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Evaluation of Corrosion Performance of LDX 2101 and UNS S32205 in Flexible Pipeline Applications: A Comparative Study

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Authors' contributions

This work was carried out in collaboration among all authors. This research was successfully conducted based on both individual and collective efforts. specifically, acknowledgments are due to author MG for conceptualizing the study, designing the methodology, conducting laboratory experiments, and drafting the manuscript, author IMO for assistance with writing, methodology, supervision, and review; author JM for efforts in writing, literature review, investigation, and methodology, authors SK and DO for their valuable contributions to writing, review, methodology, and editing. All authors read and approved the final manuscript.

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ABSTRACT

Lean duplex stainless steel (LDSS) has been used in various applications, including flexible pipelines in offshore and other industrial settings. In recent years, LDSS has become the preferred choice over standard duplex stainless steel (DSS) for flexible pipeline applications due to its lower costs, achieved by reducing nickel and molybdenum content, while still providing comparable corrosion resistance and mechanical strength properties to DSS. However, there is still limited reporting on the corrosion effects of reducing these alloys on the behaviour of lean duplex stainless

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steel in flexible pipelines. This comparative study investigates the corrosion resistance of lean duplex stainless steel, LDX 2101 and duplex stainless steel, UNS S32205 in flexible pipeline applications using linear polarization resistance (LPR). The research focuses on assessing material performance in environments containing CO2 and H2S, commonly found in oil and gas production, by conducting short-term and long-term tests to evaluate pitting and selective corrosion. The samples, LDX 2101 and UNS S32205 were immersed in a 3.5M NaCl solution, and corrosion measurements were performed using the Metrohm Autolab potentiostat. The results indicate that both materials exhibit good corrosion resistance, but there are differences in their performance under specific conditions. While lean duplex stainless steel, LDX 2101, can be used as a substitute for duplex stainless steel UNS S32205, its corrosion resistance and mechanical properties gradually decrease over time due to the reduced nickel and molybdenum content. As a result, it would not be as effective as duplex stainless steel UNS S32205 in withstanding corrosion in aggressive conditions over a prolonged period.

Keywords: Lean duplex stainless steel (LDX 2101); duplex stainless steel (UNS S32205); corrosion; flexible pipeline; nickel; molybdenum; linear polarization resistance.

1. INTRODUCTION

Flexible pipelines have been widely utilized in offshore industries for the transportation of crude oil, natural gas, and water due to their adaptable nature and ability to withstand harsh conditions [1]. These pipelines are composed of different layers with each playing a significant role in mechanical strength, corrosion resistance and the overall performance of the pipeline [2]. Due to its critical application, the pipeline should be made from a material with strong mechanical strength and corrosion-resistant properties to withstand high fluid temperatures and pressures that are normally employed in offshore applications [3].

The flexible pipeline can be bonded (for short sections only) or unbonded (for longer sections). Pipe lengths in various offshore and engineering applications typically range in hundreds of meters, with layers sliding against one another. This is only possible with unbonded flexible pipelines, which is why they are more widely utilized than bonded pipelines [5].

1.1 Project Objectives

- To assess the corrosion resistance of a low-nickel and low-molybdenum lean duplex stainless steel, LDX 2101 for use in flexible pipelines.
- To evaluate the corrosion resistance of high-nickel, high-molybdenum duplex stainless steel, UNS S32205 for flexible pipeline applications.
- To compare the corrosion resistance of LDX 2101 and UNS S32205 and evaluate the suitability of lean duplex stainless steel for use in corrosive environments.

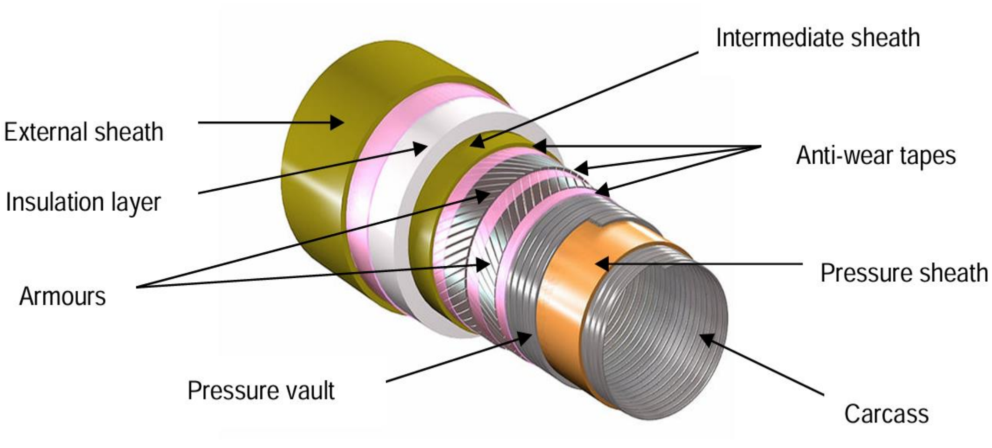

Fig. 1. Flexible pipeline structure [4]

1.2 Corrosion in Flexible Pipelines

The corrosion of metals, including flexible pipeline materials, is a costly process as it can lead to structural failures and economic losses if careful consideration is not given to the selection of materials required for applications in offshore and other industrial settings [6]. The economic impact of corrosion is substantial, with estimates suggesting it exceeds $U.S 2.5 trillion and accounts for 3.4% of the global gross domestic product (GDP) [7]. However, it is important to note that this valuation does not encompass the environmental and individual repercussions, implying that the true cost of corrosion may be even higher than currently estimated. Therefore, it is essential to have comprehensive data on the corrosion performance of materials used in flexible pipeline applications. This data allows us to predict the pipeline's service life, assess corrosion risk, and analyze structural and equipment safety in offshore and other engineering applications [8].

When designing the structure of the flexible pipeline carcass (see Fig. 1), the choice of material for this component is extremely important for the overall corrosion performance of the pipeline hence, it is essential to have comprehensive information to make well-informed decisions about the material selection for the pipeline design [3]. The carcass provides resistance to collapse under pressure and must be made from a material with strong mechanical strength and corrosion resistance properties to withstand high temperature and high-pressure fluids that typically flow through the pipe annulus. Throughout history, flexible pipelines have been fabricated using layers of polymers and steel that remain unbonded, with each layer designed to withstand specific types of stress [1,3]. Carbon steel and low-alloy steel are commonly used materials in the design of flexible pipelines due to their excellent mechanical properties and relatively low prices [9]. The fabrication of flexible pipelines for offshore applications has involved the use of various grades of steel, including AISI 304, 316, 316L, and Duplex [5]. The process fluids that pass through pipelines are usually at high temperatures and pressures and are associated with moist CO_2, H_2O, and H_2S. These compounds tend to pass through the internal polymer sheath into the pipe annulus during transportation, which can cause general and pitting corrosion, stress corrosion cracking, sulfide corrosion cracking, and hydrogen-induced cracking [10]. This can ultimately lead to pipeline failure if the correct and suitable material is not chosen at the design stage.

In flexible pipeline applications, duplex stainless steel (DSS) and lean duplex stainless steel (LDSS) are frequently utilized due to their exceptional combination of high mechanical strength, corrosion resistance properties, and varying alloy components [11-15]. These properties make them well-suited for deployment in offshore industries and other corrosive industrial applications. The lean duplex stainless steel (LDSS) is a type of duplex stainless steel (DSS) characterized by its reduced nickel (Ni) and molybdenum (Mo) content, resulting in a more cost-effective alternative to traditional DSS, and as a result of its cost efficiency, LDSS is favoured in a variety of offshore and industrial applications [16].

1.3 Corrosion Performance of Duplex Stainless Steel (DSS)

The duplex stainless steel consists of a two-phase structure with ferrite (α) and austenite (γ) [11]. Duplex stainless steel (DSS) is a microstructure consisting of approximately 50% austenite and 50% ferrite characterized by a chromium (Cr) content of over 19% and 1-7wt% nickel (Ni) [13,17]. The DSS combines the high strength of ferrite with the ductility and toughness of austenite, its weldability and corrosion resistance properties making it a suitable material for application in offshore and other aggressive environments [17-19]. At first, duplex stainless steel was created to address the intergranular corrosion issues that were common in early high carbon-austenitic stainless steel. In addition, the mixture of austenite and ferrite in DSS showed improved resistance to chloride stress-corrosion cracking compared to a fully austenitic microstructure [20]. Due to its superior properties and performance, duplex stainless steel (DSS) has been favoured over austenitic steel and has found wide applications in chemical, gas, oil, paper, offshore, and power industries [15]. The comprehensive examination of the history, application, and corrosion resistance capabilities of duplex stainless steel can be further explored in various scholarly publications and academic literature [20-22].

The modern grades of duplex stainless steel can be divided into 4 various groups as shown in Table 1.

Table 1. Chemical Composition of Duplex Stainless Steel [21].

Type	Cr%	Ni%	Mo%	N_2%	PREN
Lean	20-24	1-5	0.1-0.3	0.1-0.22	24-25
Standard	21-23	4.5-6	2.5-3.5	0.1-0.22	33-35
Super Duplex	24-29	4.5-8	2.7-4.5	0.1-0.35	>40
Hyper Duplex	27	6.5	5	0.4	49

The grades of steel are commonly known by the number that reflects their typical chromium and nickel contents for example UNS S32205 is a duplex grade with 22%Cr and 5%Ni [21]. The Pitting Resistance Equivalent Number (PREN) assesses the resistance to pitting in a general corrosive environment where duplex stainless steel materials are utilized, and it can be calculated using the following equation [14,23,24].

$$PREN = \%Cr + 3.3\%Mo + 16\%N \quad (1)$$

The PREN formula for estimating the localized corrosion resistance can also be expressed using the following equation [25].

$$PREN = wt.\%Cr + 3.3wt.\%Mo + 30wt.\%N \quad (2)$$

The equations (1 and 2) show that chromium (Cr) and nitrogen (N) are crucial factors in improving pitting resistance to corrosion, along with nickel (Ni) and molybdenum (Mo) which are known to enhance corrosion resistance in different corrosive environments. The PREN does not provide a definitive measurement of corrosion resistance and may not be relevant in all scenarios. However, it gives a general idea of the expected resistance to pitting corrosion in water-based chloride solutions [20]. The strength and hardness of duplex stainless steel (DSS) contribute to its excellent resistance to stress corrosion cracking, cavitation, erosion corrosion, corrosion fatigue, and atmospheric corrosion across a wide range of environments [17]. However, the high nickel (Ni), chromium (Cr) and molybdenum (Mo) content in DSS results in significant cost implications due to price increases of these alloys especially Ni and Mo, thereby limiting the widespread applicability of duplex stainless steel in various industrial applications [26]. These cost implications generated interest in developing an alternative material possessing comparable mechanical strength and corrosion resistance. This led to the creation of a low-cost lean duplex stainless steel (LDSS) with reduced nickel and molybdenum contents [17].

1.4 Corrosion Performance of Lean Duplex Stainless Steel (LDSS)

The lean duplex stainless steel (LDSS) is a variation of duplex stainless steel (DSS) with reduced nickel and molybdenum contents, created as a cost-effective substitute for conventional duplex and high-alloy stainless steel [12]. The decrease in nickel content in LDSS is offset by the introduction of nitrogen and manganese to maintain the material's mechanical strength and resistance to corrosion [26]. The development and application of lean duplex stainless steel result in reduced material costs, maintained duplex microstructure, and reasonably sustained steel quality [23]. In addition to addressing the high costs of high-nickel and high-molybdenum alloys in duplex stainless steel (DSS), lean duplex stainless steels (LDSS) were initially developed as substitutes for austenitic grade steels such as 304, 316, and 317 stainless steel [14]. Despite its low nickel and molybdenum content and consequently low economic cost, lean duplex stainless steel exhibits mechanical strength and toughness equivalent to duplex grades, with corrosion resistance comparable to that of austenitic steels, making it widely used in various applications [27]. Based on existing literature, it has been noted that several lean duplex stainless steels, including 2304, 2101, 2102, and 2022, exhibit mechanical strength and corrosion properties similar to those of austenitic steels 304L and 316L, despite their lower nickel and molybdenum content [17]. This suggests that these lean duplex stainless steels may offer cost advantages while delivering comparable performance. However, the lean duplex stainless steel grades are prone to localized attack in various environments such as aerated 3.5% NaCl and may not provide localized corrosion resistance properties as compared to traditional duplex stainless steel [23,27]. Based on existing literature, LDSS is generally preferred over DSS due to its lower alloy costs associated with nickel and molybdenum reduction. While some researchers have claimed that LDSS offers similar mechanical strength and corrosion resistance properties as DSS [12], there is limited or no empirical evidence to substantiate this assertion. For example, the corrosion resistance in LDSS can be improved by small amounts of nickel, usually less than 1%, which makes LDSS more cost-effective. However, this low Ni content typically minimises the pitting corrosion resistance in neutral NaCl solutions [13].

This research aims to conduct a comparative analysis of the mechanical strength and corrosion resistance of lean duplex stainless steel (LDX 2101) and standard duplex stainless steel (UNS S32205). The study focuses on evaluating the corrosion impact of reduced nickel and molybdenum in LDX 2101 in contrast to UNS S32205 with higher nickel and molybdenum content. The corrosion rates of the materials are measured using linear polarization resistance (LPR), an electrochemical technique. The findings of this study offers valuable insights into the corrosion resistance of these materials and their suitability for withstanding challenging environmental conditions and operational requirements.

2. MATERIALS AND METHODS

2.1 Materials Preparation and Procedures for LDX 2101 and UNS S32205

The materials used in this research are duplex stainless steel (UNS S32205) and lean duplex stainless steel (LDX 2101), and their chemical compositions are presented in Table 2. The terms DSS or UNS S32205 and LDSS or LDX 2101 are used interchangeably in the next sections of this paper.

The duplex stainless steel (UNS S32205) and lean duplex stainless steel (LDX 2101) samples were 20mm x 20mm in size and polished on a slow-running lathe using P180 grit silicon carbide polishing papers. After polishing, the material samples were cleaned for approximately 2 minutes with deionized water and then dried with clean air. The surface area of the samples exposed to the electrolyte for the corrosion tests was approximately 1.13 cm^2. The density and equivalent weight of the material samples were 7.85 g/cm^3 and 27.925 g/mol, respectively. Before the corrosion tests, each sample was prepared, and after the tests, the samples were cleaned, dried with dry air, and stored in a desiccator for further analysis if required. The electrochemical tests were carried out using a potentiostat autolab PGSTAT and a three-electrode setup with Ag/AgCl (Silver-Silver chloride) reference electrode, the samples as working electrodes, and a platinum counter electrode. The Metrohm Autolab Nova software 2.1 was used to set up the LPR nova protocols required for running and analyzing the corrosion measurements.

2.2 Preparation of the Electrolyte

The electrolyte used in the corrosion tests was a 3.5M NaCl solution, which was prepared by dissolving 204.7g of reagent-grade sodium chloride in 1 litre of deionized water. A magnetic stir bar was used to mix the NaCl and deionized water, and the solution was stirred for about 10 minutes at room temperature (approximately 20-22°C) and atmospheric pressure. The 3.5M NaCl solution was selected to mimic the seawater and brine environments commonly encountered in offshore industries, such as the oil and gas sector, where flexible pipelines are utilized.

2.3 Experimental Preparation and Set-Up

The experimental setup consists of a flat cell and three electrodes, as shown in Fig. 2. The tests were conducted at room temperature and atmospheric pressure, and the setup was connected to the potentiostat autolab PGSTAT (Metrohm autolab potentiostat) for the corrosion tests. As earlier mentioned, Ag/AgCl acts as the reference electrode, samples (UNS S32205 and LDX 2101) as working electrodes while platinum acts as a counter electrode. The reference electrode and flat cell were cleaned, rinsed with deionized water, and thoroughly dried with clean air before and after use in preparation for the next experiment setup. Each experiment required the flat cell to be filled with approximately 320 mL of the electrolyte solution.

Table 2. Chemical Composition of LDX 2101 and UNS S32205 [28]

Steel Grade	Chemical composition (wt.%)						
	Ni	Mn	Mo	N	Cr	Cu	C
LDX 2101	1.5	5.0	0.3	0.22	21.5	0.3	0.03
UNS S32205	5.7	2.0	3.1	0.17	22.4	-	0.02

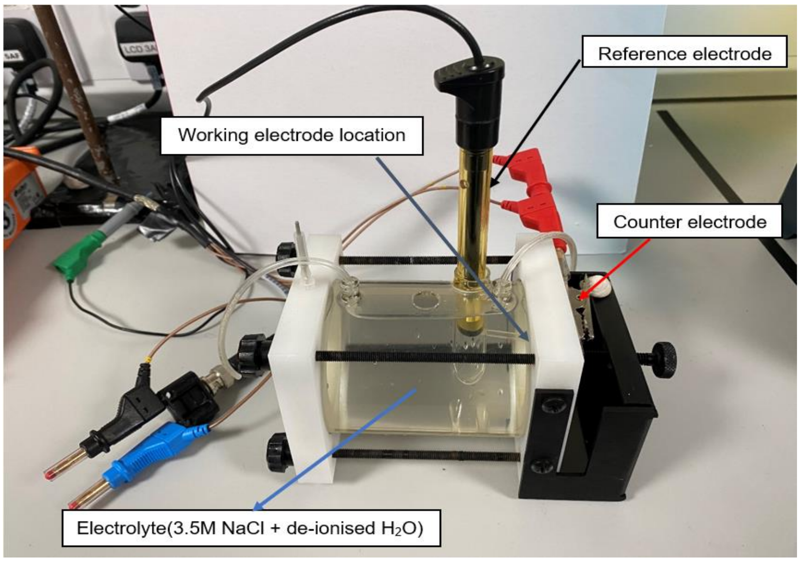

Fig. 2. Experimental set-up of the electrochemical flow cell

2.4 Electrochemical Tests Using Linear Polarization Resistance (LPR)

The study utilized the Linear Polarization Resistance (LPR) method due to its well-established reputation for providing instant corrosion rate measurements. LPR offers a non-destructive, user-friendly, and inexpensive approach to measuring corrosion rates, making it highly sensitive to small changes in corrosion measurements. The experiments were performed on duplex stainless steel and lean duplex stainless steel samples using 3.5M NaCl solution as the electrolyte in a standard three-electrode configuration, as shown in Fig. 2. The three LDX 2101 and three UNS S32205 samples were polarized to $\pm 20mV$ around the open circuit potential (Ecorr) with a scan rate of 0.5mV/sec, and three repeats were performed for each sample to improve the accuracy and reliability of corrosion measurements of the material/sample under investigation. Each sample experiment took approximately 3 hours as it involved 3 repeats with each running for approximately 1 hour. The methodology is based on the principle of linear polarization resistance (LPR). Detailed procedures and equations for calculating the polarization resistance, corrosion current density, and corrosion rates using LPR can be found in various literature sources [29-30]. The polarization resistance values, Rp, and corrosion potential (Ecorr) were obtained after thorough experimental and data analysis as shown in Table 3. Consequently, the corrosion current density and corrosion rates for the samples under investigation were calculated.

3. RESULTS AND DISCUSSION

3.1 Open Circuit Potential (OCP)

Prior to measuring corrosion rates, the open circuit potential (OCP) of the corroding material (DSS samples) was determined to achieve stability. The OCP was determined for each sample after approximately 1 hour of immersion for three consecutive repeats. Fig. 3 depicts OCP measurements over a three-hour period, with OCP values monitored and noted at each hour while performing corrosion measurements. Whereas the samples had slightly different OCP values, all the DSS (UNS S32205) and LDSS (LDX 2101) samples had OCP values ranging from -0.130 V to -0.079V. All specimens were immersed in the electrolyte before corrosion testing, and as shown in Fig. 3, the overall measured open circuit potentials for DSS and LDSS samples were relatively stable based on the range of OCP values (-0.130 V to -0.079V).

3.2 LPR Results for LDX 2101 and UNS S32205

The polarization plots were collected under controlled conditions, maintaining a consistent room temperature and atmospheric pressure. Data points were diligently recorded every 20 minutes, as depicted in Fig. 4. These plots were crucial for determining the resistance values (Rp), which are essential for accurately calculating corrosion rate values.

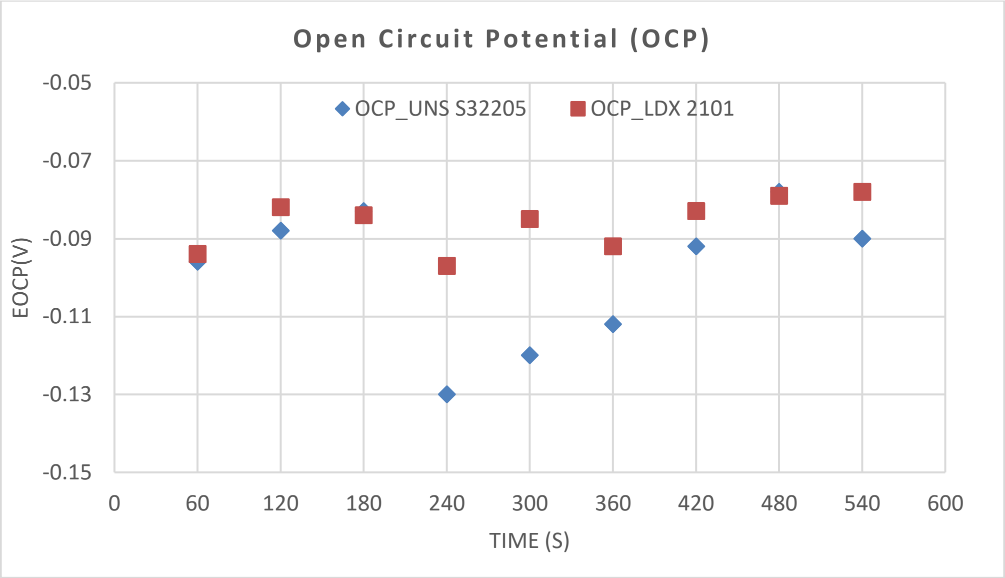

Fig. 3. Time dependence of OCP for DSS & LDSS immersed in 3.5M NaCl solution

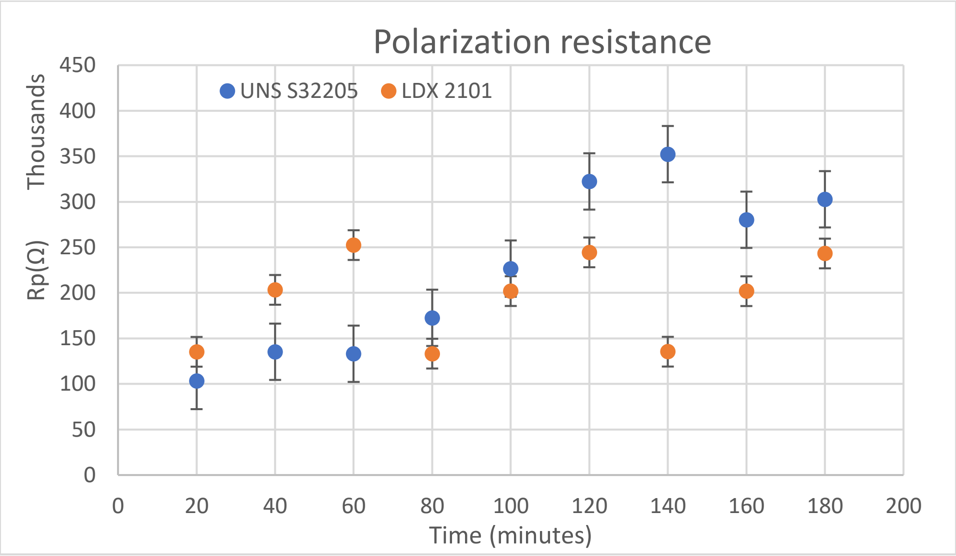

Fig. 4. LPR plots of UNS S32205 and LDX 2101 immersed in 3.5M NaCl solution

The corrosion rate measurements for UNS S32205 and LDX 2101 are displayed in Table 3 and Fig. 5 following comprehensive experiments and calculations.

3.3 LDX 2101 and UNS S32205 Corrosion Rate Measurements

From the experiments and calculations, the corrosion rate (CR-measured in mm/yr) results obtained for UNS S32205 can be seen to be lower as compared to those of LDX 2101 for each measurement and time interval. This is not consistent with the suggestions that LDX 2101 provides similar and consistent results with UNS S32205. This difference is attributed to the nickel and molybdenum alloy reduction in LDX 2101 compared to UNS S32205.

Fig. 5 displays the graphical representation of corrosion rate measurements for duplex stainless steel (UNS S32205) and lean duplex stainless steel (LDX 2101) in 3.5M NaCl solutions. As demonstrated, the results are based on multiple experiments and calculations. It is apparent that in each experiment, the corrosion rate of (LDX 2101) is higher than that of (UNS S32205). This indicates that flexible pipelines constructed from

LDX 2101 and other lean duplex grades deteriorates more rapidly due to corrosion compared to pipelines made from (UNS S32205) and other standard duplex steel grades. The differences in the values of Icorr and Rp obtained during the LPR tests can be attributed to several factors. The sample preparation was conducted at different times, and the exposure time of the samples to corrosion tests varied, as shown in Table 3. Additionally, the sample chemical composition of LDX 2101 and UNS S32205 differs, as illustrated in Table 2. Although the experimental set-up, instrument used, and electrolyte composition were consistent, inconsistencies may arise due to the above-mentioned reasons and variations in environmental conditions such as temperature and humidity, as well as potential interference or equipment noise.

Table 3 and Fig. 5 shows that the LDSS (LDX 2101) samples had the highest corrosion rate measurements compared to the duplex stainless steel (UNS S32205). This means that according to the measured data, LDX 2101 is more prone to corrosion as compared to UNS S32205. As observed in Table 3 for example, the highest corrosion rate in LDX 2101 is 0.002722 mmpy while the highest in UNS S32205 is 0.000960 mmpy. While corrosion measurements show varying trends for each measurement, at any immersion time, the corrosion rate values for lean duplex stainless steel (LDX 2101) are higher than those of duplex stainless steel (UNS S32205). This trend is observed in every UNS S32205 and LDX 2101 sample experiment, and the overall corrosion rate is observed to be higher in LDX 2101 samples. The presence of higher nickel and molybdenum content in UNS S32205 increases its pitting resistance properties making it more suitable to overcome pitting corrosion, stress corrosion and fatigue corrosion in offshore and other engineering applications as compared to LDX 2101. The error bars in the corrosion rate and linear polarization values represent the standard error in corrosion measurements. However, it is not clear how these errors affect corrosion results and correspond to the in-service performance of duplex and lean duplex stainless steel materials in flexible pipeline applications. While many publications claim that lean duplex stainless steel has comparable corrosion resistance properties to duplex stainless steel [12, 26], Fig. 5 shows that there is a significant difference as DSS (UNS S32205) measured corrosion rates are much lower than the measured LDSS (LDX 2101) corrosion rates in the same 3.5M NaCl solution. As already mentioned, these results can be attributed to the fact that the higher nickel and molybdenum content in DSS (UNS S32205) enhances its mechanical strength and corrosion resistance properties unlike in LDSS (LDX 2101) where these contents are reduced.

3.4 Comparison of Experimental Results with Theoretical Corrosion Rate Measurements

The corrosion current density, Icorr can be obtained using the Stern Geary expression as shown in equation 3 [30].

$$\boldsymbol{I_{corr}} = \frac{\boldsymbol{\beta_a \beta_c}}{\mathbf{2.303}\boldsymbol{R_p(\beta_a+\beta_c)}} \qquad (3)$$

where Rp is the polarization resistance, Icorr is the corrosion current density, $\boldsymbol{\beta a}$ and $\boldsymbol{\beta c}$ are anodic and cathodic tafel parameters respectively.

The theoretical corrosion rate measurements of the materials under consideration (LDX 2101 and UNS S32205) can then be calculated using Equation 4 [31].

Theoretical corrosion rate (mmpy)

$$=0.00327 I_{corr}\left[\frac{EW}{d}\right] \qquad (4)$$

where EW is the equivalent weight, and d is the material density.

To calculate the theoretical corrosion rate measurements for the LDX 2101 and UNS S32205, the following parameters are considered;

[i] The equivalent weight for both the material samples is 27.925g/mol
[ii] The density of the samples under investigation is 7.85g/mm^3
[iii] The anodical, βa and cathodic parameters, βc for this analysis were set at 52.1mV/dec.

The polarization resistance, Rp for the sample materials is calculated by obtaining the slope of current and potential response in LPR measurements. The Rp for LDX 2101 and UNS S32205 was calculated and obtained to be 19459Ω and 226541Ω respectively. The summarized measured values are illustrated in Table 4.

Table 3. Corrosion parameters of UNS S32205 and LDX 2101 in 3.5M NaCl solution

	DSS (UNS S32205)			LDSS (LDX 2101)		
Time(mins)	**Icorr(mA)**	**Rp(Ω)**	**CR(mm/yr)**	**Icorr(mA)**	**Rp(Ω)**	**CR(mm/yr)**
20	0.2231	103,250	0.000960	0.1935	135,297	0.002722
40	0.1925	135,344	0.001198	0.1540	203,323	0.001524
60	0.1957	133,148	0.000801	0.1076	252,450	0.001153
80	0.1510	172,606	0.000755	0.1955	133,294	0.002011
100	0.1150	226,635	0.000618	0.1290	201,934	0.001327
120	0.0808	322,354	0.000383	0.1066	244,454	0.001095
140	0.1927	352,310	0.000598	0.1955	135,420	0.002019
160	0.3165	280,257	0.000496	0.1290	201,853	0.001315
180	0.2608	302,767	0.000485	0.1066	243,251	0.001785

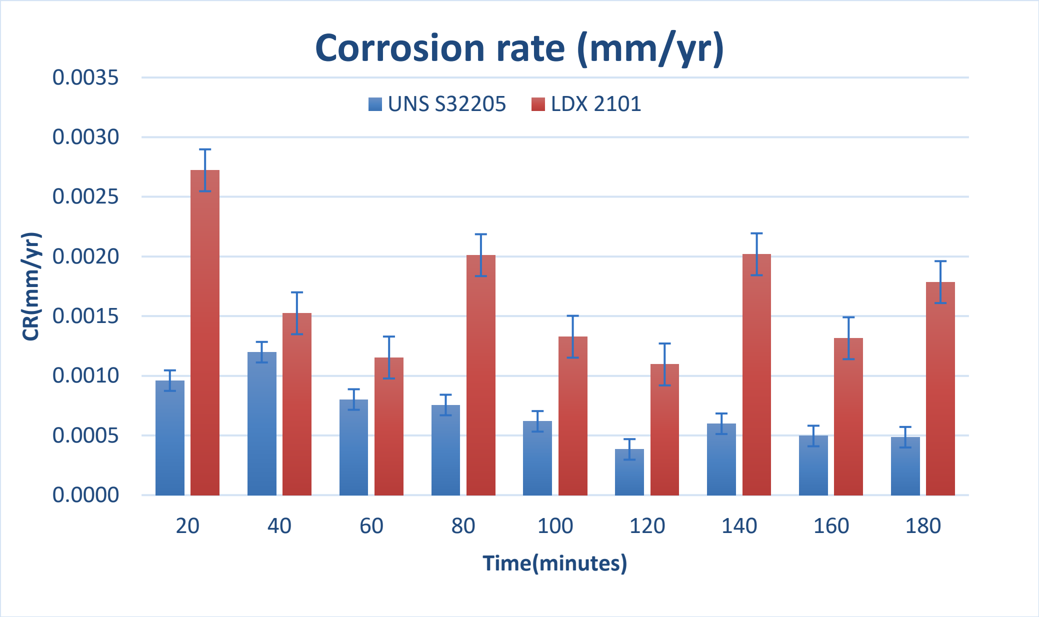

Fig. 5. Corrosion rate comparison of UNS S32205 and LDX 2101 in 3.5M NaCl

Table 4. Measured corrosion parameters of material samples under investigation.

Measured values	**Equivalent weight (EW)**	**Density of samples (d) [g/mm^3]**	**Rp (Ω)**	**βa (mV/dec)**	**βc (mV/dec)**
LDX 2101	27.925	7.85	19459	52.1	52.1
UNS S32205	27.925	7.85	226541	52.1	52.1

3.4.1 Lean duplex stainless steel, LDX 2101 corrosion results

From equation (3), $I_{corr} = \frac{52.1*52.1}{2.303*19459*10^{-3}(52.1+52.1)} = 0.5813mA$

Theoretical corrosion rate, CR (mmpy) = $0.00327 * 0.5813\left[\frac{27.925}{7.85}\right] = 0.006762\text{mmpy}.$

3.4.2 Duplex stainless steel, UNS S32205 corrosion results

$$I_{corr} = \frac{52.1*52.1}{2.303*226541*10^{-3}(52.1+52.1)} = 0.0499mA$$

Theoretical corrosion rate, CR (mmpy) = $0.00327 * 0.0499\left[\frac{27.925}{7.85}\right] = 0.000581\text{mmpy}.$

The experimental and theoretical data both indicate low corrosion rates for both materials. However, just like experimental results, the calculated theoretical corrosion rate values for lean duplex stainless steel, LDX 2101 are higher than those for duplex stainless steel, UNS S32205. This difference is due to the lower nickel and molybdenum content in LDX 2101, which makes it more prone to pitting and crevice corrosion compared to UNS S32205 over time.

There are minimal discrepancies observed in theoretical data when compared with the experimental results. These discrepancies are attributed to two major reasons. The LPR method is unable to calculate the Tafel constants (βa and βc) due to its limited range of potential perturbation. Instead, it relies on extrapolated Tafel constants from literature or other techniques such as Electrochemical Frequency Modulation (EFM) and potentiodynamic polarization (PDP). Additionally, although the technique assumes a linear potential-current relationship, most polarization curves deviate from linearity even before the overpotential reaches ±10mV of Ecorr[30]. These assumptions and variations arising from changes in the experimental setup and environmental conditions, such as temperature and humidity, introduce errors in LPR corrosion measurements, leading to discrepancies between the experimental and theoretical corrosion results. Despite these discrepancies, the theoretical corrosion measurements for these materials are consistent and closely agree with the results obtained from the experimental data presented in Table 3 and illustrated in Fig. 3.

4. CONCLUSION

This research paper presents a comparative analysis of the corrosion behaviours between LDX 2101 and UNS S32205. The analysis involved experimental data and an examination of the results obtained using the Metrohm Autolab potentiostat and the linear polarization resistance electrochemical technique. The samples were submerged in a 3.5M NaCl solution at room temperature and atmospheric pressure to replicate the corrosion conditions experienced in flexible pipelines for offshore and other industrial applications. The results show that the reduction of nickel and molybdenum in lean duplex stainless steel, LDX 2101, is cost-effective. However, this material offers similar corrosion resistance and mechanical strength properties to duplex stainless steel only for a short period. Over time, this alloy reduction significantly affects the performance of lean duplex stainless steel materials. Consequently, prolonged exposure of lean duplex stainless steel, LDX 2101, in aggressive corrosive environments leads to faster development of cracks and pits in these materials, causing a faster rate of material failure due to corrosion compared to duplex stainless steel, UNS S322O5.

Based on the discussions and results presented in this paper, it is clear that the reduction of nickel and molybdenum in lean duplex stainless steel has an impact on its mechanical strength and corrosion resistance in flexible pipelines over time. However, despite this, lean duplex stainless steel demonstrates effective corrosion resistance in the short term, and further research can explore ways to enhance its corrosion performance for longer durations while still retaining its economic advantages over standard duplex stainless steel. Additionally, more research is needed on different grades of lean duplex steel to comprehensively understand their overall performance, as the current research is limited to one specific lean stainless steel material, LDX 2101. Finally, even though the experiments and corrosion analysis in this research were conducted at room temperature and atmospheric pressure, it's important to note that in offshore and other industrial applications, the pressures and temperatures are typically much higher. Therefore, further research should be conducted at these elevated temperatures and pressures to better understand the real-time effects on the corrosion behaviour of these materials in flexible pipeline applications.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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