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Assessment of the Flow-Induced Corrosion Behaviour of Welded Low Alloy Steel in Seawater Environment

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ABSTRACT: *The effect of varying flow velocities and temperatures on the flow-induced corrosion behaviour of welded low alloy steel in seawater environment was assessed. The impact of mono ethylene glycol (MEG) on the steel's corrosion rate was also investigated. The parent metal, welded metal, and heat-affected zones of the steel were marked out, sectioned, and their surfaces prepared. The mass-loss and corrosion rate of the sectioned samples were obtained using the submerged impingement jet rig in 1wt% NaCl and NaCl/MEG environments at temperatures of 0 °C and 25 °C (ambient temperature). Results obtained reveal that the mass-loss and corrosion rate of all zones of the steel appreciated with increasing flow velocity for both temperatures. Also, all zones corroded extensively in 1wt% NaCl environment at a low temperature (0 °C) while corrosion was significantly inhibited in NaCl/MEG environment at low temperature but slightly at ambient temperature.*

KEYWORDS: *Flow-induced corrosion, welded low alloy steel, submerged impingement jig rig, seawater environment*

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I. INTRODUCTION

Low alloy steels are chiefly employed in deep waters for construction of ship hulls, submarines, bridges, and transport pipes [1]. The presence of alloying elements such as nickel, molybdenum, copper, and chromium confer advanced mechanical properties on the steel especially at low temperatures [2]. The good weldability of low alloy steels is one of the majorly exploited properties. Most fabrications of low alloy steels are done through welding processes which afterwards induces three different phases – the parent metal (PM), the heat-affected zone (HAZ), and the welded metal (WM). The corrosion behaviour of these three phases in different environments have been reported especially in flow-induced conditions. Flow-induced/assisted corrosion causes the rapid dissolution of the protective oxide layer on a metal surface such that the base metal corrodes to create another layer. This phenomenon is dependent on the flow velocity, nature of the material, constituents and pH of the fluid [3].

Peculiar features of seawater/marine are the flow velocity and concentration of aggressive agents such as chloride ion (Cl^-) and carbon dioxide (CO_2). These features affect significantly the corrosion behaviour of low alloy steel. Heitz[4] asserted that flow velocity enhances corrosion rate, especially in the marine environment. Seawater contains predominantly sodium chloride, as well as some minerals and organic matters. It is generally more corrosive than freshwater, frequently producing pitting and crevice corrosion resulting in the reduction of the service life of low alloy steels. The chloride ions in seawater hinder passivation and penetrate through defects on the metal surface. This causes continuous damage to the permanent corrosion product layer resulting in the breaking down of the metal surface [5, 6]. Therefore, the need for drastic corrective measures is without doubt pertinent. One of such panacea to this type of corrosion specific to this service area is the addition of inhibitors such as mono ethylene glycol (MEG) [7]. Several reports have recorded that MEG gets absorbed on steel surface to displace corrosion products away from the anodic region, thereby inhibiting the formation of more corrosion product layer [8,9,10].

Therefore, due to the nature of this environment and the admissibility of MEG to mitigate corrosion rate, this research assessed the flow-induced corrosion behaviour of welded low alloy steel in a 1wt% NaCl and NaCl/MEG environment at both low and ambient temperatures and varying flow velocities.

II. MATERIALS AND METHODS

2.1 Materials

The chemical composition of the welded low alloy steel investigated in this research is given in Table 1. Theparentmetal (PM), weld metal (WM), and heat-affected zones(HAZ) were identified, marked, and cut out into rectangular samples of dimension, 1.5 cm × 1.5 cm × 1.5 cm. The surface of the samples were then prepared by grinding using silicon carbide emery papers of Standard ANSI grit of 60,120, 240, 300, 420, 520, and 600. The corrosive environments employed was prepared using sodium chloride (NaCl), tap water, and MEG. About 10 g dry sample of analytical grade NaCl was measured and placed in a 1000 ml conical flask filled with tap water. The mixture was stirred vigorously using a hand stirrer until the NaCl had dissolved completely in the water. Another 1000 ml solution made of 80% NaCl solution and 20% Ethanediol (MEG) was then prepared.

Table 1. Chemical composition of experimental welded low alloy steel

Element	C	Mn	Si	P	S	Cr	Ni	Mo
Wt.%	0.18	1.3	0.3	0.25	0.10	0.30	030	0.12

2.2 Method

The flow-induced corrosion of the test samples extracted from the welded low alloy steel was simulated using the submerged impingement jet rig (Fig. 1) which has been previously used and proven accurate [11, 12]. A laboratory set-up of the rig is shown in Fig. 2. The initial weights of the samples were measured and recorded. Each samples were stimulated for thirty minutes twice at varying flow velocities (1-3 m/s) and temperatures of 0 °C and 25 °C. Each sample was placed in the sample holder contained in a reservoir filled with 1wt% NaCl solution until complete submersion was achieved. The nozzle was then set at 90° to ensure direct impingement of the solution on the sample surface. The experiment was run at a temperature of 0 °C by placing ice block within the reservoir and the temperature observed using a thermometer. The above procedure was repeated for the NaCL/MEG solution. The final weights of the samples were measured. The mass-losses were noted and their corrosion rates were evaluated using Equation 1.

$$\text{Corrosion rate (R)} = {(K\times W)}\Big/{(A\times T\times D)} \quad . \quad . \quad . \quad . \quad (1)$$

where K-corrosion constant (cm/year), T- time of exposure in hours, A- area in cm^2, W-mass loss in grams, and D-density in g/cm^3.

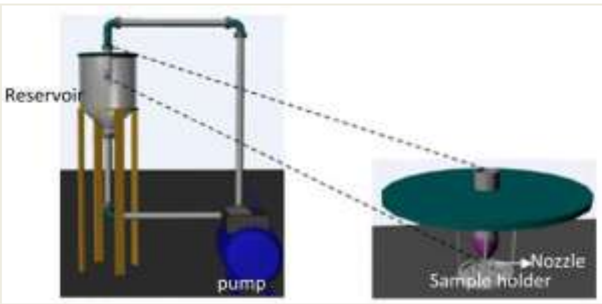

Fig. 1. Impingement Jet (SIJ) Rig (Barker *et a*l., 2011)

Fig. 2. Laboratory setup of the SIJ

III. RESULTS AND DISCUSSION

3.1 Mass-loss of samples in 1wt% NaCl environment

Fig. 3 presents the result of mass-loss obtained from the flow-induced corrosion of the PM, WM, and HAZ samples at 0 °C (temperature of ice water mixture) and 25 °C (ambient temperature) in 1wt% NaCl solution. It is noteworthy that the effect of flow velocity on the mass-loss of samples at ambient temperature (25 °C) was less pronounced compared to at 0 °C. Further, it was deduced that at static condition (0 m/s), the PM and HAZ exhibited negligible mass-loss while WM showed evidence of mass-loss for both 0 °C and 25 °C conditions. This implies that without turbulence flow, no feasible mass-loss occurs at the PM and HAZ of the welded low alloy steel irrespective of the service temperature.

More so, the mass-loss of the HAZ was observed to be relatively low which may be due to phenomena such as recrystallization and phase redistribution [13]. The notable mass-loss observed at the WM zone may be ascribed to the compositional heterogeneity of this region which initiates anodic-cathodic reactions [4]. From Fig. 3a, it is quite evident that the mass-loss of all zones is directly proportional to flow velocity. However, the mass-loss of WM was more pronounced up to a flow velocity of 2 m/s after which it reduces while the mass-loss of the PM and HAZ increases with increasing flow velocity. This may be due to the increased turbulence flow which removes the passive layer formed on the base metal surface, thereby facilitating the penetration of chloride ions. From Fig. 3b, it is quite obvious that a somewhat similar trend was observed for all phases at ambient temperature (25 °C). The mass-loss of the WM increases drastically above flow velocity of 1 m/s while the mass-loss of the PM and HAZ exhibited a sinusoidal trend, though the mass-loss of PM supersedes that of HAZ. Nonetheless, from the results, it can be inferred that mass-loss was more pronounced at low temperature with increasing flow velocity.

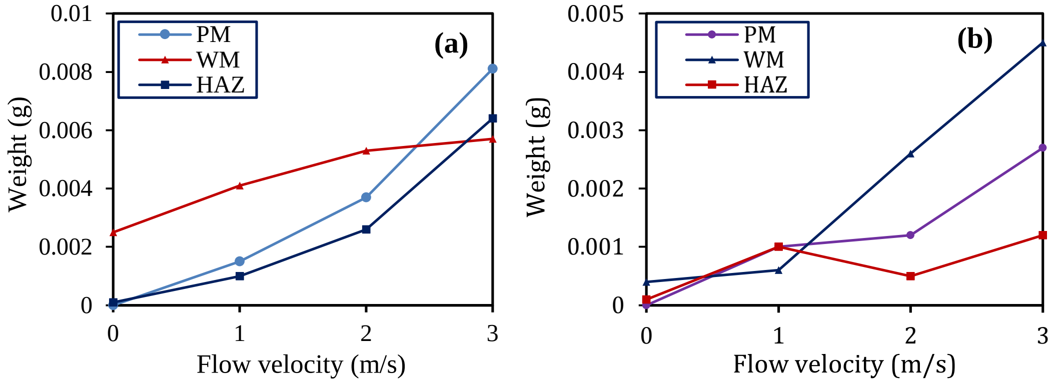

Fig.3. Variation of mass-loss with flow velocity for the flow-induced corrosion of the PM, WM, and HAZ samples at zero (a), and ambient (b) temperatures in NaCl environment

3.2 Mass-loss of samples in NaCl/MEG environment

Fig. 4 presents the result of mass-loss obtained from the flow-induced corrosion of the PM, WM, and HAZ samples 25 °C (ambient temperature) in NaCl/MEG environment. The samples were observed to exhibit negligible mass-loss at 0 °C in NaCl/MEG environment. This is quite expected because MEG has been reported to significantly inhibit mass-loss at low-temperature condition [7]. From the result, it is quite obvious that no mass-loss occurred for the PM sample while the WM and HAZ samples exhibited increasing mass-loss as the flow velocity increases. Zhang *et al*. [14] asserted that at high velocities, the steel is pliable to high turbulence which removes the passive film and corrosion scales formed by mechanical erosion effect. Also, it was observed that the WM experienced more mass-loss than the HAZ due to aforementioned reasons. It can be inferred that mass-loss of the welded low alloy steel was significantly hindered by the use of MEG. This findings tailor accordingly to that achieved by [7] and [11]. This may be ascribed to the fact that MEG being an inhibitor gets absorbed on the steel surface which prevented the formation of corrosion product layer [8].

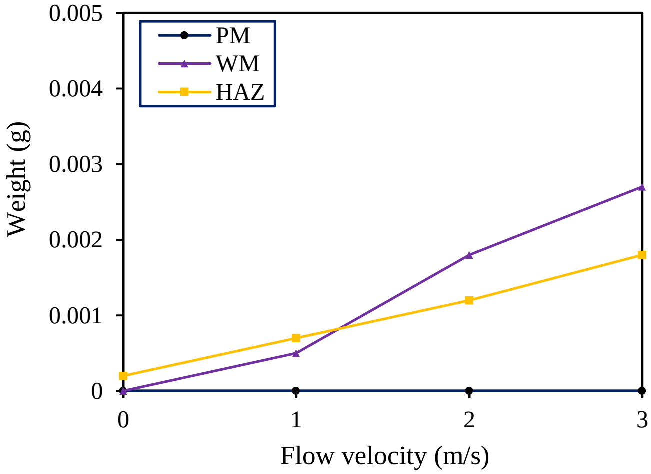

Fig. 4. Variation of mass-loss with flow velocity for the flow-induced corrosion of the PM, WM, and HAZ samples at ambient temperatures in NaCl/MEG environment

3.3 Corrosion rate of samples in NaCl environment

Fig. 5 presents the variation of the corrosion rate of the PM, WM, and HAZ samples with flow velocity at temperatures of 0 °C and 25 °C. It is quite obvious that the corrosion rates of the samples for both temperatures differ significantly. This implies that at low temperature, welded low alloy steel corrodes faster and failure of the steel in service is imminent at high turbulence as reported by [4] and [15]. From Figure 4a, at static condition (0 m/s), the corrosion rate of the PM was notably negligible while the corrosion rate of the WM sample was higher than the HAZ sample. As the flow velocity increases, the PM corrosion rate became more vivid, being highest at 3 m/s. The corrosion rate of the WM and HAZ samples also appreciated with increasing turbulence. This implies that increased turbulence flow significantly increases the corrosion rate of all zones at very low-temperature condition. However, the corrosion rate was greatly reduced at ambient temperature, though the WM corroded faster than other zones of the welded low alloy steel.

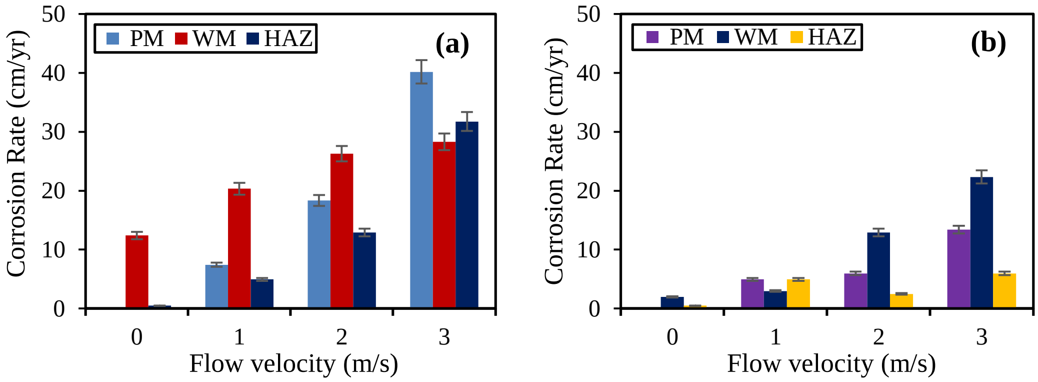

Fig. 5. Corrosion rate of the PM, WM, and HAZ samples at zero (a), and ambient (b) temperatures in NaCl environment

3.4 Corrosion rate of samples in NaCl/MEG environment

The corrosion rate of the PM, WM, and HAZ samples at 25 °C (ambient temperature) in NaCl/MEG environment was evaluated and the result presented in Fig. 6. Also, in this environment, there was no observable deterioration of all the samples at 0 °C. This implies that all the samples retained their weights in the environment despite increasing the flow velocity. From the result, it is quite obvious that the corrosion rate of the PM and WM samples were negligible. However, as the flow velocity increases the corrosion rate of the WM and HAZ samples appreciated. Corrosion rate was significantly reduced due to the presence of MEG in the environment.

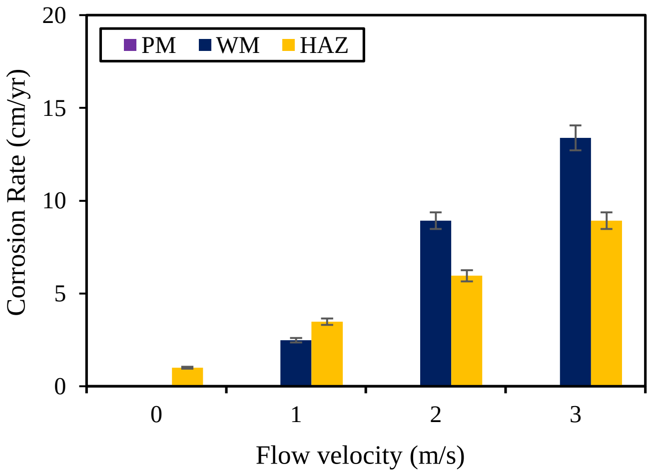

Fig. 6. Corrosion rate of the PM, WM, and HAZ samples at ambient temperatures in NaCl/MEG environment

IV. CONCLUSION

The applicability of welded low alloy steel in seawater environment cannot but be emphasized. Therefore, a critical assessment of its flow-induced corrosion behaviour at both low and ambient temperatures in 1 wt% NaCl and NaCl/MEG solutions was carried out. Inferences drawn can be summarized as follows:

i. For both temperatures, the mass-loss and corrosion rate of the parent metal, welded metal, and heat-affected zones of the welded low alloy steel were observed to increase with increasing flow velocity.

ii. Also, all zones corroded extensively in 1wt% NaCl environment at low-temperature condition of 0 °C while corrosion was significantly inhibited in NaCl/MEG environment both at low temperature and ambient temperature.

In summary, the addition of MEG in the seawater environment is recommended to inhibit flow-induced corrosion in welded low alloy steel.

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