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Mechanical Response of EN24T and EN36 Steels Subjected to Corrosion

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***Abstract*—** The purpose of this investigation was to examine the effect of corrosion on mechanical behavior of structural steels. Natural sea water was utilized to induce corrosion for the durations of 250, 500, 750, and 1000 hours. Two types of structural steels were considered: EN24T steel and EN36 steel. In order to characterize the behavior of steels under corrosion, tensile and hardness tests were conducted and their associated parameters were measured and compared with non-corroded samples. To analyze the effect of corrosion on the surface, microstructure analysis was carried out using scanning electron microscopy. The microstructure results reveal that, as the immersion time intervals increase nucleation of pits and exfoliation of surface layers is observed. Tensile test results and the associated parameters show a decreasing trend with increase in exposure durations in natural sea water. Finally, the comparative study signifies that EN24T steel shows a better resistance to natural sea water corrosion when compared with EN36 steel.

Keywords- *EN 24 T Steel; EN 36 Steel; Corrosion; Mechanical Properties*

I. Introduction

EN24 and EN36 are nickel-chromium-molybdenum based alloy steels widely used in automobile applications as shafts, rollers, screws, punches, dies, studs, axels, retaining rings, connecting rods and gears. EN24 is readily available in tempered (T) condition. The ability of these steels to be hardened easily encourages for the use in heavy duty applications where wear, hardness, and high tensile strength are of prime importance [2-3]. Additionally, nickel in EN36 increases resistance to shock loads. Case carburizing increases its tensile strength and promotes its use in heavy load applications of high strength gears, connecting rods, heavy shafts, and couplings [4-5]. Mechanical performance of these alloy steels under critical environmental conditions will deteriorate. Applications under offshore conditions, steels will be subjected to chloride induced corrosion with increased conductivity of electrolytic film on the metal surface which destroys the passivity [6-10]. The frequent change in temperature, dissolved inorganic nitrogen, and other contamination also induces corrosion particularly with aqueous precipitation such as fog and salinity in coastal regions [11]. The critical research survey signifies that, the inducement of atmospheric corrosion results in pitting and excessive exfoliation of passive layers and prolonged exposure leads to hydrogen embrittlement which finally results in deterioration of mechanical strength and service life of the material. If these materials are exposed to corrosive environment that contains ions of chloride, the passivity that resist corrosion will breakdown resulting in formation of micro pits at local surface areas while remaining area will retain passivity. Thus, there will be phase difference on the surface that leads to exfoliation of the surface. With increase in exposure durations, there is continuous pit formation and exfoliation resulting in material loss leading to deterioration of mechanical properties.

Most of the nucleated micro pits are concealed by corrosion products and are unrevealed. These unrecognized pits will have either stable or metastable propagation creating flaws that leads to intergranular attack. As a result, there will be a catastrophic pre-mature failure of the components [12-16]. References [17-19] describe the influence of corrosion on microstructure of metallic materials. The microstructure analysis of corroded surface shows the presence of dark phases that would contain excess of Fe atoms which promote corrosion and bright phases which indicate exfoliated passive layers. Concentrated dark spots on the surface are the pits formed due to corrosion [20]. There are several literatures that describe the influence of corrosion on chemical behavior and degradation effect on mechanical behavior of high strength steels [21-31]. However, the effect of corrosion on mechanical properties of EN24T steel and EN36 steel is seldom reported. In this investigation, EN24T and EN36 steels are exposed to sea water for different time intervals and the corrosion effect on microstructure and mechanical behavior is discussed.

II. Experimental program

A. *Test materials and specimens*

EN24T and EN36 steels were used to study the effect of natural sea water corrosion on their mechanical properties. The steels were purchased in the form of circular rods of diameter 20 mm and length 1000 mm, from Hi-Tech Sales Corporation Private Limited, India. The detailed chemical composition (wt. %) is given in Table 1.

Table 1 – Chemical Composition of EN24T and EN36 steels

Materials	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
EN 24T	0.38	0.20	0.45	0.05	0.05	0.90	0.2	1.3	remaining
EN 36	0.12	0.1	0.3	0.05	0.05	0.6	0.01	3	remaining

In order to investigate the mechanical behavior, the corrosion test samples were prepared for tensile test as shown in Fig. 1(a) where the specifications of ASTM E8 [32] were applied. On the other hand, round shaped specimens with diameter of 16 mm and 10 mm thickness were prepared to measure the hardness in accordance with ASTM E92 [33] as shown in Fig. 1(b). A set of two specimens was utilized for each test.

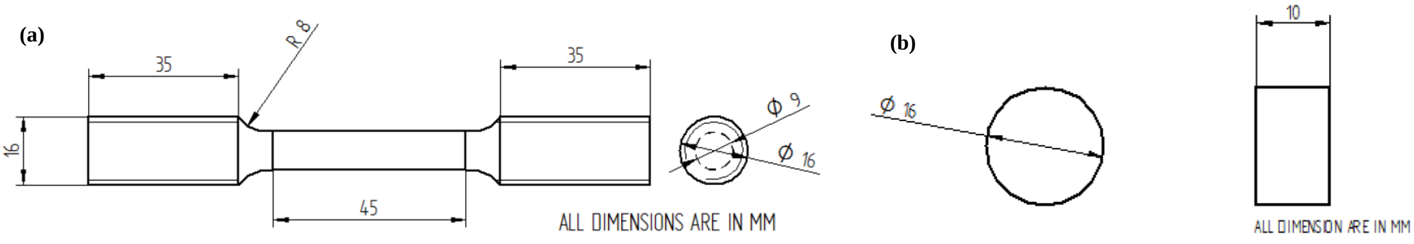


Figure1. Specimen geometry (a) Tensile test (ASTM E8); (b) Hardness test (ASTM E92)

B. Method for Corrosion

Naturally manifested corrosion was permitted to occur by immersing the tensile and hardness test specimens in sea water under fully submerged conditions as shown in Fig. 2. Prior to immersion, the test specimens were polished using sandpaper and rinsed with distilled water. The specimens were immersed in sea water at room temperature for different durations of 250, 500, 750 and 1000 hours. The sea water in the trays was continually replaced at a course of two days to sustain the pH and allow adequate oxidation to the specimens to imitate the real field operating conditions. The sea water was taken from seashore at Mangaluru area in Karnataka, India.

Figure 2. Test specimens immersed in sea water

C. Test procedure

To examine the effect of corrosion on mechanical properties of EN24T and EN36 steels, quasi static tensile tests were conducted with a crosshead speed of 1 mm/min. A universal testing machine (Company: Fuel Intruments and Engineers Pvt. Ltd) with a capacity of 1000 kN was used. Further, to investigate the surface degradation due to corrosion Vickers Hardness test was conducted. The microstructure of the specimens was examined using Σ IGMA^{TM} Field Emission Scanning Electron Microscope (Carl Zeiss SMT AG Company). The tests were conducted for as received and corroded samples for different immersion durations at room temperature.

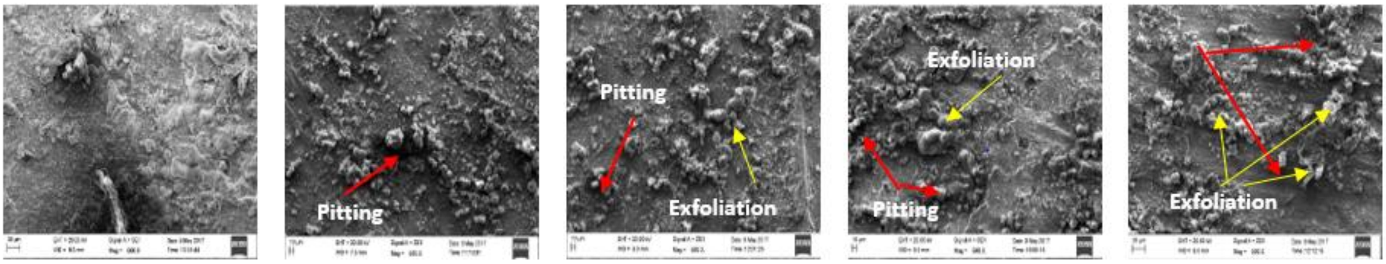
III. RESULTS AND DISCUSSIONS

A. Surface studies

Fig. 3 shows the surface of corroded specimens immersed for 1000 hours in sea water. Clear formation of inhomogeneous black and reddish patches on both materials can be observed. The increase in immersion duration leads to excessive formation of pits and exfoliation of surface layers resulting in extensive material loss [8-10].

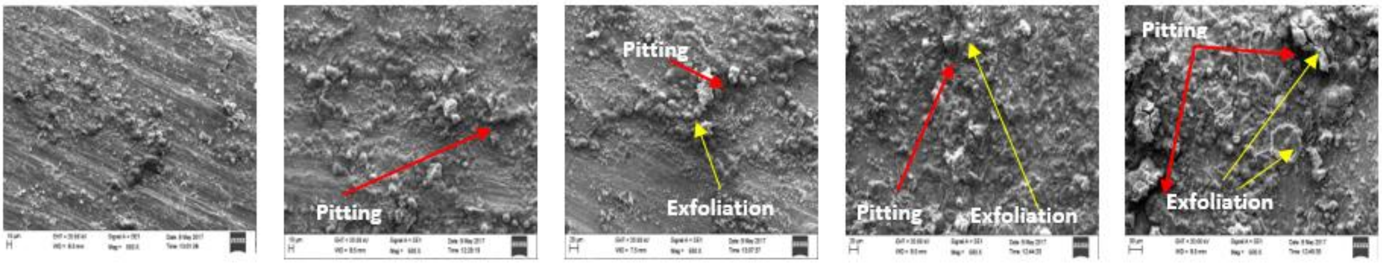
Figure 3. Test specimens after 1000 hours of exposure

The corrosion effect in the form of pitting and exfoliation was analyzed using Scanning Electron Microscopy and the results are shown in the Fig.4. and Fig.5, for EN24T and EN36 steels, respectively. It is observed that the surfaces exposed to corrosion degrades with increase in exposure time. There is considerable material loss at the end of 1000 hours of exposure.



(a) Without Corrosion (b) 250 Hours Exposure (c) 500 Hours Exposure (d) 750 Hours Exposure (e) 1000 Hours Exposure

Figure 4. Morphology of EN24T Steel for different hours of Exposure



(a) Without Corrosion (b) 250 Hours Exposure (c) 500 Hours Exposure (d) 750 Hours Exposure (e) 1000 Hours Exposure

Figure 5. Morphology of EN36 Steel for different hours of Exposure

At 250 hours, nucleation of micro pits can be observed (Fig 4(b) and Fig. 5(b)). Further, with increase in exposure durations enlargement of pits can be observed. Enlarged pit formations are seen at 1000 hours for both the materials (Fig. 4(e) and Fig. 5(e)). Exfoliation of bright passive layers begins at 500 hours and increases with increase in exposure durations. It can be noted that the surface morphology of EN36 depicts maximum pit depth attributing to intergranular attack [25-26]. The rate of exfoliation is high in EN36 when compared with EN24T.

B. Tensile Test

. The mechanical properties were determined using quasi-static tensile experiment. Fig. 6(a) and Fig. 6(b) shows the stress - strain for as-received and corroded samples for different hours of corrosion. The degradation of mechanical properties increases with the increase in immersion time. To study the degradation effect, yield strength, tensile strength, elongation at yield, young's modulus, modulus of resilience and toughness was examined. The retention in mechanical properties is estimated as R = Ra/Ro, where Ro corresponds to value of as-received sample and Ra represents the value after corrosion as reported in Table 2. The variation of yield strength and tensile strength is shown in Fig. 7 (a) and Fig. 7 (b) for EN24T and EN36 steels, respectively. A decreasing trend in yield strength is observed for both materials with EN36 showing significant reduction as compared to EN24T (Fig. 7(a)). Tensile strength decreases with increase in exposure durations with EN24T and EN36 steels showing similar variations at 750 and 1000 hours of exposure (Fig. 7(b)). At 1000 hours, EN24T has 64% retention of yield strength and 72.2% retention of tensile strength while EN36 has 49.6% retention of yield strength and 62.6% retention of tensile strength. The decrease in yield and tensile strength can be attributed to the degradation of grain boundary due to corrosion promoting intergranular attack resulting in brittle failure [14].

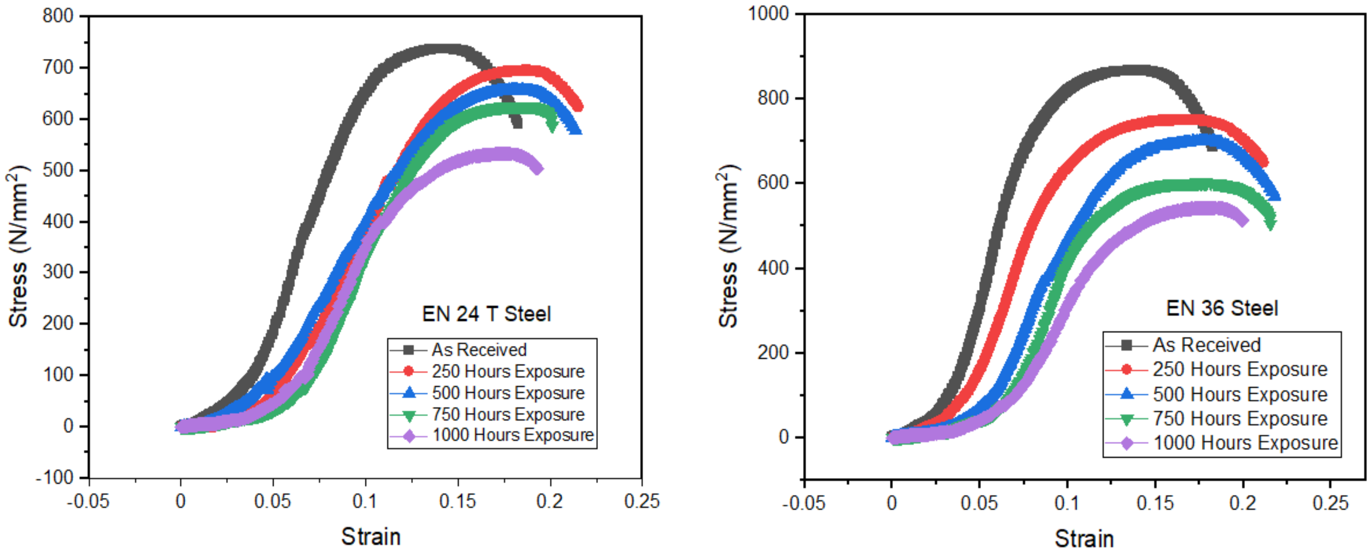


Figure 6. (a) Stress – Strain curves for EN24T; (b) Stress – Strain curves for EN36 Steels with exposure time

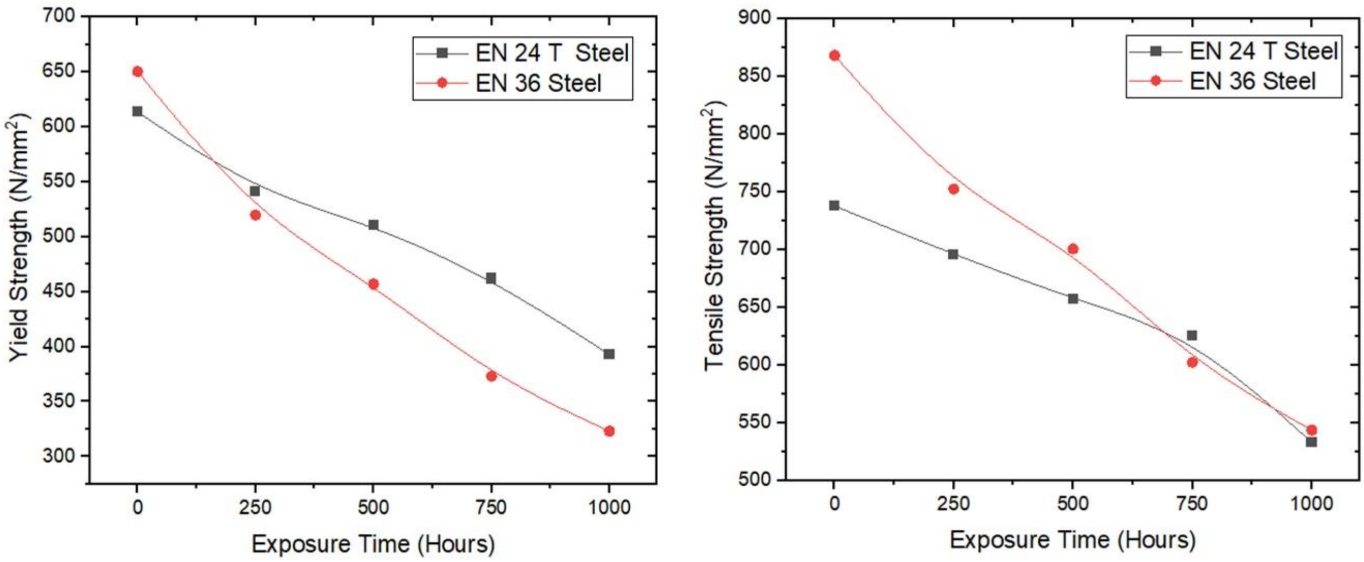


Figure 7. Variation of (a) Yield Strength and (b) Tensile Strength for EN24T and EN36 Steels with exposure time

Young's modulus decreases with exposure time for both the materials. At 1000 hours EN24T has 81.5% while EN36 has 74.3% retention of young's modulus. (Fig 8(a)). The decrease in young's modulus attributes to reduction of material stiffness which is caused by excessive material loss which can be clearly observed in Fig. 3.

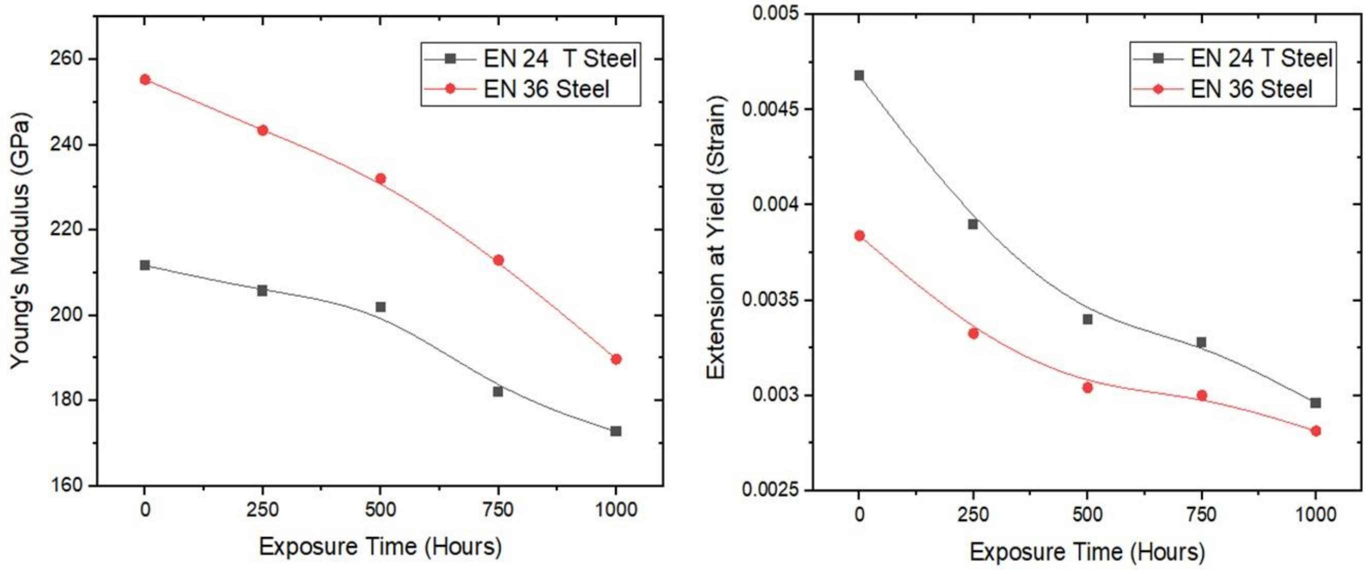


Figure 8. Variation of (a) Yield Strength and (b) Tensile Strength for EN24T and EN36 Steels with exposure time

The strain at yield decreases with increase in exposure time (Fig 8. (b)), this correlates to reduction in material's ductility with corrosion. A reduction in strain at yield is observed for both materials. At 1000 hours EN24T has 63.2% while EN36 has 73.2% retention of strain at yield. Modulus of resilience, which is a measure of material's ability to store elastic strain energy was determined by integrating the area under the stress-strain curve up to the yield point. Fig. 9 (a) shows the variation of modulus of resilience, a decreasing trend was observed for both the materials resulting in pre-mature failure caused by embrittlement. At 1000 hours EN24T has 52.6% while EN36 has 45.1% retention of modulus of resilience. The overall toughness, which is a measure of material's ability to store energy before rupture was determined by integrating the area under the stress-strain curve up to fracture. Toughness also shows decreasing trend with exposure time for both the materials as shown in Fig. 9(b). A significant decrease is observed for EN36 Steel as compared to EN24T. At 1000 hours EN24T has 65.5% while EN36 has 53.6% retention of toughness.

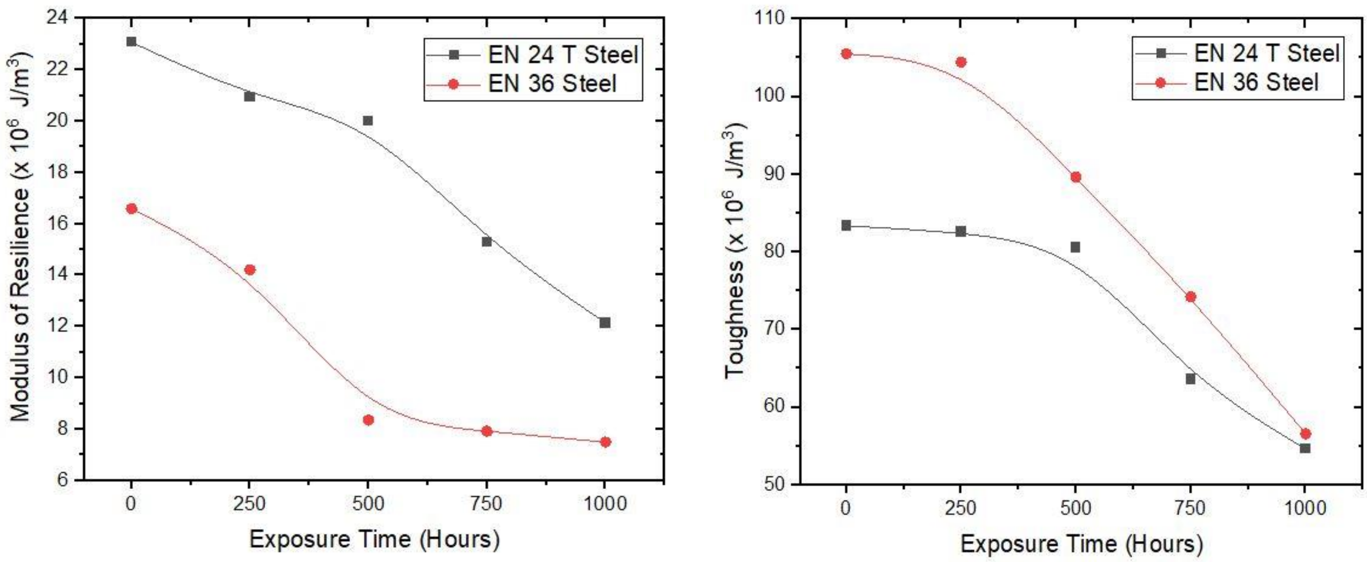


Figure 9. Variation of (a) Modulus of Resilience and (b) Toughness for EN24T and EN36 Steels with exposure time

Due to corrosion, there is decrease in strength, stiffness, and energy storing ability of EN24T and EN36 steels representing the deterioration of strength and ductility of the steels. The considerable reduction in mechanical properties of EN36 steel as compared to EN24T steel is a repercussion of large amount of formation of pits and exfoliation as observed in Fig. 5. This degradation of mechanical properties of steels subjected to corrosion can be attributed to the aggressive salt attack resulting in pitting, exfoliation of surface layers and hydrogen embrittlement [13].

Table 2 - Retention of tensile properties with exposure time

Material	**Exposure Time (Hours)**	**Stress at yield** $R_{\sigma y}$	**Strain at yield** R_{ϵ}	**Young's Modulus** R_E	**Ultimate Stress** $R_{\sigma t}$	**Toughness** R_T	**Modulus of Resilience** R_M
EN 24 T	0	1	1	1	1	1	1
	250	0.8823	0.833	0.9740	0.9432	0.9905	0.9079
	500	0.8324	0.7296	0.9536	0.8906	0.9665	0.8671
	750	0.7527	0.7008	0.86	0.8478	0.7628	0.6629
	1000	0.64	0.6324	0.8158	0.7224	0.6552	0.5263
EN 36	0	1	1	1	1	1	1
	250	0.8	0.866	0.953	0.8696	0.9899	0.8569
	500	0.7026	0.7921	0.9090	0.8068	0.8496	0.5036
	750	0.5736	0.7813	0.8346	0.6936	0.7034	0.4771
	1000	0.4968	0.7326	0.7433	0.6261	0.5362	0.4517

C. Hardness Test

Vickers's hardness test was conducted on EN24T and EN36 steels to analyze the effect of corrosion. The variation in Vickers's Hardness Number (VHN) of EN36 and EN24T steels exposed to sea water corrosion is shown in Fig.10.

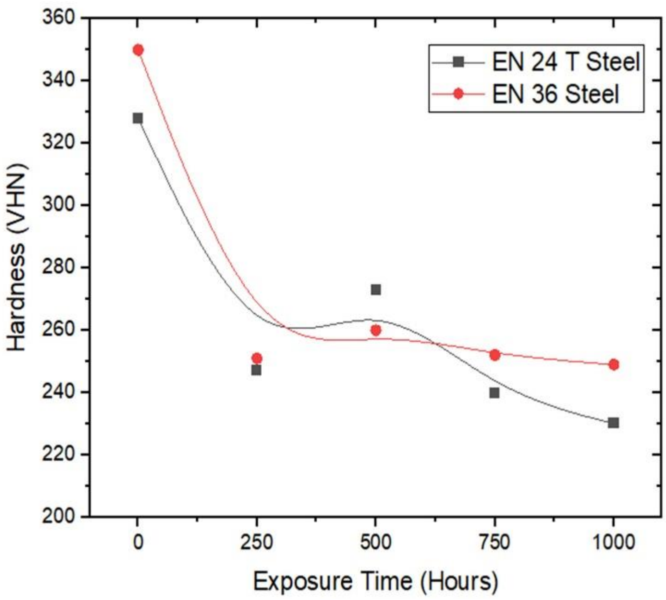


Figure 10. Variation of Vickers's Hardness Number for EN24T and EN36 Steels with exposure time

Hardness of both the materials decreases extensively at 250 hours of exposure due to surface degradation. Further, an increase in hardness is observed at 500 hours of exposure. This might be due to embrittlement of the surface. At 1000 hours of exposure a 24.9% reduction in hardness is observed for EN24T and 28.9% reduction is observed for EN36. The reduction in hardness correlates with the investigation of surface study showing increasing in pit formation and exfoliation at 1000 hours for EN36 as compared to EN24T steel (Fig. 5).

IV. CONCLUSIONS

The mechanical performance of EN24T and EN36 steels subjected to different durations of natural sea water corrosion was investigated in this paper. The following conclusions can be drawn:

1. Corrosion resulted in formation of red and black patches on the surface of both the materials thereby degrading the surface at the initial stages. Prolonged exposure culminated in pitting and exfoliation of superficial layers followed by intergranular corrosion.
2. The mechanical properties of EN24T and EN36 steels deteriorate with increase in sea water immersion durations. Significant decrease in tensile strength, yield strength, stiffness, and toughness are observed. After corrosion, the hardness of EN24T and EN 36 steels reduce significantly with increase in the exposure durations. Comparatively it can be concluded that EN24T steel shows a better performance than EN36 steel when subjected to natural sea water corrosion.

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