 ㎜, however it was constructed according to No. 14B of JIS Z2201. And welding part is located at center of the test specimen and groove angle during being welded is 35±5°, and gave artificial notches having width of 0.5 ㎜, depth of 4.8 ㎜ on both sides of HAZ for attracting fracture in the HAZ and schematic diagram is shown in Fig. 1.

Table 1 shows the chemical composition, mechanical properties of RE 36 steel and chemical composition of filler metal. And welding conditions are shown in Table

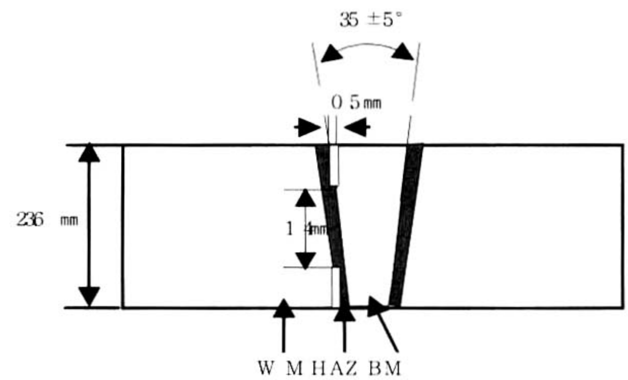



**Fig. 1.** Schematic diagram of welding groove in FCAW

**Table 1. Chemical composition and mechanical properties of RE36 steel pecimen and chemical composition of filler metals**

(a) Chemical composition of RE36 steel(%)

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

(b) Mechanical properties of RE36 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 |

**Table 2. Welding parameters in FCAW**

| Pass No. | Welding process | Shielding gas | Filler metals | | Type & polarity | Current (A) | Voltage (V) | Travel speed (cm/min) |
|---|---|---|---|---|---|---|---|---|
| | | | AWS class | Dia.(mm) | | | | |
| 1 | | | | | | 180~240 | 23~29 | 10~20 |
| 2 | FCAW | $CO_2$ | E80T1-K2 | 1.2 | DCRP | 220~280 | 25~32 | 20~30 |
| 3~8 | | | | | | 250~300 | 28~32 | 20~40 |

2 and a welding method for the present investigation is adopted with FCAW(Flux Cored Arc Welding). PWHT condition is that the degree of heating temperature at per hour in 80℃ and heated until at 550℃, 600℃, 650℃ and kept for 1.5 hours at each temperature, after that, it was annealed.

Although it is commonly reported that the temperature for PWHT is between 550℃~650℃.[17)] In the present study PWHT was performed at temperature of at 550℃, 600℃, 650℃ and an optimum temperature for corrosion resistance was also observed in electrochemical view.

### 2.2 Experimental method

#### 2.2.1 Electrochemical test

The surface area of the test specimen for measuring corrosion potential was divided into 2 ways. One is 6.5 ㎠ involving together BM, HAZ, WM parts with polished sand paper No. 600 and other parts was also insulated with silicon coating. Another is 8 ㎟ for individual measuring of each part(BM, HAZ, WM) with polished sand paper No. 2000.

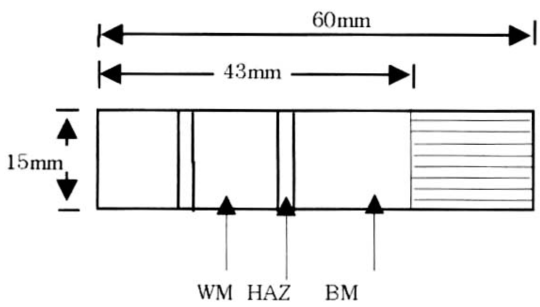



**Fig. 2.** Schematic diagram of corrosion potentialtest specimen and polarization experimental specimen

On the other hand, the equipment of polarization measurement was CMS 100 for Gamry CO. LTD and polarization curves was measured with scanning speed 1 ㎷/sec using Reference Electrode of SCE and Counter Electrode of Pt, and the size of test specimen for measuring corrosion potential including all parts of welded area are shown in Fig. 2. And calculated corrosion current densities by using Stern-Geary equation or diffusion limiting current density in anodic and cathodic polarization curves.

### 2.2.2 SSRT test

Fig. 3 show an equipment for SSRT test as shown in

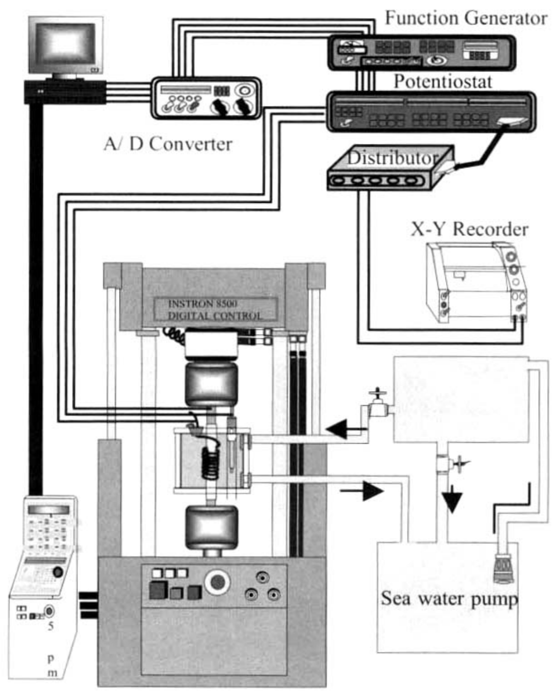



**Fig. 3.** Schematic diagram of slow strain rate test experimental apparatus

Fig. 3, measuring surface area of test specimen is directly subject to in sea water cell and upper and lower part of specimen was fitted with jack of instrong machinery (Model : 8500) and sea water of the cell was flowed continuously from expansion tank to bottom tank by circulating pump. And SSRT test was carried out with speed of 10-6/sec during constant polarization potential was applied to the measuring surface of cell with potentiostat (HA501G) and with function generator(HB-111) equipments. Chemical composition of sea water used in the present measurement are shown in Table 3.

**Table 3. Qualities of natural sea water solution used in the SSRT experiments**

| Temperature | Specific resistance | pH | Chloride | Dissolved oxygen | Redox potential |
|---|---|---|---|---|---|
| 23℃ | 21.46 Ωcm | 8.0 | 16,197ppm | 7.7ppm | +210mV |

## 3. Results and discussion

### 3.1 Mechanical property

Tensile test was carried out on the HAZ part having a artificial notch of the test specimen subject to sea water cell with SSRT method by applying constant polarization potential so that HAZ part was certainly fractured during tensile test with parameters such as As-welded, PWHT, and variation of applied polarization potential to HAZ part of test specimen.

Table 4 shows mechanical properties obtained from as a function of applied cathodic potential in case of As-welded condition and PWHT at 550℃, which are maximum tensile strength, yield strength, fracture strength, elongation, time to failure and strain ratio and variation of maximum tensile strength are shown in Fig. 4 as a function of applied cathodic potential in case of As-welded and PWHT at 550℃, as shown in Fig. 4, in case of As-welded, the maximum tensile strength at -770 ㎷(SCE) indicated the most high value among those values obtained in other potential and their values are decreased according to shifting to low applied potential gradually, on the other hand maximum tensile strength in case of PWHT at 550℃, show almost constant value regardless of applied cathodic potential, especially maximum tensile strength with PWHT at 550℃ exhibited high values more than that of As-welded condition in applied cathodic potential range from -875 ㎷(SCE) to -1000 ㎷(SCE).

**Table 4. Mechanical properties obtained on the HAZ with As-welded and PWHT by SSRT method as a function of applied cathodic polarization potential.**

| | | Stress at Max Load(MPa) | | Yield Strength (MPa) | | Stress at Final Failure (MPa) | | Elongation (%) | | Time to Fracture(Hrs) | | Strain to Failure Ratio | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | As-welded | PWHT | As-welded | PWHT | As-welded | PWHT | As-welded | PWHT | As-welded | PWHT | As-welded | PWHT |
| at Air | | 659.2 | 677.1 | 493.4 | 612.7 | 220.7 | 238.7 | 5.51 | 6.14 | 45.94 | 50.36 | | |
| at Sea Water | Ecorr | 625.8 | 642.7 | 229.0 | 458.9 | 215.2 | 217.8 | 4.75 | 5.61 | 38.96 | 46.09 | 0.8623 | 0.8669 |
| | -770㎷ | 673.5 | 624.6 | 508.9 | 386.9 | 228.5 | 210.7 | 5.49 | 5.76 | 45.54 | 47.33 | 0.9955 | 0.8901 |
| | -850㎷ | 608.0 | 613.0 | 451.1 | 471.1 | 210.6 | 242.9 | 4.64 | 4.93 | 37.31 | 39.52 | 0.8418 | 0.7605 |
| | -875㎷ | 592.9 | 609.4 | 461.1 | 484.5 | 284.6 | 208.4 | 4.16 | 4.49 | 33.81 | 37.15 | 0.7544 | 0.6932 |
| | -900㎷ | 590.7 | 617.7 | 470.2 | 445.4 | 231.6 | 239.8 | 4.00 | 4.38 | 32.91 | 35.96 | 0.7293 | 0.6757 |
| | -1000㎷ | 484.2 | 610.6 | 385.2 | 432.0 | 288.7 | 225.3 | 2.54 | 3.66 | 20.81 | 30.09 | 0.4604 | 0.5655 |

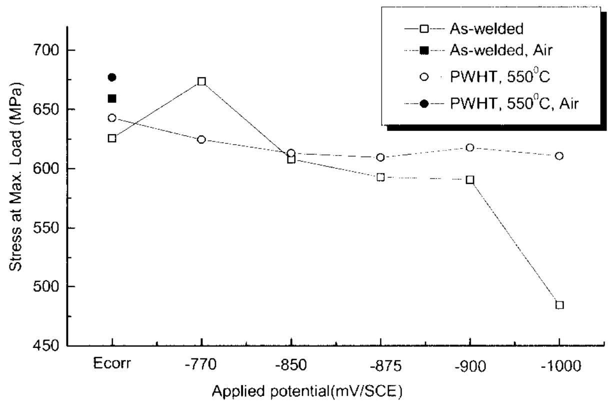



**Fig. 4.** Relationship between stress at max. load and applied cathodic potential in case of As-welded and PWHT of 550℃

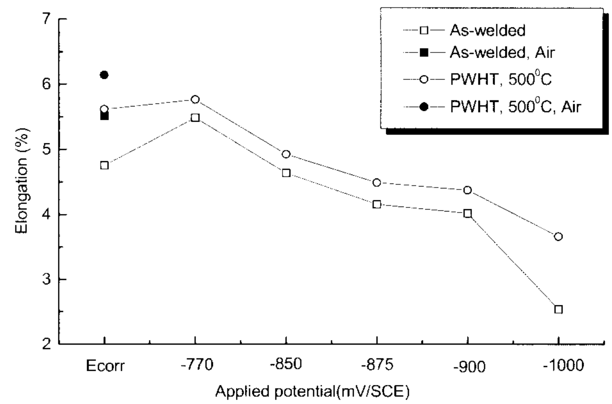



**Fig. 6.** Relationship between elongation and applied cathodic potential as a function of PWHT condition in FCAW

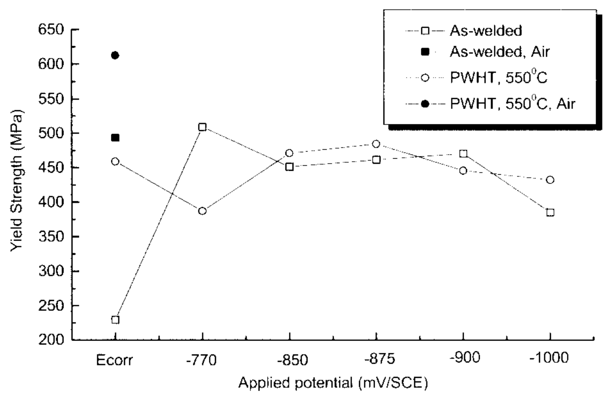



**Fig. 5.** Relationship between yield strength and applied cathodic potential as a function of PWHT condition in FCAW

Fig. 5 shows yield strengths as a function of applied potential, as shown in Fig. 5 it is considered that there is no a special correlation between yield strength and applied potential in both cases of PWHT at 550℃ and As-welded condition.

Fig. 6 shows that elongation is being decreased with applied potential shifting to low cathodic potential which is easy to get hydrogen evolution reaction however elongation values with PWHT at 550℃ is thought to be bigger more or less than those of As-welded condition through applied all potentials range, therefore it is suggested that hydrogen embrittlement is easier to product when applied cathodic potential have a lower potential gradually and it is thought to lead the possibility of hydrogen embrittlement when the applied cathodic potential is shifted to under -875 ㎷(SCE).

Until now mechanical properties of RE 36 steel was investigated by SSRT method with constant cathodic polarization potential and from these results it is assumed to be the susceptibility of hydrogen embrittlement caused

**Photo. 1.** SEM fractography at air, $E_{corr}$ and applied potential -770 mV(SCE), -850 mV(SCE) in HAZ parts

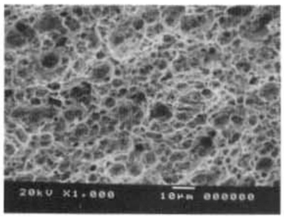
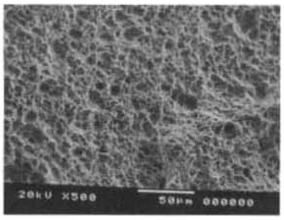
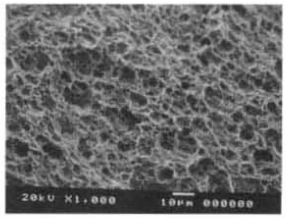
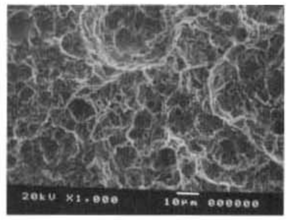
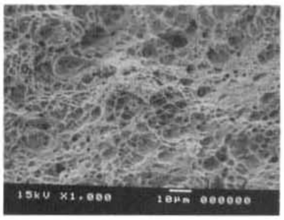
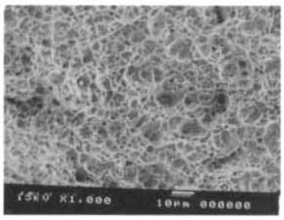
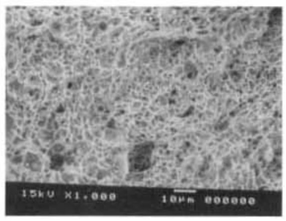
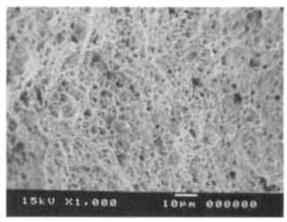
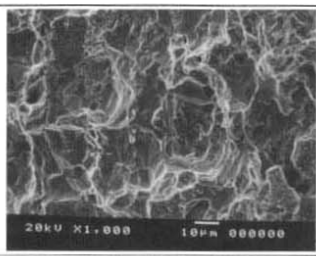
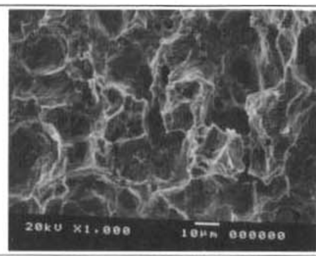
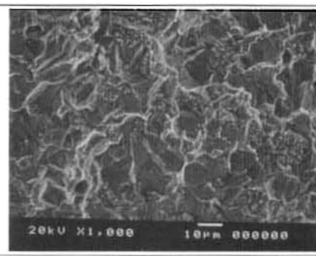
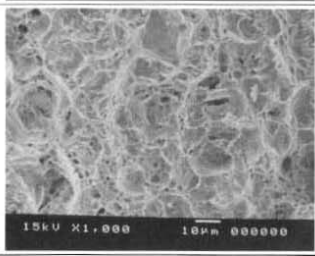
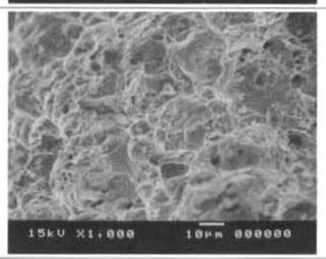
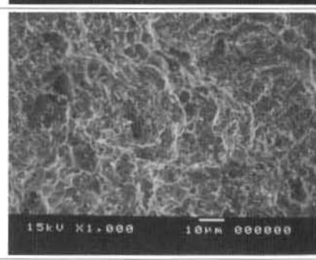
| | Air | $E_{corr}$ | -770 mV(SCE) | -850 mV(SCE) |
|---|---|---|---|---|
| As-welded |  |  |  |  |
| PWHT |  |  |  |  |

**Photo. 2.** SEM fractography at applied potential of -875 mV(SCE), -900 mV(SCE) and -1000 mV (SCE) in HAZ parts

| | -875 mV(SCE) | -900 mV(SCE) | -1000 mV(SCE) |
|---|---|---|---|
| As-welded |  |  |  |
| PWHT |  |  |  |

by low cathodic potential with hydrogen evolution, however these investigation are not quantitatively examined but qualitatively. If hydrogen embrittlement can be estimated in terms of quantitative view, it will be available to provide a beneficial reference.

Photo. 1 and photo. 2 show the SEM fractographies of fractured surface by SSRT method as a function of applied cathodic potential. As shown in photo. 1 dimple was indicated wholly at air, $E_{cor}$, and -770 mV(SCE) regardless of PWHT or As-welded condition. However at -850 mV (SCE), Fractography of As-welded condition shows the mixed phenomena with dimple and Q.C(quasi cleavage) while dimple was only observed in PWHT condition. On the other hand brittle fractures involving Q.C(quasi cleavage) fracture mode was wholly observed at -875 mV (SCE), -900 mV(SCE), and -1000 mV(SCE) with As-welded condition however in PWHT condition, it seems to be mixed phenomena with a little dimple and Q.C(quasi cleavage) at -875 mV(SCE), -900 mV(SCE), while Q.C (quasi cleavage) was wholly indicated at -1000 mV(SCE) thus Q.C(quasi cleavage) fracture mode is generally considered to be observed in the range of hydrogen embrittlement.[21)-23)] From these results it seems that the susceptibility of hydrogen embrittlement is predominantly decrease with increasing elongation and the amount of dimple observed in the brittle fractured surface due to

PWHT. On the other hand, although the cathodic potential of -850 mV(SCE) is the range of concentration polarization due to oxygen reduction reaction, the influence of hydrogen embrittlement appeared at -850 mV with As-welded condition. So it is considered that this is why that atomic hydrogen (H) owing to $H^{+}+e \rightarrow H$ reaction with decreasing of pH by hydrolysis reaction ($FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl$) in the inside of notch can be entered to interior of metal.[24)-25)] Consequently it is suggested that an optimum cathodic protection potential range not causing hydrogen embrittlement is from -770 mV(SCE) to -850 mV(SCE) in As-welded condition, while is from -770 mV(SCE) to -875 mV(SCE) in PWHT condition of 550℃.

## 4. Conclusion

Corrosion resistance was increased with PWHT, especially an optimum corrosion resistance effect was apparently observed with PWHT of 550℃ with corrosion potential shifting to nobel direction, however the effect of corrosion resistance using PWHT of various temperature was not certainly indicated at all times.

Hydrogen over voltage on the cathodic polarization curves was increased with PWHT of 550℃ compared to As-welded condition. On the other hand it seems that there is no correlative relation between maximum tensile strength, yield strength and hydrogen embrittlement, however the value of elongation was decreased with applied potential shifting to low potential direction which may be caused by hydrogen evolution and Q.C(quasi cleavage) fracture mode was also observed in the low potential range, and was significantly increased with decreasing the value of elongation due to shifting to low potential. Thus hydrogen embrittlement is considered to be observed in the low potential range which may be caused by atomic hydrogen evolution.

The susceptibility of hydrogen embrittlement was also decreased with increasing elongation and the amount of dimple due to PWHT of 550℃ than that of As-welded condition.

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