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Experimental investigation on corrosion resistance and tribological properties of steel coated with glass-reinforced polymer

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Abstract

This work presents a comprehensive electrochemical corrosion analysis conducted on steel coated with glass-reinforced polymer (GRP), low alloy steel and stainless steel, focusing on their performance in a simulated aggressive environment (3 % NaCl). The corrosion rates were established and the corrosion mechanisms governing each material's behaviour were elucidated. By comparing the electrochemical behaviour of these materials, we aim to evaluate the efficacy of GRP coatings in preventing corrosion compared to conventional metallic materials used for pipeline systems. Furthermore, in addition to the corrosion analysis, the coefficient of friction determination between the GRP-coated steel and 25CrMo4 (EN 10083-3) steel was conducted to assess their tribological compatibility. Understanding the frictional behaviour between these materials is essential for optimising pipeline performance, minimising wear and ensuring operational efficiency in dynamic environments encountered in the petroleum and gas industry. The study includes, also, an evaluation of cumulative linear wear to quantify the material loss. This comprehensive approach provides a complete understanding of the interplay between corrosion resistance and mechanical durability.

1. Introduction

Corrosion remains one of the most pervasive challenges facing the integrity and longevity of industrial piping systems, particularly in aggressive environments such as those encountered in the transportation of fluids in the petroleum and chemical processing industries. Traditional materials like low alloy steel and stainless steel have long been employed for their mechanical strength and resistance to corrosion [1,2]. Nevertheless, in hostile environments, steel pipes are susceptible to degradation due to internal or external corrosion, which can lead to partial or complete failure of the pipe [1]. To address this issue, recent advancements in composite materials technology have introduced fibre-reinforced polymer (FRP) coatings as a promising alternative to conventional metallic alloys, offering improved corrosion resistance, durability and life cycle performance [3-6].

FRP composite pipes are becoming increasingly cost-effective to install, making them preferred for various applications. With commendable mechanical properties, FRP enhances stiffness, strength, pressure capacity, durability, cost-effectiveness and environmental sustainability when utilised in conjunction with other materials [7-11]. In the 1980s, the pipeline industry witnessed the introduction of a novel approach that combined composite materials with steel, marking a significant advancement. This innovation involved the application of composites over steel sleeves, which rapidly became a standard method for pipeline repairs [3]. Another method involves winding FRP composite material (while still in its wet and uncured stage) circumferentially around a steel pipe to enhance pressure capacity and offer environmental protection against corrosion [3].

FRPs remain unaffected by electro-mechanical or electro-chemical deterioration and exhibit resistance to aggressive corrosive agents such as acids, alkalis, salts and similar compounds across a broad spectrum of temperatures. Furthermore, the FRP layers create a protective barrier layer intended to inhibit subsequent corrosion of the steel [12-15]. To minimise the corrosion of pipes in the oil and gas industry, liners are commonly employed as protective measures. Liners serve as barriers between the corrosive substances flowing through the pipes and the pipe material itself [16]. Glass-reinforced polymer (GRP) liners consist of a composite material reinforced with glass fibres and a polymer matrix, offering exceptional strength and corrosion resistance. These liners are typically prefabricated and then inserted into the pipe, providing a seamless and chemically resistant barrier. GRP liners are lightweight, easy to install and highly durable, making them well-suited for harsh oil and gas environments.

The effectiveness of composite materials like carbon-fibre-reinforced polymers (CFRP) and glass-fibre-reinforced polymers (GFRP) in mitigating rebar corrosion was investigated by Ananthkumar et al. [17] and the results revealed reductions in corrosion potential, suggesting ongoing corrosion of steel rebars. Conversely, CFRP and GFRP specimens exhibited minimal corrosion potential, indicating a low risk of corrosion. Calculated corrosion rates, based on Tafel and LPR constants, were notably lower for CFRP and GFRP compared to other specimens, affirming the efficacy of these materials in limiting corrosion.

Alabtah et al. [15] investigated the corrosion performance of hybrid steel/GFRP composite pipes in highly concentrated solutions of hydrochloric acid, sodium chloride and sulphuric acid for up to one year. The findings demonstrate that the hybrid pipes exhibit outstanding corrosion resistance, with a corrosion rate of less than 1 % compared to conventional steel pipes. Zhou et al. [18] examined the impact of incorporating CFRP and GFRP composites on the corrosion resistance of innovative steel/FRP composite bars in NaCl solution. Their findings revealed that the corrosion rates of carbon-type and glass-type composites were less than 1/10 and 1/100, respectively, compared to those of conventional steel bars.

Pop et al. [7] investigate the effects of sulphuric, nitric and hydrochloric acids in concentrations of 10 and 20 % on composite materials consisting of resin reinforced with fibreglass. These composite materials, which can be manually fabricated, are versatile and can be used to create various containers, such as those for water storage. Additionally, the study explores the suitability of these composite materials for the temporary storage of acids. Experimental research presented in the paper reveals that certain composite materials, incorporating specific combinations of fibreglass layers, demonstrate promising potential for temporary acid storage applications.

Some commonly used corrosion testing methods include salt spray testing (ASTM B117), electrochemical testing, immersion testing, weight loss analysis and cyclic corrosion testing [19]. Among these methods, the electrochemical method offers several advantages, including straightforward equipment setup, cost-effectiveness, precise measurements, broad applicability and heightened sensitivity [20]. The Tafel plot technique can be utilised to determine corrosion rates by analysing the corrosion current intensity and Tafel slopes [21].

In the present work, a comprehensive analysis is conducted on GRP-coated steel, low alloy steel and stainless steel, focusing on their performance in a simulated aggressive environment containing 3 % NaCl. The choice of these materials and test conditions is based on their widespread use in industrial applications where corrosion resistance is critical. The 3 % NaCl solution is representative of saline environments commonly encountered in the petroleum and chemical processing industries, providing a relevant and challenging setting for evaluating material performance. By conducting a systematic electrochemical corrosion analysis using advanced techniques such as Evans diagrams and Tafel curves, this study aims to contribute to the understanding of corrosion behaviour in industrial piping systems and to offer insights that enhance the reproducibility and practical relevance of the findings. Only the GRP-coated steel was specifically selected for tribological tests due to its promising potential in enhancing surface properties and its relevance to applications where both corrosion and wear resistance are crucial. Low alloy steel and stainless steel were primarily evaluated for their corrosion resistance to provide a baseline comparison with GRP-coated steel.

2. Materials and methods

2.1 Determination of electrochemical parameters

According to the mixed potential theory, any electrochemical reaction can be divided into two or more oxidation and reduction reactions, without accumulating electric charges during the reactions. In a corrodible system, oxidation of the metal (corrosion) and reduction of certain elements in the solution occur at the same rate and the net current measured is zero. When a metal or alloy is placed in contact with a solution, the metal will assume a potential that is dependent on the nature of the material and the nature of the solution. This open circuit potential, without the application of any potential from outside the cell, is the corrosion potential E_{corr}.

Many of the modern corrosion techniques are based on the theoretical analysis of the shapes of the Stern-Geary polarisation curves. Because corrosion rate CR is usually expressed in units of length/time (mm/year or milli-inch/year – mpy) it can be calculated in mpy as [22-24]:

$$CR = 0.13 \frac{EW}{\rho} I_{corr}, \quad (1)$$

where EW is equivalent weight, ρ is material density in g/cm^3 and I_{corr} is corrosion current density in μA/cm^2.

Regarding the samples used for the electrochemical corrosion test, they were made of stainless steel X10CrNi18-8 (EN 10088), low-alloy steel 25CrMo4 (EN 10083-3) and 25CrMo4 steel coated with GRP. The samples were coated to a thickness of 25 μm in accordance with ASTM B16.34 requirements for non-metallic coating. The samples were mechanically processed in the form of discs having Ø $16_{-0.1}$ mm and 2 mm thickness. The steel sample coated with GRP is shown in Figure 1.

The process for coating the steel samples is based on the general principle of any casting method, i.e. a liquid mixture, with a suitable viscosity, is deposited in a form whose configuration it copies after hardening.

In the present case, the shape is the steel sample and the liquid is pure resin or mixture (resin + filler). It is aimed to create internal protections with a vinyl ester resin, which is based on a bisphenol A resin. The final coating thickness is reached in several stages: preparing metal surfaces (sandblasting); preparing mixtures for pouring; casting two layers of pure resin; and pouring four layers of mixture (resin + fibre). The base product is SIRESTER VE 45-M-90/AT (epoxy based on bisphenol A) diluted in styrene, accelerated and thixotropic [25]. To make the mixture, in addition to the resin SIRESTER VE 45-M-90/AT, peroxide KETANOX B180 and aluminium powder (filler) NEUKADUR AS 011 are used.

Figure 1. GRP-coated sample

The electrolyte used for the electrochemical corrosion test was water with 3 % NaCl. The corrosion cell (Fig. 2) works with a saturated calomel reference electrode, graphite counter electrodes and specimen holder which expose 1 cm^2 of the specimen to the 1000 cm^3 of test solution. The electrochemical corrosion test was performed according to ASTM G5 standard [26].

Figure 2. Corrosion cell

Potentiostat Voltalab 10 was used to measure the corrosion current density, specifically recording it with respect to an exposed area of 1 cm^2. The corrosion current density measurement serves as a critical parameter in the calculations, forming the basis from which is determined the corrosion rate, using Equation (1).

2.2 Determination of tribological properties

The assessment of tribological properties is critical for understanding the performance and durability of materials used in pipelines, especially in the aggressive environments of the petroleum and gas industry. A friction couple with cube-on-disc configuration was used to determine the coefficients of friction and wear, on a CSM Instruments tribometer. Figure 3 shows the main active elements of the tribometer used to perform the investigation. The cube samples (steel 25CrMo4) were processed to the dimensions 3.97 × 3.97 × 4 mm and the coated disc (steel 25CrMo4 coated with GRP) to the dimensions Ø 20 × 5 mm.

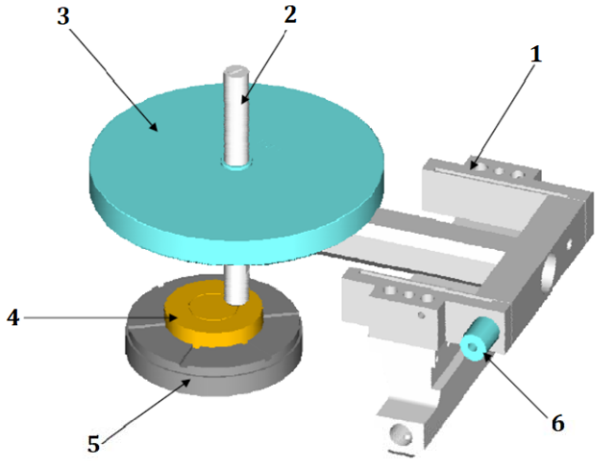

Figure 3. Principle scheme of the tribometer: 1 – elastic lamella; 2 – support ball, tip or flat specimen; 3 – weights; 4 – testing specimen; 5 – mandrel for holding the testing specimen; 6 – tangential force sensor

Three repetitive tribological tests were performed. The coefficient of friction was calculated from the ratio of the tangential friction force and the normal force [27,28]. Cumulative linear wear was calculated as the difference between the final and the initial penetration depth.

The parameters and conditions for the tribological test have been set as follows: temperature of 20 °C; relative humidity of 57 %; testing environment was air; radius of rotation of the cube centre on the disc of 6 mm; tangential speed of 0.2 m/s; sliding distance of 200 m; and normal load of 1 N (pressure of 0.063 N/mm^2).

The preparation of the samples consists in degreasing all surfaces by immersion in methyl ethyl ketone, followed by air drying.

3. Results and discussion

3.1 Electrochemical corrosion analysis

Figures 4 and 5 depict the linear polarisation curves and Evans diagram with Tafel plots, respectively, for the analysed materials (uncoated stainless steel, uncoated low-alloy steel and low-alloy steel coated with GRP).

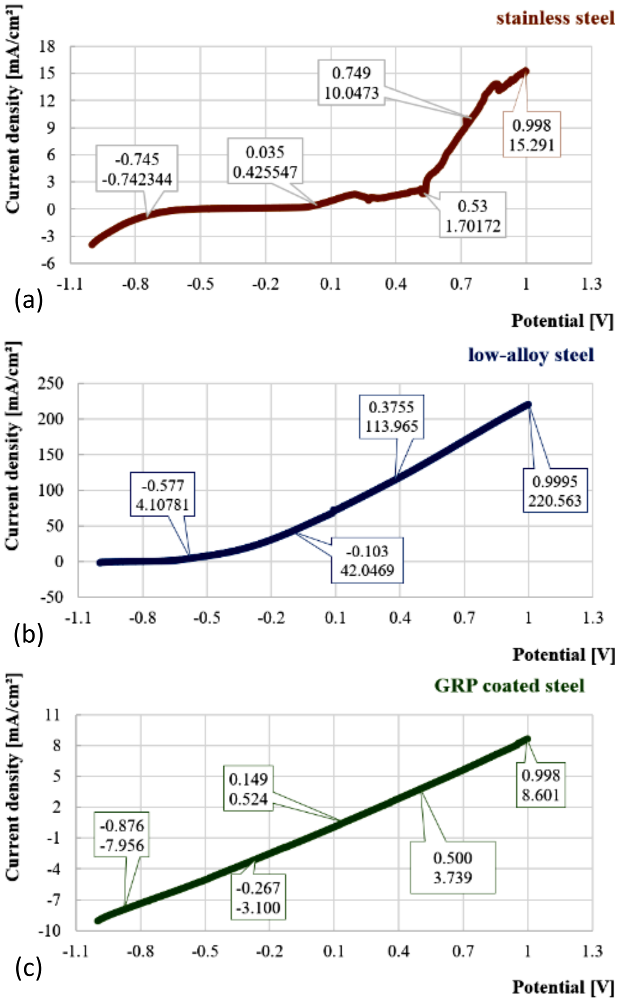

Figure 4. Linear polarisation curves: (a) uncoated stainless steel, (b) uncoated low-alloy steel and (c) low-alloy steel coated with GRP

It can be seen from Figure 6 that when the low-alloy steel surface is coated with GRP, the corrosion rate decreases approximately 8 and 403 times compared with uncoated stainless steel and uncoated low-alloy steel, respectively. Similarly, Alabtah et al. [15], found that the corrosion rate of hybrid steel/glass-fibre-reinforced polymer (GFRP) was less than 1 % of the corrosion rate for conventional steel pipes. Also, Zhou et al. [18] revealed that the actual corrosion rate of a steel/carbon-type fibre-reinforced polymer composite bar is less than 1/10 that of an ordinary steel bar, and the corrosion rate of a steel/glass-type fibre-reinforced polymer composite bar is less than 1/100 of an ordinary steel bar.

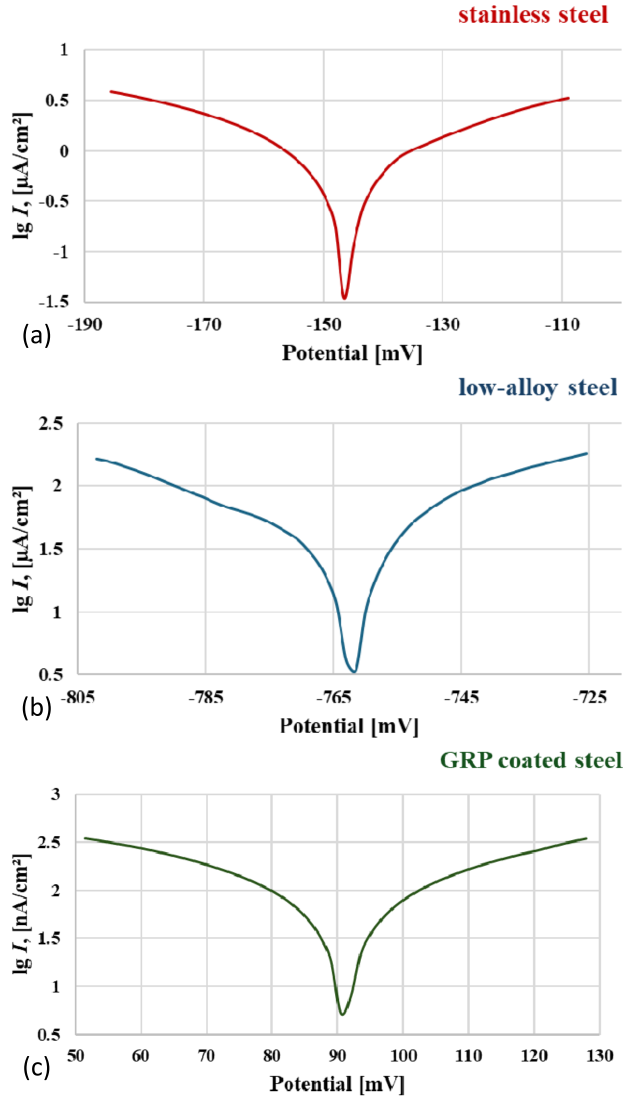

Figure 5. Evans diagram with Tafel plots: (a) uncoated stainless steel, (b) uncoated low-alloy steel and (c) low-alloy steel coated with GRP

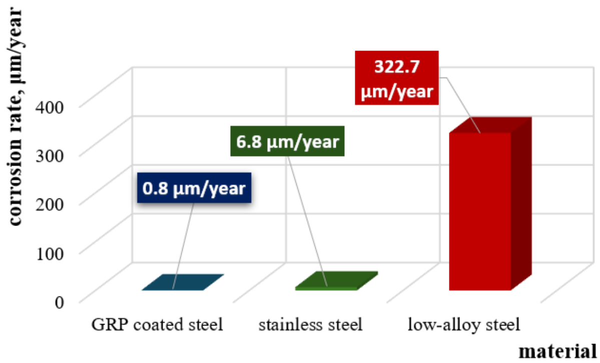

Figure 6. Comparison between the values of corrosion rate for the analysed materials

In the oil industry, equipment can be made of low-alloy steel (pipes) or stainless steel (valves). The application of GRP coatings significantly mitigates corrosion by providing a robust barrier between the steel substrate and the corrosive environment. A GRF coating on low-alloy steel effectively reduces the corrosion rate to very low levels. This is particularly beneficial in preventing corrosion phenomena such as sizing and oxygen concentration pile effects, which are known to cause issues like blocking in shutdown valve equipment. By applying GRP coatings, these detrimental effects are avoided, ensuring smoother and more reliable operation of valves and other critical components.

The justification for using GRP-coated low-alloy steels instead of stainless steels lies in the economic and performance benefits. Low-alloy steels, when coated with GRP, offer good corrosion resistance at a lower cost compared to stainless steels. This makes them an attractive choice for many applications within the oil industry, providing a cost-effective solution without compromising on durability and reliability.

Therefore, GRP coatings play an essential role in extending the lifespan of low-alloy steel components, reducing maintenance costs and enhancing the overall efficiency of oil industry operations by minimising the risk of corrosion-related failures.

3.2 Coefficient of friction and wear analysis

As explained previously, tribological tests were performed only for the GRP-coated steel. It is observed that the cumulative linear wear shows a sudden increase after approximately 73 m, as can be seen from Figure 7, which probably indicates the removal of the GRP layer.

It is also noted that the stabilised value of the coefficient of friction is 0.464 ± 0.013 and that the coating does not influence this value. Cumulative linear wear (the linear wear of both the disc sample and cube sample) resulted as 169 ± 1.4 μm. The GRP coating provides a smooth surface that reduces friction and enhances wear resistance. This makes GRP-coated steel an excellent choice for pipelines where reduced friction can lead to energy savings and where the coating protects the underlying metal from abrasive wear.

4. Conclusions

In this study, steel coated with GRP was subjected to thorough examination to evaluate its corrosion resistance and tribological properties. The study encompassed two main aspects: cumulative linear wear and coefficient of friction analysis and electrochemical corrosion analysis. The electrochemical corrosion analysis provided deeper insights into the corrosion performance.

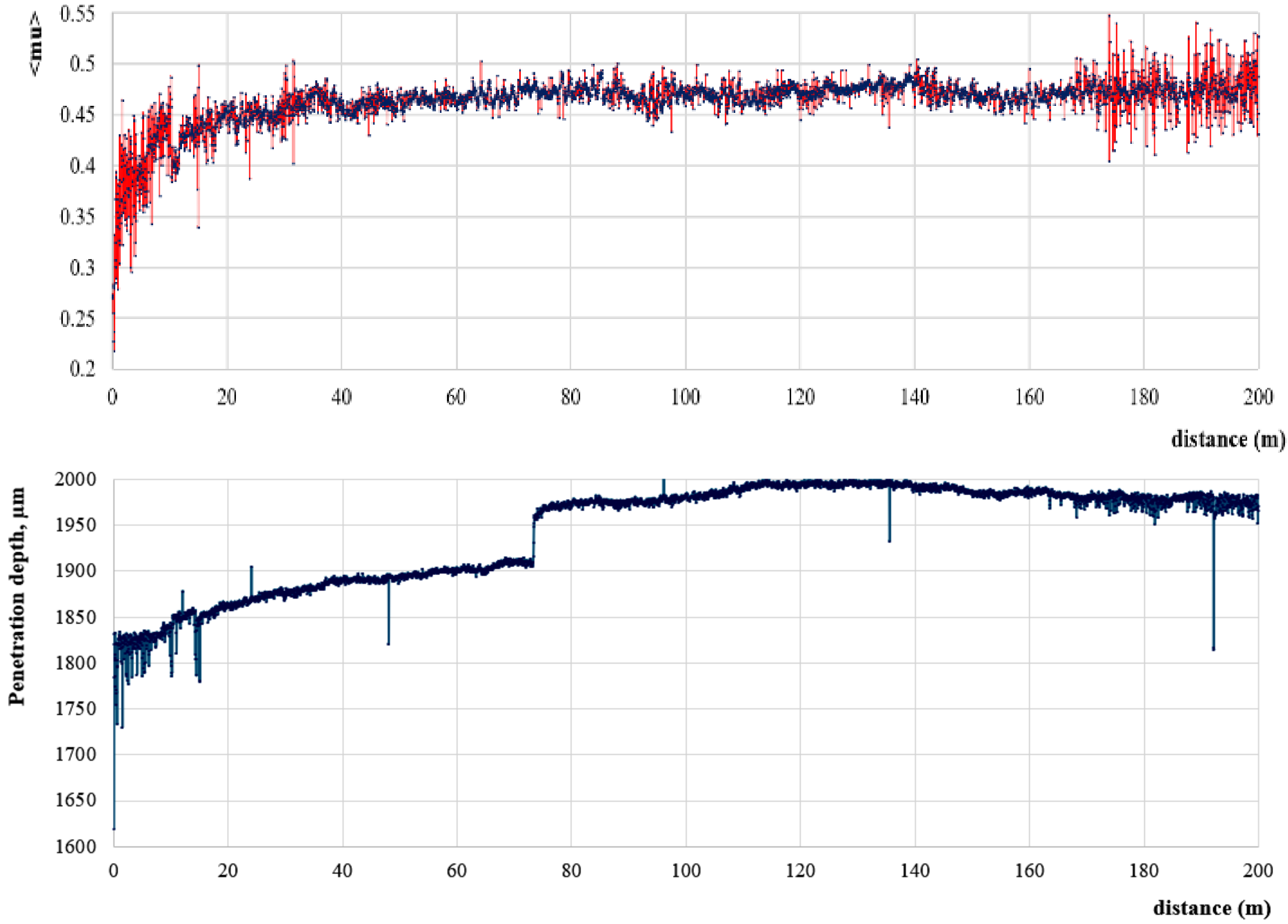

Figure 7. Variation of coefficient of friction and cumulative linear wear vs. sliding distance

It was observed a substantial decrease in corrosion rate when the steel surface is coated with GRP, approximately 8 and 403 times lower compared to uncoated stainless steel and uncoated low-alloy steel, respectively. This significant reduction in corrosion rate highlighted the effectiveness of the GRP coating in inhibiting corrosion. Corrosion can have detrimental effects on the structural integrity and longevity of steel materials, especially in environments where they are exposed to moisture, chemicals, or other corrosive agents. Therefore, finding ways to reduce corrosion is essential for maintaining the durability and performance of steel structures and components.

Deposition of the GRP coating on low-alloy steel reduces corrosion to minimal levels, offering a cost-effective alternative to stainless steel while maintaining excellent corrosion resistance. This approach not only extends the lifespan of low-alloy steel components but also reduces maintenance costs and enhances the overall efficiency of oil industry operations by minimising the risk of corrosion-related failures. Thus, GRP coatings ensure smoother and more reliable operation of critical components, making them an economically and operationally attractive solution for the oil industry.

One of the primary limitations of this study is the potential restriction in sample size and scope, as the research may have been confined to specific types of steel and particular coating thicknesses. This limitation suggests that the findings might not be universally applicable to all variations of steel and GRP coatings. Additionally, the experiments were likely conducted under controlled laboratory conditions, which do not fully replicate real-world environments. Factors such as temperature fluctuations, varying humidity levels and exposure to diverse chemicals can significantly influence corrosion and wear properties.

Given these limitations, future research should focus on conducting experiments in diverse environmental conditions, to evaluate the performance of GRP-coated steel in different corrosive environments. Additionally, investigating the long-term performance and durability of GRP coatings is essential. This includes examining the coatings under cyclic loading and environmental ageing to determine how they perform over extended periods.

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