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Influence of voltage, feed speed and CTWD on the corrosion resistance of Inconel 625 alloy coatings deposited by MIG

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ABSTRACT

Annually, high investments are made in the maintenance of pipelines used in the oil industry around the globe. Thus, solutions are sought that combine low cost, reproducibility and properties that are consistent, mainly against corrosion. One of these is the use of materials that have high mechanical and anticorrosive properties in the form of coatings, which could be deposited by welding. The objective of this study was to evaluate the effects of different welding parameters on the corrosion resistance of coatings based on the Inconel 625 alloy, deposited by metal inert gas welding metal (MIG) process in API 5L X70 steel. The parameters were optimized using the factorial experimental design and the results analyzed by the Response Surface Methodology (RSM). Three deposits with ½ overlap were performed MIG, followed by a cross section cut in the samples for analysis of the dilution, iron content and corrosion resistance by potentiodynamic polarization (PP) through corrosion potential (Ecorr), corrosion current (Icorr) and polarization resistance (Rp). The coatings obtained presented values of the dilution ranging from 5.8% to 15.01%. The coating that presented lower dilution value, also was the one with lower Icorr and Fe, besides higher Rp and Ecorr, thus, greater corrosion resistance.

Keywords: Steel, Coating, Inconel, Corrosion, MIG.

1. INTRODUCTION

Oil production needs to be optimally planned as the path of underwater pipelines is prone to failure due to many factors that can result in long downtime, high system maintenance costs, inspection and costly support services of companies, guarantee suppliers [1].

Transport is commonly performed through steel pipelines, classified according to the API (American Petroleum Institute), according to their applications and mechanical strengths. Its compositions range from API 5L A25 to API 5L X80, and the last digits are from the yield strength of each steel (in ksi), such as API 5L X70, which have yield strength of 70 ksi or 481 MPa, approximately. They are used in high'-pressure pipelines, which in turn are susceptible to corrosion [2, 3].

These steels, despite having high mechanical resistance and some resistance to corrosion, are still subject to this last phenomenon, due to the aggressive conditions of the environment in which these ducts are located, being characterized for example, by the presence of oxides, sulfates, and water salinity [4]. According to the literature, corrosion can be defined as the deterioration of a material, usually metallic, by chemical or electrochemical action of the operating environment, being or not associated with mechanical stresses, partially or totally impairing the use of this material [5].

Considering that the highest intensity of corrosion in underwater environments comes from pitting corrosion [6], this generates maintenance costs for oil-carrying pipelines in the billions per year. According to the Brazilian Corrosion Association (ABRACO), these losses reach the level of 3.5% of the Brazilian GDP, in addition to harming marine life around the globe, so it is studied to obtain alloys and new materials, which

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are resistant to the damage that can be caused by these reactions [7, 8].

One of the solutions studied is the deposition of nickel alloys/superalloys, such as Inconel in steels that, by nature, are subject to these harsh environments. These alloys are especially characterized by their good creep and fatigue resistance, high mechanical strength [9], high-temperature corrosion and assisted fracture by the environment [9, 10]. In particular, the Inconel 625 alloy can be highlighted, which is used due to its mechanical and corrosion resistance (Nb, Cr, Ni, Mo), as well as its ease of manufacture. Its service temperature ranges from -157ºC to 982ºC, requiring no heat treatments to increase resistance [11].

For deposition of this type of alloy, the metal inert gas welding (MIG) process for coatings can be used, which has characteristics that makes it a good option, considering the other welding processes for coatings, which are: there is no slag formation (which would lead to its inevitable removal); versatile in terms of material type and thickness; penetration into the base metal is uniform; dilution can be controlled; distortions and residual stresses are smaller compared to other welding processes [12].

In this welding process, it is expected that the dilution level will be reduced both to decrease the iron content [13] on the bead surface and to prevent corrosion-susceptible microstructures from being formed [14]. To achieve such results, the welding parameters must be adjusted according to the experimental design.

Factorial experimental design tends to reduce the number of experiments. With the simultaneous analysis of factors, more than one answer can be obtained at the same time, besides the calculation of the experimental error [15]. Statistical analysis has been replacing empiricism in scientific studies, as it may help to obtain satisfactory results through the precision of response and lower cost [16-18]. The technique is already used by many authors to optimize welding parameters [19].

The factorial design can be represented by b^k, where “k” represents the number of factors and “b” the number of levels chosen. The simplest case is where each factor “k” is present on only two levels “b” (2^k factorial) [20].

The objective of this work is to evaluate the effect of different welding parameters on the corrosion resistance of Inconel 625 alloy base coatings applied by the MIG welding process on API 5L X70 steels. Thus, a coating can be deposited by welding, seeking optimal parameters that improve the properties of the weld metal. To be deposited profitably, several possibilities can be considered and the choice of the right process is crucial for obtaining an optimal result.

Experimental Procedure

The base material used in the study was the API 5L X70 steel used in pipeline manufacturing. The chemical composition is presented in Table 1, while the filler metal was AWS ER NiCrMo-3 wire with a diameter of 1.2 mm, known commercially as Inconel 625, the chemical composition of which is presented in Table 2. The welding process used was metal inert gas welding (MIG).

Table 1: Chemical composition of API 5L X70 steel.

wt.%	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Ti	Fe	Nb+ta
API 5L X70	0,19	0,24	0,7	0,018	0,018	0,064	0,008	0,07	-	-	-	-	-

Source: APL 5L [21].

Table 2: Chemical composition of the AWS ER NiCrMo-3 filler metal (wt.%).

wt.%	Ni	Cr	Mo	Fe	C	Mn	Si	P	S	Co	Nb+Ta	Al	Ti
Minimum	58	20	8								3,15		
Maximum		23	10	5	0,1	0,5	0,5	0,015	0,015	1	4,15	0,4	0,4

Source: Haynes Wire Company [22].

Experimental planning

In the present work, factorial experimental planning, this tool was used to evaluate the influence of the welding parameters, since they were prepared following a complete factorial design (2^3) with the addition of three experiments at the central point, totaling 11 experiments per matrix. In the evaluation of the results obtained by the experimental design, the response surface and variance analysis (ANOVA) methodology were used as an auxiliary tool. The independent factors (welding voltage (U), wire feed speed (Va) and contact tipworkpiece distance (CTWD) were evaluated at the -1, 0 and +1 coded levels, according to Table 3. Table 4 shows the eleven experiments resulting from the factorial design, carried out in a random sequence. All experiments were performed in random order to avoid systematic errors.

Table 3: Real and coded levels of the factors investigated.

independent factors	Levels		
	-1	0	1
U (V)	20	25	30
Va (m/min)	6	7,5	9
CTWD (mm)	20	24	28

Table 4: Experimental design matrix 2^3 + 3 central points.

Experiments	Random sequence	U (V)	Va (m/min)	CTWD (mm)
1	11	-1 (20)	-1 (6)	-1 (20)
2	4	+1 (30)	-1 (6)	-1 (20)
3	10	-1 (20)	+1 (9)	-1 (20)
4	7	+1 (30)	+1 (9)	-1 (20)
5	3	-1 (20)	-1 (6)	+1 (28)
6	8	+1 (30)	-1 (6)	+1 (28)
7	6	-1 (20)	+1 (9)	+1 (28)
8	1	+1 (30)	+1 (9)	+1 (28)
9	5	0 (25)	0 (7,5)	0 (24)
10	2	0 (25)	0 (7,5)	0 (24)
11	9	0 (25)	0 (7,5)	0 (24)

For the deposition of the coatings, a sequence of passes was made respecting an initial length "L" for the first pass, subsequently, the second pass was started at L/2 and continued until 3L/2, following the same logic for the third and last pass, as shown in Figure 1. The "interpass" temperature was 100°C.

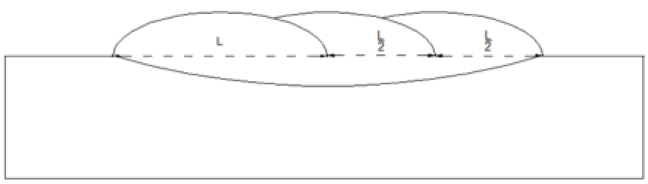
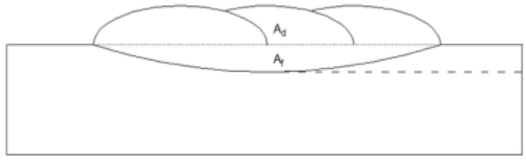


Figure 1: Pass sequencing scheme.

Dilution and Analysis of chemical composition

The dilution ratio is the percentage of the base metal that dissolves with the filler metal forming the chemical composition of the weld metal. For evaluation of the dilution (D%), the samples were taken from the cross-section of each coated plate to obtain mean values and their respective variation for the D (%), calculated as illustrated in Figure 2. Analysis of chemical composition (iron content) was performed by means Energy Dispersive X-ray Spectroscopy (EDX) using Analytical QX-2000 equipment.



% Dilution = [Af/(Af+Ad)]

Figure 2: Weld bead geometry and illustration of D (%) calculation..

Corrosion tests

The electrochemical corrosion tests were performed using Potentiodynamic Polarization (PP). Electrochemical measurements for corrosion analysis were performed in a conventional three-electrode electrochemical cell in chloride medium, NaCl 3.5 % (m/v). The working electrode consisted of the API 5L X70 steel substrate coated with the inconel 625 nickel alloy with an exposed area of 1cm², and counter electrode consisted of a Pt foil of 1cm² ; all potentials refer to silver/silver chloride (Ag/AgCl), which was the reference electrode (SCE). The inconel 625 nickel alloys were submitted to Open Circuit Potential (OCP) analyzes aiming at electrochemical system stabilization, following to PP. The tests were conducted by an AUTOLAB PG STATE 30 potentiostat/galvanostat. The acquired data were treated with the GPES software for the analysis of PP. The results were analyzed using NOVA software version 1.9.

2. RESULTS AND DISCUSSION

The matrix of the experimental design with the evaluated factors, the results of D(%), chemical composition, Fe (wt %), Rp (kΩ), Ecorr (V), and Icorr (A) is presented in Table 5.

Table 5: Experimental planning matrix: levels (coded and real) and results.

Experiments	Levels (coded and real)			Results				
	U (V)	CTWD (mm)	Va (m/min)	D (%)	Fe (%)	Rp (kΩ)	Ecorr (V)	Icorr (A)
1	20	20	6	9.46	7.78	343.22	-0.639	10.16
2	30	20	6	10.35	8.1	341.87	-0.682	10.85
3	20	20	9	9.33	7.63	343.98	-0.640	10.13
4	30	20	9	14.6	9.66	299.34	-0.704	11.17
5	20	28	6	5.8	4.64	475.66	-0.525	8.35
6	30	28	6	11.8	8.82	314.44	-0.691	10.99
7	20	28	9	6,53	4.81	433.12	-0.550	8,75
8	30	28	9	15.01	16.84	230.96	-0.720	11.61
9	25	24	7,5	8.15	6.38	363.97	-0.598	9.51
10	25	24	7,5	8.24	7.1	347.96	-0.620	9.86
11	25	24	7,5	8.1	6.19	404.54	-0.558	8.88

For analysis of the results, statistical software was used, adopting a confidence level of the results of 95%, that is, $p \leq 0,05$. This confidence level is selected because welding is a complex process.

Pareto Charts obtained for each dependent variable are shown in Figure 3A-7A. One can notice that all effects considered (excluded those of non-significance for model acquisition) have an influence on the responses of D, Fe, Rp, Ecorr and Icorr. ANOVA results assure that the models obtained represent the experimental data as the coefficients of determination (R^2) showed good adjustment for all responses. The ANOVA informs that of the observed variations are explained by the factors analyzed for both D, Fe, Rp, Ecorr and Icorr.

The empirical mathematical models found, coded as first order, with their respective statistical parameters, are presented in Equations 2a6, where the values in bold correspond to the statistically significant items of the model, at the 95% confidence level.

$$D\,(U, Va) = 47{,}256 - 1{,}589*U - 2{,}096*Va + 1{,}248*U + 0{,}114*U*Va - 0{,}888*Va - 33{,}975 \quad (2)$$

$$Fe\,(U, Va) = 96{,}215 - 2{,}81*U - 6{,}573*Va + 2{,}088*U + 0{,}159*U*Va + 3{,}384*Va - 75{,}945 \quad (3)$$

$$Rp\,(U, Va) = -\,1148{,}511 + 47{,}903*U + 63{,}239*Va - 47{,}616*U - 1{,}404*U*Va - 42{,}144*Va + 1600{,}478 \quad (4)$$

$$Ecorr\,(\text{CTWD}, U) = -1{,}492 + 0{,}026*\text{CTWD}*U - 0{,}001*\text{CTWD}*U - 0{,}0003*\text{CTWD} - 0{,}0045*U + 0{,}146 \quad (5)$$

$$Icorr\,(U, \text{CTWD}) = 25{,}30 - 0{,}456*U - 0{,}785*\text{CTWD} + 0{,}023*U*\text{CTWD} + 0{,}0675*U + 0{,}1125*\text{CTWD} - 3{,}7 \quad (6)$$

Table 5 presents the results obtained for deposition of isolated weld beads, having dilution values that varied from 5.80% to 15.01%, refering to experiments 5 and 8, respectively. Experiments 2, 4, 6 and 8 were those that were within the range that Murugan and Parmar [23] indicate that there may be continuity of anticorrosive properties. In this case, austenitic steel coatings (309L and 316L) deposited on IS 2062 structural steel substrate were considered. Percentages above 15% dilution would indicate an excessive iron content in the weld metal, which would lead to the possible formation of corrosive elements on the surface of the formed alloy. Facts also verified by Gomes [24], who used the AWS E 71T-1 coated tubular electrode process on 1020 ABNT carbon steel substrate.

In Figure 3A, only the voltage (U) showed a statistically significant influence on the dilution, whereas the other parameters and their respective interactions: CTWD and feed rate did not present, obtaining an R^2 adjustment of 87.73%., with statistical reliability of 95%. The positive value in the voltage coefficient represents that with a higher voltage value, greater dilution should be obtained.

Analyzing the data presented in Figure 3B, it was verified through the response surface that the highest dilution levels were found with 30 V voltage, allied to the feeding speed of 9 m/min, with CTWD at 24 mm, generating a higher than 14%, which corroborates the result found in experiment 8, in which the same parameters were used to obtain the coating, except for the CTWD, which was also maximum.

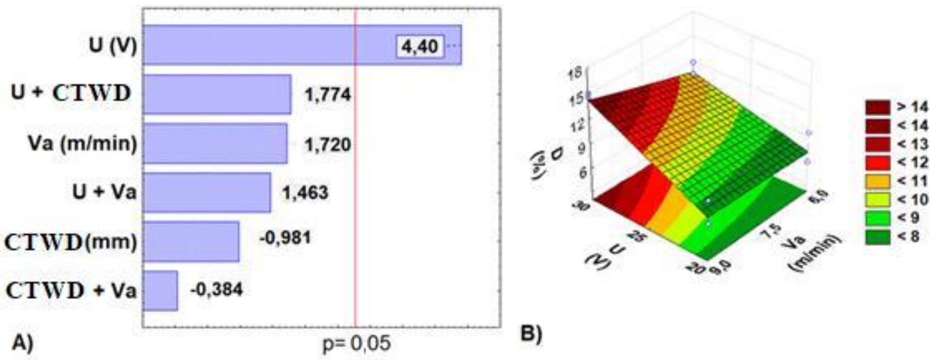


Figure 3: (A) Pareto graph for the effects of independent variables on dilution D(%). (B) Dilution versus voltage response surface versus feed rate.

It can be noted that for the same voltage value, the dilution tends to decrease with decreasing feed rate. This behavior is expected as there is less material being deposited on the base metal surface. Also verified by Sonasale [25], who used MIG welding with AWSER 70S-6 electrode and, with the variation of voltage and wire feed speed, in addition to other parameters, found that the dilution increased directly proportionally to these. Other work also verified these changes, Choteborský et al, [26], used “OK Tubrodur 15.43” as an electrode, deposited on S235JR steel, reaching similar results, regarding the variation of the mentioned parameters.

These same results can be seen in the pairs of experiments 1 and 2, 3 and 4, 5 and 6, 7 and 8, in which only the voltage of the welding parameters was changed from 20 V to 30 V and as a consequence the dilution had an increment, keeping the other welding parameters fixed, in relation to the mentioned pairs.

As quoted by Correia et al, [27], when using an ER70S-6 electrode deposited on AISI 1020 carbon steel plates through a MIG process, that by varying the feed rate, the dilution values tend to increase directly proportionally to This parameter is due to an increase in the current in the electric arc, increasing the dilution. Assuming what was cited at the end of the previous paragraph, the feed rate for sample pairs 1 and 3, 2 and 4, 5 and 7 and finally 6 and 8 which were increased by 3 m/min, thus taking to an increase in their respective dilutions.

Regarding the variation in the CTWD, Lopes et al [28] indicate that with the increase in CTWD values, there is a decrease in the dilution values acquired in the experiments, since the amount of material , in addition to the greater height at which they will be flowing, will cause less penetration, as well as increase in width and, in general, the other welding parameters, will remain constant, so it can be appreciated that the increase CTWD values will result in a decrease in dilution.

These changes can be verified from 1 to 5, 3 to 7, but do not follow the same characteristics as 2 to 6 and 4 to 8, where the dilution increases to an increase in CTWD, which may indicate that from a certain height, the dilution does not have a marked dependence on the CTWD with respect to the other welding parameters.

According to Table 5, iron content values ranged from 4.64% (experiment 5) to 16.84% (experiment 8). By observing Figure 4A, the Pareto graph shows that only the voltage, among all variables and their respective interactions, presents statistical significance in relation to the change in iron content values, it can be observed that with the increase of the welding voltage, the percentage of iron will also rise, due to the positive coefficient of column "U" of the Pareto chart. The R^2 correlation coefficient was calculated, which was 87.53%, with a 95% confidence interval.

The response surface was also constructed through statistical analysis, which can be observed in Figure 4B. Increasing the voltage (U) and feed speed (Va) values from 20 to 30 V and from 6 to 9 m / min, respectively, and keeping the CTWD constant at 24 mm, results in Fe content greater than 12%. This is explained by the longer length of the electric arc generated, as well as the greater amount of material deposited on the weld bead due to the higher thermal input and the higher feed speed which, in addition to increasing penetration and dilution, also increases the width of the weld bead. Close results were found by Aguiar, [29], in which several nickel alloys were used, including Inconel 625, which was deposited on ASTM 516 Gr 60 steel substrate by MIG.

Correlating these effects with the experiments performed, it can be seen in experiment 8, which used the same parameters, but with the 28 mm CTWD, resulted in a percentage of 16.84%, allying with the value of 15.01% dilution. These factors indicate that there may be a higher propensity to corrosion, since with greater dilutions there will be greater participation of the base metal in the weld metal constitution and, invariably, the percentage of iron in the area analyzed increases.

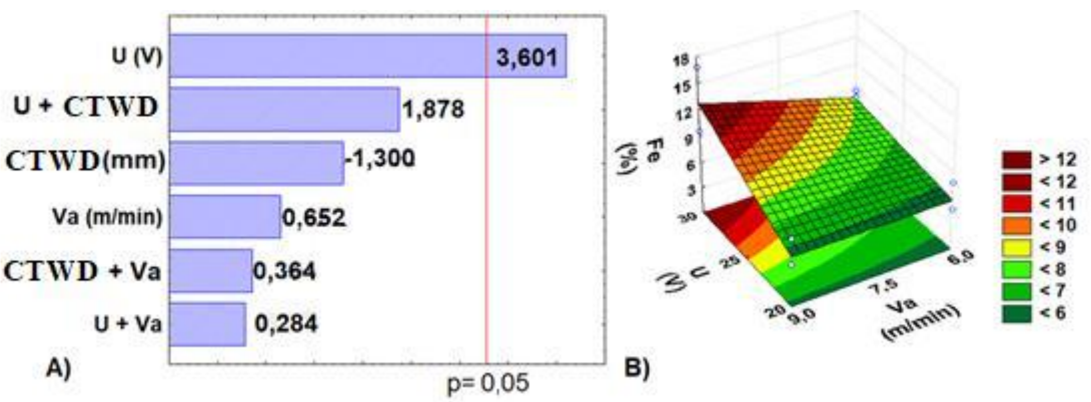


Figure 4: (A) Pareto graph for the effects of independent variables on iron (Fe) content [%]. (B) Iron content response surface versus U versus feed rate (Va).

Table 5 shows that Rp values ranged from 230.96 kΩ (experiment 8) to 475.66 kΩ (experiment 5). Through Figure 5A, the Pareto graph was plotted and showed that two parameters have a statistical significance about the polarization resistance, namely: voltage (U) and the interaction between voltage (U) and CTWD. Besides, the negative values of the coefficients show that decreasing these parameters increases polarization resistance and consequently there must be continuity of anticorrosive properties.

The response surface of Figure 5B was constructed by varying the voltage (U) and feed speed (Va) from 20 to 30 V and 6 to 9 m / min, respectively, keeping the CTWD constant at 24 mm. Through this construction, it is noticed that with the decrease of the voltage and the feed speed, the polarization resistance is taken to levels higher than 460 kΩ. Sample 5 is an example in which maximum voltage and feed speed values were used with 28 mm CTWD. With the increase in speed and tension, it favored the formation of a passivation film that increased corrosion resistance. Due to the high speed associated with high tension, it favored the formation of an oxide film, probably nickel and chromium, thus favoring the increase in corrosion resistance.

The linear correlation coefficient R^2 was calculated and had a value of 93.166%, in addition to a statistical significance of 95%.

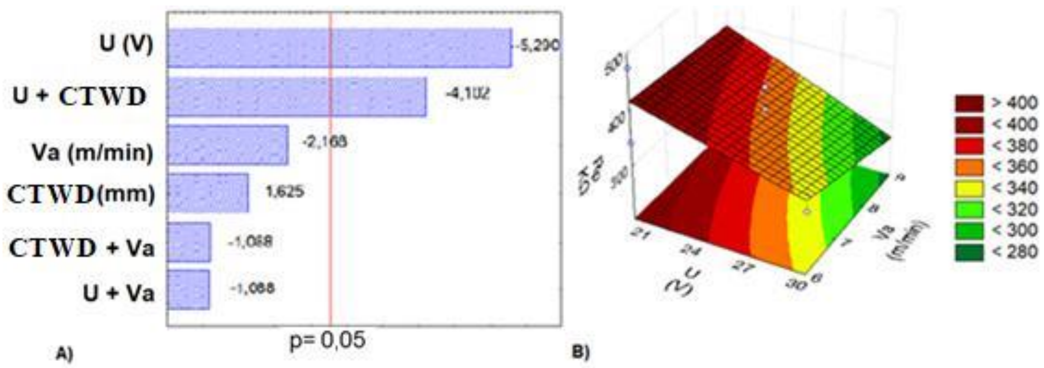


Figure 5: (A) Pareto plot for the effects of independent variables on polarization resistance Rp (kΩ). (B) Response surface of polarization resistance versus U versus feed speed (Va).

It can be related, also through Table 5, that the values of the corrosion potential (Ecorr), which in turn were in a range between -0,720 V (8) and -0,525V (5). Polinski [30] found results that are in agreement with those approached in this study, using MIG/MAG welding on SAF 2205 duplex steel substrate, depositing OK Autrod 22.09 wire as a coating.

From the analysis of Figure 6A, the Pareto graph shows that the only parameter that had statistical significance in the potential was the voltage (U), and all the others and their respective interactions did not present this characteristic. The negative value of the welding voltage coefficient indicates that the corrosion potential, Ecorr, varies inversely proportional to the voltage, in other words, with decreasing voltage the potential will increase.

Thus, it was possible to construct the response surface of Figure 6B, in which it was verified that with the decrease of the voltage (30 - 20 V) and the increase of CTWD (20 - 28 mm), maintaining at a constant feed speed of 7.5 m /min, there is an increase in Ecorr values, reaching levels higher than 0.56 V.

In those experimented in this work, we can compare with samples 5 and 7, which were performed with voltage and CTWD values equivalent to those found on the response surface, but with different feed rates, these being 6 and 9 m / min, respectively. The linear correlation coefficient R^2 was equivalent to 82.048%, with statistical reliability of 95%.

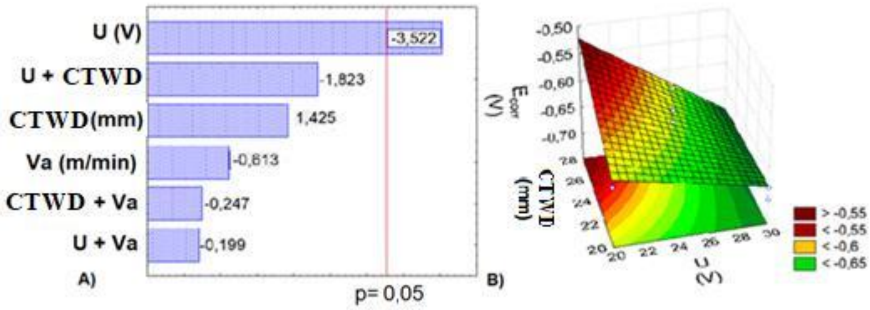


Figure 6: (A) Pareto graph for the effects of independent variables on corrosion potential (Ecorr) [V]. (B) Corrosion potential response surface versus CTWD versus U.

The corrosion current values (Icorr) ranged from 8.35 A (experiment 5) to 11.61 A (experiment 8), as can be seen from Table 6. The linear correlation coefficient R^2 was also obtained, having a response of 82.476% with a statistical significance of 95%.

Figure 7A shows the Pareto graph, where voltage (U) is the only independent variable that had statistical significance in the variation of the corrosion current. As the voltage increases, the corrosion current also rises, as shown in the same graph.

And through Figure 7B, one can analyze the response surface generated by the responses obtained on the Pareto graph. It was built by varying the voltage values of 20 - 30 V and the CTWD of 20 - 28 mm, making the feed speed constant at 7.5 m/min.

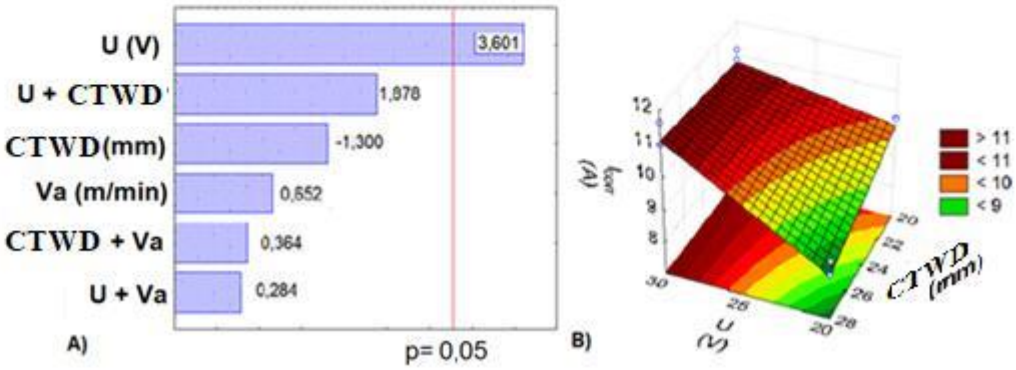


Figure 7: (A) Pareto graph for the effects of independent variables on the corrosion current (Icorr) [A]. (B) Response surface of corrosion current versus U versus CTWD.

Potentiodynamic Polarization *Measurements*

The polarization curves of experiments 8 and 5 are shown in Figure 8, which had the highest and lowest level of dilution, 15.01% and 5.8% respectively, among the 11 experiments performed, obtained in corrosive NaCl médium (3.5 % m/v) at an ambient temperature of 25 ± 2 °C. Figure 11 also shows the behavior of the steel polarization curve without API 5L X70 inconel 625 coating.

There is a shift in the corrosion potential (Ecorr) to more noble values in the experiment 5 (-0.525 V) compared to the experiment 8 (-0.720 V). The dissolution process was observed for both coatings from the potential of corrosion. However, experiment 5 showed a lower corrosion current density compared to experiment 8 (Table 5). These results confirm the higher corrosion resistance of the experiment 5 . A similar result was obtained in a study on the anti-corrosion properties of the PTA-P welding process obtained coatings [31], where the authors also observed that the increase in the dilution in the coating reduces the corrosion resistance.

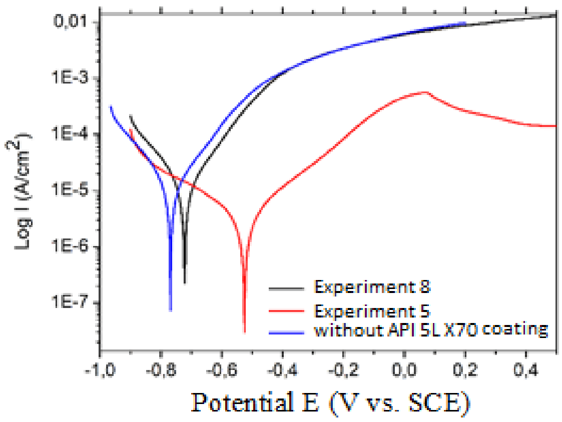


Figure 8. PP curves of experiment 5, experiment 5 and without API 5L X70 inconel 625 coating, obtained in corrosive NaCl medium (3.5 % m/v) at room temperature of 25 ± 2°C.

3. CONCLUSIONS

Based on the study of this work, the following conclusions can be drawn: The factorial design was satisfactory to obtain the best results, both dilution and chemical composition, as well as corrosion in the experiments.

To achieve the lowest dilution result, voltage (20 V) and feed rate (6 m / min) were used, as well as a 28 mm CTWD, generating a value of 5.80% for sample 5. Also, for this sample, the following was generated: Fe and Icorr content (4.64% and 8.35 A); and larger: Ecorr and Rp (-0.525 V and 475.66 kΩ).

The MIG welding process was successfully used for coating welding and the above objectives were met.

4. ACKNOWLEDGMENTS

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