# Effects of Heat Treatment on the Corrosion Behavior of ASTM A-36 Steel

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*Abstract*—**The effects of different tempering temperatures and heat treatment times on the corrosion resistance of rolled ASTM A-36 steel in various concentrations of hydrochloric acid (HCl) and sodium chloride (NaCl) were studied in this work, using the conventional weight loss measurement. Rolled and heat-treated specimens were placed in the acidic media for five days and for seven days in NaCl, respectively, and the corrosion rates were evaluated. The microstructure of steel before and after heat treatment was studied. Corrosion resistance revealed remarkable changes from the effect of tempering after water or oil quenching of steel. Generally, the corrosion rate increases from the effect of steel hardening. Tempering of water-quenched steel at 450C$^o$ for one hour highly improves the corrosion resistance of 0.27% carbon steel.**

***Keywords-corrosion; HCl; NaCl, A-36 Steel***

## I. INTRODUCTION

The high cost of the corrosion effects of industry, domestic applications, and public sector worldwide highlights the need for improved corrosion measures. Effective corrosion inhibition has a high economic value, as the annual corrosion cost is estimated to reach 3–4% of the GDP in developed countries [1-4]. In the oil, gas, and chemical industries, corrosion is one of the most challenging tasks, and it is assumed that it costs $170 billion per year. It is not only the high cost of corrosion, but also the health and environmental risks associated with potential failures of the oil and gas industry that drive the developments of corrosion-resistant materials and improved corrosion mitigation strategies worldwide [5-9]. Low-cost carbon steels are used as the preferred construction material across industries and are considered a more economical option than the costly corrosion-resistant alloys. Carbon steels typically contain less than 1.5% carbon content along with the minute presence of Mn, Si, P and S. Based on the percentage of carbon (C), the classification is further divided into three forms, namely low-carbon steels (<0.25% C), medium-carbon steels (0.25–0.70% C) and high-carbon steels (0.70–1.05% C). Carbon steels are used in a wide range of applications, such as structural components, industrial pipes, and kitchen appliances. With regard to applications in the oil and gas industry, the carbon dioxide ($CO_2$) corrosion could be considered as one of the major forms of corrosion [10-13]. In this study, we discuss carbon steel as the most employable material for the construction of gas and oil pipelines, desalination plants, and water treatment construction and equipment. Most of the corrosion issues occurring in the oil and gas and water treatment industries are related to pipelines and the conditions of exposure of the carbon steel that deem the selection of the suitable type of carbon steel.

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## II. EXPERIMENTAL WORK

Steel ASTM A-36 (chemical composition shown in Table I) was heated to the austenitizing temperature of 870$^\circ$C for one hour followed by water quenching (WQ), oil quenching (OQ), air-cooling (AC) and furnace cooling (FC). Representative samples of WQ and OQ medium-carbon steel were subjected to tempering at temperatures of 250$^\circ$C, 350$^\circ$C, 450$^\circ$C and 550$^\circ$C (T1, T1, T3 and T4, respectively). Corrosion tests were carried out for as-rolled (AR) and heat-treated (HT) steels in various concentrations of HCl and NaCl, as shown in Table II. Specimens were placed for five days in the acidic media and for seven days in NaCl. Corrosion rates were calculated using the weight loss method in mils per year (mpy- 1mil=$10^{-3}$inch). An optical micrograph was investigated for the AR and HT steels. The effect of tempering temperatures on the corrosion rate of water-quenched steel has been investigated according to Table III.

TABLE I. CHEMICAL COMPOSITION OF AR ASTM A-36 STEEL IN WT.%

| C | Mn | Si | Cu | Al |
|---|---|---|---|---|
| 0.27 | 0.84 | 0.24 | 0.095 | 0.003 |
| **P** | **S** | **Zn** | **V** | **Ta** |
| 0.02 | 0.02 | 0.05 | 0.006 | 0.06 |

TABLE II. CONCENTRATIONS OF USED HCL AND NACL FOR CORROSION TESTS

| | Concentration (%) | | | | |
|---|---|---|---|---|---|
| **HCl** | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 |
| **NaCl** | 0.4 | 0.45 | 0.5 | 0.55 | 0.6 |

TABLE III. HEAT TREATMENTS FOR ASTM A-36 STEEL

| AC | FC | WQ/870$^o$C | | | |
|---|---|---|---|---|---|
| | | **WQT1** | **WQT2** | **WQT3** | **WQT4** |
| 870°C | 870°C | 250°C | 350°C | 450°C | 550°C |
| **AC** | **FC** | **WQ/870$^o$C** | | | |
| | | **OQT1** | **OQT2** | **OQT3** | **OQT4** |
| 870°C | 870°C | 250°C | 350°C | 450°C | 550°C |

## III. RESULTS AND DISCUSSION

### *A. Corrosion Rate of ASTM A-36 Steel in HCl*

Figure 1 shows the effect of the cooling rate from the austenitizing temperature on the corrosion rate of ASTM A-36 steel using HCl with different concentrations for 5 days. The corrosion rate slightly decreased with a decreasing cooling rate at 0.1% HCl. By increasing the cooling rate, the corrosion rate increased to the maximum of 0.25% HCl. With a further increase in the HCl concentration to 0.3%, the corrosion rate decreased. In general, AR steel revealed a lower corrosion rate compared to HT steel. The corrosion rate increases for the AC and FC specimens after heating to 870°C to about twice the corrosion rate of the AR steel. The corrosion rate for the oil-quenched steel shows a maximum corrosion rate of up to 0.2% HCl. With a further increase of HCl, the water-quenched steel reveled a higher corrosion rate. This could be explained by the effect of the martensite phase produced after WQ. The effect of the tempering temperature after WQ revealed a remarkable effect on the corrosion rate of the used steel in HCl. As shown in Figure 2, the corrosion rate reaches its maximum after tempering at 350°C (WQT2) and 250°C (WQT1) respectively. Tempering at 450°C (WQT3) revealed remarkable improvement in the corrosion rate for the water-quenched steel. A further increase in the tempering temperature up to 550°C (WQT4) leads to an increase in corrosion resistance. It can be summarized that tempering at 450°C is the best for the corrosion resistance of WQ ASTM A-36 steel.

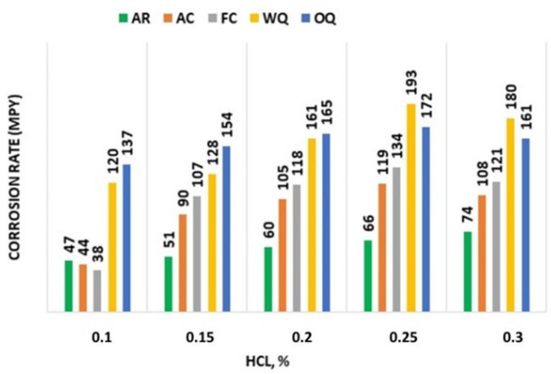


Fig. 1. Effect of the cooling rate after austenitizing treatment on the corrosion rate of ASTM A-36 steel (using HCl)

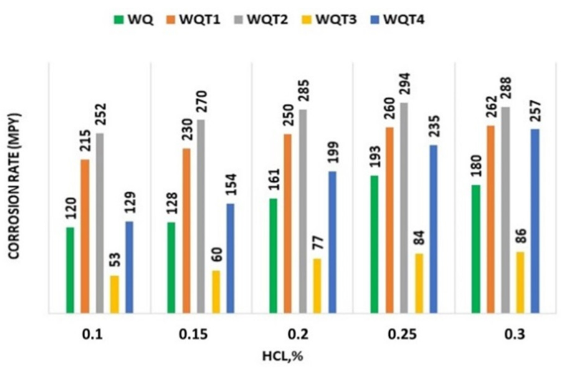


Fig. 2. Effect of tempering temperature after WQ on the corrosion rate of ASTM A-36 steel (using HCl)

The effect of the tempering temperature of the OQ steel on the corrosion rate in HCl is summarized in Figure 3. The maximum corrosion was measured after tempering at 250°C (OQT1). By increasing the tempering temperature, the corrosion rate gradually decreased. Generally, the corrosion rate of ASTM A-36 steel after OQ and tempering is higher than the one after WQ and tempering. Thus, if the mechanical properties of this steel need to be increased, tempering of OQ steel is not recommended if this steel will be subjected to HCl.

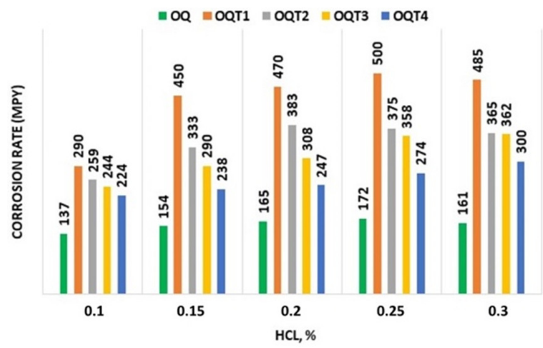


Fig. 3. Effect of tempering temperature after OQ on the corrosion rate of ASTM A-36 steel (using HCl)

### *B. Corrosion Rate of ASTM A-36 Steel in NaCl*

The corrosion rates of the heat-treated specimens in a marine medium (NaCl) are low when compared to the AR steel, as shown in Figure 4. This is because the AR steel consists mainly of a pearlitic-ferritic structure in which each crystal consists of alternate layers of ferrite and cementite. It was observed that ferrite is anodic to cementite and this corrodes with moisture as the electrolyte. This was confirmed from the microstructure of the AR steel shown in Figures 7-9. Figure 4 shows the effect of the cooling rate from the austenitizing temperature on the corrosion rate of this steel using NaCl with different concentrations for 7 days.

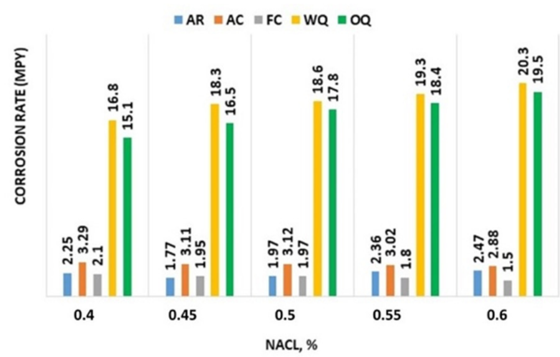


Fig. 4. Effect of heat treatment on the corrosion rate of ASTM A-36 steel (using NaCl)

The AC steel shows a little increase in the corrosion rate compared to the AR steel. On the other hand, the FC steel recorded a slight decrease in the corrosion rate. A further increase in the cooling rate from the austenitizing temperature of ASTM A-36 steel revealed a higher increase in the corrosion rate, which reaches its maximum after WQ and OQ. It was noticed that the corrosion rate of ASTM A-36 steel in HCl is much higher compared with the corrosion rate in NaCl, as shown in Figures 1 and 4. The corrosion resistance of this steel is good when using NaCl even without heat treatment. It is recommended to avoid using WQ or OQ treatments if heat treatment is required for this steel. The tempering temperature after WQ revealed a remarkable effect on the corrosion rate of the used steel in NaCl, as shown in Figure 5. The corrosion rate sharply decreases after tempering at different temperatures, with a minimum corrosion rate after tempering at 450°C (WQT3).

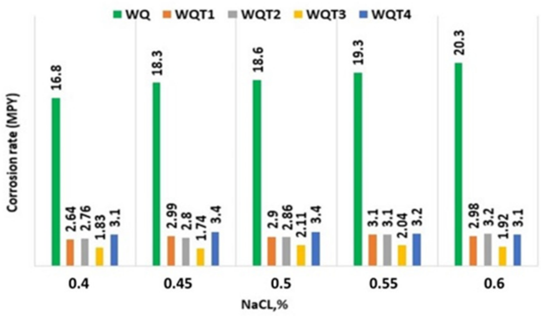


Fig. 5. Effect of tempering temperature after WQ on the corrosion rate of ASTM A-36 steel (using NaCl)

The effect of the tempering temperature of the OQ steel on the corrosion rate in NaCl is summarized in Figure 6. The corrosion rate highly increased to double after tempering at 250°C (OQT1). By increasing the tempering temperature, the corrosion rate sharply decreased, revealing minimum values after tempering at 450°C (OQT3). Generally, the corrosion rate of ASTM A-36 steel after OQ and tempering is much lower than WQ and tempered steel. Thus, if the mechanical properties of this steel need to be increased, tempering of WQ or OQ steel at 450°C is the best heat treatment if this steel will be subjected to NaCl.


Fig. 6. Effect of tempering temperature after OQ on the corrosion rate of ASTM A-36 steel (using NaCl)

## C. *Microscopic Observation of ASTM A-36 Steel*

The microstructures obtained are shown in Figures 7-9. The microstructure produced by the AR steel consists of a pearlitic-ferritic structure, while the microstructures produced by the processes consist of a duplex ferrite martensite microstructure. The strong deformable second phase consists predominantly of martensite, with some bainite and retained austenite. Martensite provides the strength in the steel whereas the ferrite provides the ductility. The strong second phase is dispersed in a soft ductile ferrite matrix. The effect of different cooling rates from solution treatment temperatures are shown in Figure 7. This revealed mainly a pearlite in ferrite matrix. A martensite phase was clearly revealed after a high cooling rate. This could explain the higher increase in the corrosion rate of the WQ and OQ steel in HCl and NaCl.

(a)

(b)

(c)

(d)

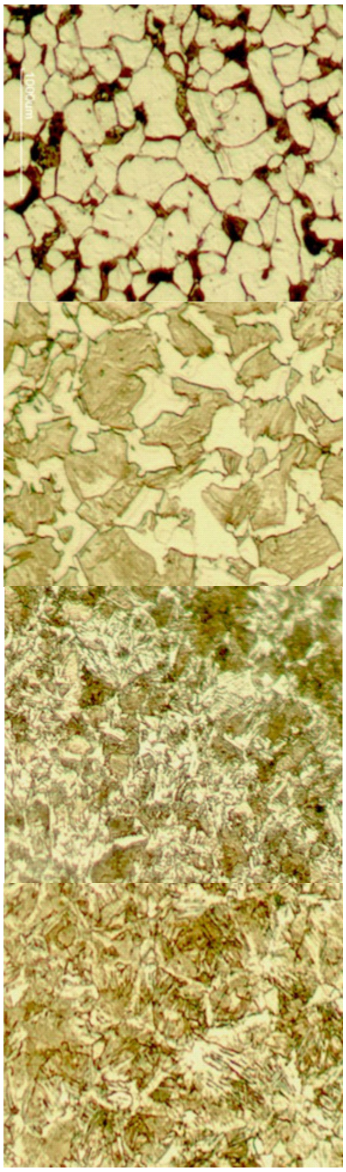

Fig. 7. Effect of different cooling rates on the microstructure of ASTM A-36 steel: (a) AR, (b) AC, (c) OQ and (d) WQ, X200

The effect of the tempering temperature on the microstructure of ASTM A-36 steel is summarized in Figures 8 and 9. Figure 8 shows the optical micrograph of the WQ steel after tempering at different temperatures. Remarkable changes in the microstructure and different phases have been revealed.

The shape of the martensite phase obtained by rapid quenching changed and became courser after tempering. In addition, after tempering, WQ steel shows changes in the microstructure as shown in Figure 9. In contrast with the corrosion results, these changes in microstructure after heat treatment could be the reasons for the change in corrosion rate.

(a)

(b)

(c)

(d)

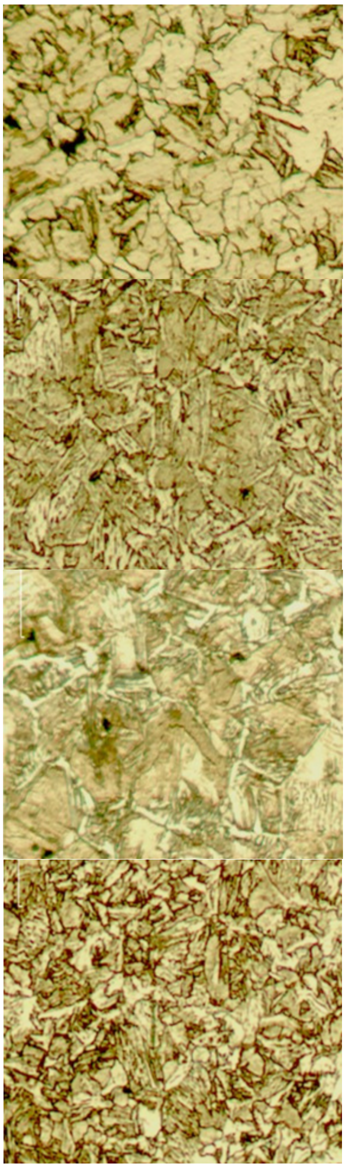

Fig. 8. Effect of tempering temperature on the WQ ASTM A-36 steel: (a) 250°C, (b) 350°C, (c) 450°C and (d) 550°C, X200

## IV. CONCLUSION

The research results have shown that the corrosion rate changes as an effect of heat treatment and tempering conditions. Also, the results revealed that the corrosion resistance of the rolled ASTM A-36 steel can be improved by carrying out heat treatment on this steel. This is because better corrosion properties were obtained from the heat-treated steel samples compared with the as-rolled medium-carbon steel.

(a)

(b)

(c)

(d)

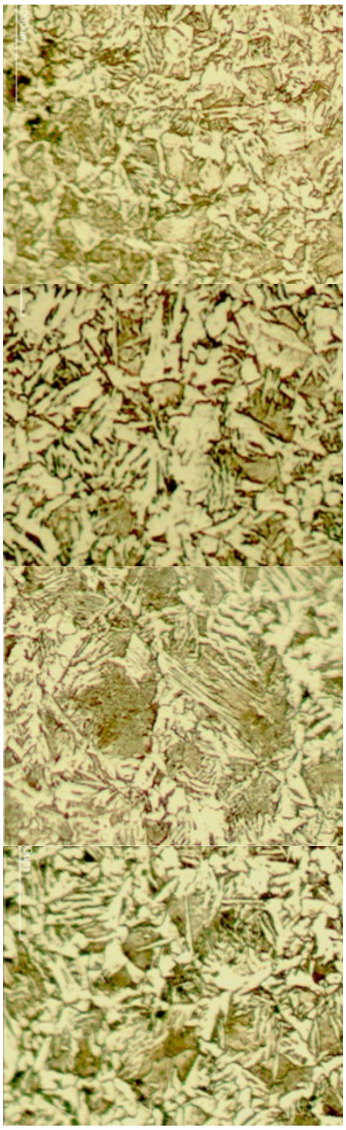

Fig. 9. Effect of tempering temperature on the OQ ASTM A-36 steel: (a) 250°C, (b) 350°C, (c) 450°C and (d) 550°C, X200

Thus, this steel can be used safely in oil and gas industries and water treatment fields. Generally, the corrosion rate increases due to the effect of hardening of the steel. Tempering of water-quenched steel at 450C$^{o}$ for one hour improves highly the corrosion resistance of ASTM A-36 steel.

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