Journal of Engineering and Applied Sciences 3 (5): 396-400, 2008
ISSN: 1816-949X
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# Evaluating the Corrosion Rates and Tensile Properties of Quenched and Tempered Mild Steel Rods

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**Abstract:** The corrosion rates and tensile properties of mild steel rods, quenched in water and tempered within temperature range of 200-600°C at an interval of 100°C, were experimentally investigated and presented. Sodium chloride solution containing approximately 3.5% weight of solute, prepared from 97.5% table salt, was used as the corrosive medium. Some as-quenched and tempered specimens were retained as non-corroded specimens while other identical specimens were totally immersed in seawater medium for 90 uninterrupted days. Corrosion in saltwater was found to have adverse effects on both the strength and ductility of the specimens; the ultimate tensile strength and percentage elongation at fracture of as-quenched specimen were found to decrease from 523.44-498.68 MPa and from 12.007.14%, respectively due to corrosion in saltwater. Also, increase in tempering temperature was observed to have reduction effects on strength but increasing effect on ductility; the ultimate tensile strength and percentage elongation at fracture of as-quenched specimen were observed to vary from 523.440-470.39 MPa and from 12.0015.28%, respectively due to tempering at 400°C for 45 min. Weight loss of test specimens was measured to evaluate the corrosion rate. However, the susceptibility of the specimens to corrosion is reduced with increase in tempering temperature. Remarkable resistance to corrosion was observed within temperature range of 300600°C; the corrosion rate of as-quenched specimen decreases from 31.43-17.85 mils year$^{-1}$ due to tempering at 400°C for 45 min. The percentages of resilience retained after tempering are found to be closer in values to the percentage corrosion rates of identical specimens. This shows corrosion rate to be a function of the level of resilience retained in the specimens.

**Key words:** Residual stress, stress corrosion failure, corrosion rates and tempering

## INTRODUCTION

Corrosion is the primary means by which metals deteriorate and it is affected by the properties of both the metal and its environment. Corrosion often causes exorbitant losses of materials, energy and money and results in increased maintenance, unplanned shut-downs and possible serious accidents in engineering installations including offshore facilities. Metals are usually observed to fail by stress corrosion cracking-A failure mechanism that is caused by combined action of corrosive medium and tensile stress above some minimum threshold values. The tensile stress may be due to previous cold working or quench-hardening of the metal.

Several research works on stress corrosion cracking of steel in aqueous environments have centered mainly on the effect of inhibitors (Lotto, 1992; Oni, 1997) on the corrosion rates of metals. Also, stress corrosion of iron base alloys was found (Parkins, 1972; Oni and Ashaolu, 1991) to be assisted by hydrogen embrittlement and its inhibition caused by substances forming insoluble products with iron. Inhibition efficiency for uniform corrosion could be evaluated (Lotto, 1992; Pallos and Wallwork, 1982) using corrosion rate but for localized phenomenon such as stress corrosion cracking, time-to–fracture is usually employed. The synergistic inhibitive action of coal-tar fraction/halide mixtures has been found (El-Hosary and Saleh, 1985) to be better than that of the halide or coal tar-based products used alone in sulphuric acid. Also, many investigations (Oni, 1997, 1999; Stiksma and Bradford, 1985) have used elongation parameter and time-to-fracture to evaluate stress corrosion cracking resistance of metals.

In the present investigation, the corrosion rates and tensile properties of quenched and tempered mild steel rods were investigated. Constant extension rate tensile tests were carried out on as-quenched and tempered mild steel rods, strength and elongation parameters are used to determine the resistance to corrosion of the specimens.

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## MATERIALS AND METHODS

**Materials used and specimens' preparations:** The work materials used in this research work were mild steel rods of the same batch having 10 mm initial diameter. Chemical analysis showed the approximate composition of the specimens as 98.1% Fe, 0.25% C, 0.04% S and 0.04% P with other very-low percentage impurities. Tensile test specimens of length 80 mm having 40 mm long gauge section of 6 mm diameter were machined.

### Experimental test procedures

**Quenching and tempering:** All the respective specimens were heated in a Czechoslovakia-made electric furnace to a temperature of 900°C for 45 min, removed and quenched in water to room temperature. The temperatures attained in the electric furnace are within an accuracy of ±2°C. Some specimens were retained as as-quenched while others were tempered for 45 min within temperature range of 200-600°C at a temperature interval of 100°C. The temperature of each specimen was continuously measured by a chromel-alumel thermocouple inserted into a hole drilled into a mild steel rod of identical dimension, acting as a dummy. The specimens were then removed and allowed to cool in still air.

**Corrosion:** Some as-quenched and tempered specimens were retained as non-corroded specimens while other identical specimens were totally immersed in seawater medium for 90 uninterrupted days. Weight loss of test specimens was also measured to evaluate the corrosion rate.

Sodium chloride solution containing approximately 3.5% weight of solute, prepared from 97.5% table salt, was used as the corrosive medium. This approximates to the average salt concentration in quiet seawater (Kamma and Anagbo, 1989).

Corrosion rate of the specimen is evaluated (Fontana and Greene, 1978) as:

$$\text{C.R. (mils year}^{-1}\text{)} = 534\ w/\rho At$$

where, w is weight loss of material (mg), ρ is density of steel = 7.86 g cm$^{-3}$, A is area of immersion, $2\pi Rl$ = 2.9217 sq. inches (R and l being specimen's radius and length, respectively), t is immersion time, 90 days (i.e., 2160 h).

**Tensile test:** Tensile test specimens were used for determining the resistance to corrosion of the specimens. Respective non-corroded and corroded as-quenched and tempered tensile specimens were subjected to tensile test on a Tensometer. As straining continued, the tensile force versus displacement graph was plotted on a recording sheet with the aid of the rotating drum and cursor on the Tensometer. The force versus displacement curves were used to obtain the corresponding stress-strain curves, tensile properties such as elastic limit stress, resilience, yield strength, ultimate tensile strength and percentage elongation at fracture were obtained from the curves.

To confirm initial readings, a repeated test was done on a Universal Testing Machine made by Avery Denison Limited, England. They showed good agreement to ±3%.

## RESULTS AND DISCUSSION

**Corrosion and tensile properties:** Figure 1 shows the tensile stress-strain curves for non-corroded as quenched and tempered mild steel rods. From Fig. 1, the increases of tempering temperatures have reduction effects on strength but increasing effects on percentage elongation at fracture. Remarkable increase in elongation at fracture starts from tempering temperature of 400°C. From the assessment of the area under the curves, the highest resilience is exhibited in as-quenched specimens, while substantially-enhanced ductility and toughness are displayed by 500 and 600°C tempered mild steel rods.

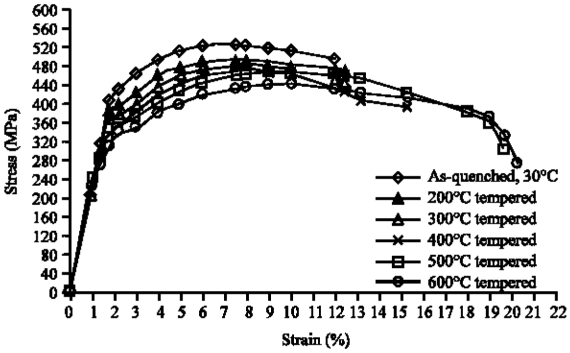

Fig. 1: Stress-strain curves of non-corroded quenched and tempered mild steel rods

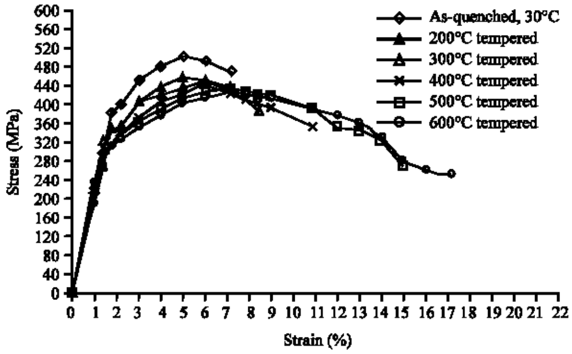

Fig. 2: Stress-strain curves of corroded quenched and tempered mild steel rods

Table 1: Variations of tensile properties of non-corroded and corroded mild steel rods with tempering temperatures

| | Non-corroded specimens | | | | Seawater-corroded specimens | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Tempering temperature T (°C) | Elastic limit stress (MPa) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation at fracture (%) | Elastic limit stress (MPa) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation at fracture (%) | Elongation ratio |
| 30 | 406.73 | 427.95 | 523.44 | 12.00 | 381.9 | 399.65 | 498.68 | 7.14 | 0.595 |
| 200 | 386.05 | 393.12 | 491.61 | 12.43 | 346.60 | 353.68 | 456.24 | 7.85 | 0.631 |
| 300 | 367.42 | 375.95 | 484.54 | 13.14 | 321.85 | 350.14 | 445.63 | 8.43 | 0.641 |
| 400 | 307.70 | 353.68 | 470.39 | 15.28 | 290.01 | 339.53 | 438.56 | 10.86 | 0.711 |
| 500 | 286.48 | 350.14 | 466.85 | 19.71 | 265.26 | 332.46 | 431.49 | 15.00 | 0.761 |
| 600 | 244.04 | 335.53 | 440.65 | 20.28 | 236.96 | 325.38 | 424.41 | 17.14 | 0.845 |

Figure 2 shows the corresponding tensile stress-strain curves for as-quenched and tempered mild steel rods corroded in seawater for 90 uninterrupted days. The comparison of the curves with those in Fig. 1 shows that corrosion has reduction/adverse effects on both the strength and ductility of the specimens.

Largest elongation at fracture among corroded specimens exhibited by 600°C tempered mild steel rod shows that it has highest resistance to the corrosive action of the seawater medium.

Table 1 shows the tensile properties of non-corroded and corroded mild steel rods at various tempering temperatures. From Table 1, the respective as-quenched specimen is found to be the strongest but least ductile of all the specimens since it exhibits highest values of elastic limit stress, yield strength and ultimate tensile strength but least percentage elongation at fracture. This could be attributed to the distorted lattice and the action of the quenched-in solute atoms that impede dislocation motion and thus strengthen the metal (Budinski, 1992).

Increases of tempering temperature necessitate more degrees of ease of dislocation movement and result in reduced strength but increased ductility and toughness of the specimens.

Figure 3 shows the variations of yield strength and ultimate tensile strength of non-corroded and corroded mild steel rods with tempering temperature. It can be seen that the strength of the mild steel rods decrease with an increase in tempering temperature, while the corrosive action of the seawater medium also has reductions effects on the strength of all specimens. Lesser reductions are observed in the values of yield strength compared to ultimate tensile strength values within temperature range of 300-600°C.

Figure 4 shows the variations of percentage elongation at fracture of non- corroded and corroded mild steel rods with tempering temperature. Increases of tempering temperature have increasing effects on the elongations of the specimens hence showing improvements in ductility.

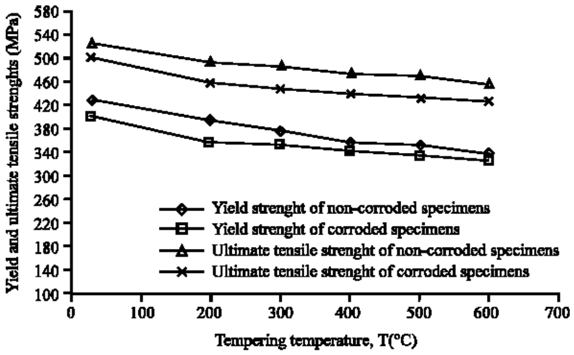

Fig. 3: Plot of yield and ultimate tensile strengths of non-corroded and corroded mild steel rods with tempering temperatures

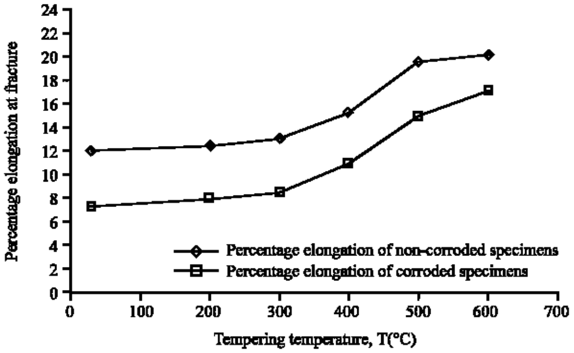

Fig. 4: Plot of percentage elongation at fracture of non-corroded and corroded mild steel rods with tempering temperatures

Ductility increases gradually with increase in tempering temperature up to 300°C, however, within temperature range of 300-600°C there are significant increases in ductility. Corrosion decreases the ductility of all the specimens, the least reduction effect is exhibited in 600°C tempered mild steel rod and thus indicating that it has highest resistance to the corrosive action of the seawater medium.

An effective measure of evaluating the susceptibility or, otherwise, resistance of a material to stress corrosion

Table 2: Variations of resilience, corrosion rates and percentages retained with tempering temperatures

| Tempering temperature T (°C) | Non-corroded specimens |  | Seawater-corroded specimens |  |  |
|---|---|---|---|---|---|
|  | Resilience (MPa) | Resilience retained (%) | Weight loss (mg) | Corrosion rate (mils year$^{-1}$) | Corrosion rate (%) |
| 30 | 0.4136 | 100.0 | 2920 | 31.43 | 100.0 |
| 200 | 0.3726 | 90.1 | 2722 | 29.30 | 93.2 |
| 300 | 0.3375 | 81.6 | 2450 | 26.37 | 83.9 |
| 400 | 0.2367 | 57.2 | 1658 | 17.85 | 56.8 |
| 500 | 0.2052 | 49.6 | 1380 | 14.85 | 47.3 |
| 600 | 0.1489 | 36.0 | 917 | 9.87 | 31.4 |

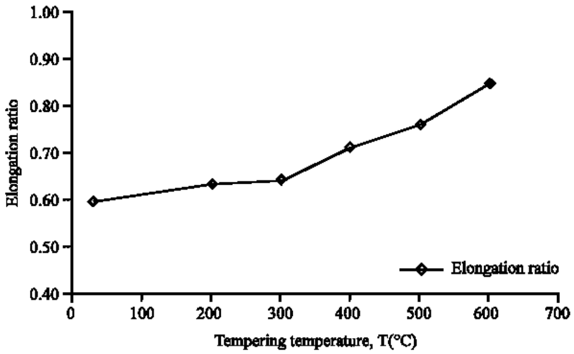

Fig. 5: Plot of elongation ratio of mild steel rods with tempering temperatures

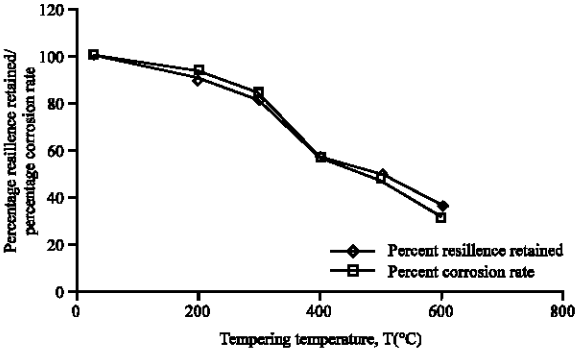

Fig. 6: Comparison between percentage resilience retained and percentage corrosion rate

cracking in a corrosive medium is the ratio of elongation at fracture of a corroded specimen to the elongation at fracture of the corresponding non-corroded specimen. If the ratio evaluated is near 1.0, then there is virtually no susceptibility to stress corrosion attack (Stiksma and Bradford, 1985).

Figure 5 shows the variations of elongation ratio of the corroded mild steel rods with tempering temperatures. Corroded as-quenched specimen shows the least value of elongation ratio of 0.595 (Table 1) indicating that it is the most susceptible to stress corrosion cracking of all the specimens.

The increase in elongation ratio with increase in tempering temperature up to 300°C shows gradual improvement in resistance to corrosion, however, further remarkable increases in elongation ratio are recorded, rising to 0.845 (Table 1) for 600°C tempered specimen exhibiting a very good resistance to corrosion.

**Resilience and corrosion rates:** Table 2 shows among others the variations of resilience and corrosion rates of mild steel rods with tempering temperatures. Resilience, $U_R$, is defined as the ability of a material to absorb energy when it is elastically deformed), ($U_R = \sigma_e^2 / 2E$) where $\sigma_e$ and E are the elastic limit stress and Young modulus of elasticity of the material, respectively. Young modulus of elasticity for mild steel is 200 GPa. Resilience and corrosion rates are found to decrease in values with tempering temperature. Using the method of linear regression, the empirical equation relating resilience, $U_R$ (MPa), with tempering temperatures, T (°C), within the range ($30°C \leq T \leq 600°C$) is given as:

$$U_R = 0.5487 - 0.000772T$$

with coefficient of linear correlation r = -0.9774.

The highest resilience exhibited by as-quenched mild steel rod can be explained by the peak level of martensitic phase as compared to the tempered specimens having various degrees of tempered-martensites. Also, as-quenched specimen displays highest corrosion rate of 31.43 mils year$^{-1}$. This may be attributed to accumulation of galvanic corrosion cells by the action of the quenched-in solute atoms and the distorted lattice coupled with the impedance to dislocation motion.

However, increases in tempering temperature have reduction effects on the corrosion rate of the as-quenched specimen; lowest corrosion rate of 9.87 mils year$^{-1}$. is exhibited by 600°C tempered mild steel rod. This can be explained by the reduction in inter-granular boundary layer with corresponding decreases in galvanic corrosion cells. The empirical equation, relating corrosion rate, C.R. (mils year$^{-1}$), to tempering temperatures, T (°C), is given as:

$$C.R. = 35.31 - 0.0405T$$

with coefficient of linear correlation r = -0.9665.

From Table 2, the percentages of resilience and corrosion rates of mild steel rods retained are found to decrease with increase in tempering temperatures. Figure 6 shows the effects of tempering temperatures on the percentages resilience of non-corroded specimens retained and the percentage corrosion rates of identical specimens.

In the present research work, the percentages of resilience retained after tempering are found to be closer in values to the percentage corrosion rates of identical specimens. This shows corrosion rate to be a function of the level of resilience retained in the specimens.

## CONCLUSION

The results in this research work can be concluded as follows:

- Corrosion is found to have reduction effects on both the strength and ductility of mild steel rods. However, the susceptibility of the specimens to corrosion is reduced with increase in tempering temperature. Remarkable resistance to corrosion is observed within temperature range of 300-600°C.
- Corrosion rate is found to be a function of the level of resilience exhibited by the specimens.

## ACKNOWLEDGEMENT

The authors acknowledge the University of Lagos, Akoka, Nigeria for the permission to use their Universal Testing Machine.

## NOMENCLATURE

$\sigma_e$ : Elastic limit stress.
E : Young modulus of elasticity.
$U_R$ : Resilience.
T : Tempering. temperature (°C).

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