ANÁLISE ESTATÍSTICA DOS PARÂMETROS DE DEPOSIÇÃO DE UM REVESTIMENTO PELO PROCESSO FCAW PULSADO COM AÇO MARTENSÍTICO 410 NiMo UTILIZANDO O MÉTODO DE TAGUCHI E MODELOS DE REGRESSÃO

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Resumo: A análise e otimização de parâmetros de soldagem por deposição utilizando processo de arame tubular pulsado (FCAW – *Flux Cored Arc Welding*) foi o objetivo do presente trabalho. Foram utilizadas corrente média, frequência de pulsação, velocidade de soldagem e distância bico de contato-peça como variáveis de influência, com cada uma sendo testada em três níveis diferentes. As características geométricas avaliadas (variáveis de resposta) foram largura, reforço, penetração, área de reforço, área de penetração e área de diluição. Foram usadas ferramentas estatísticas para análise, usando o método de Taguchi para estabelecer quais combinações de parâmetros seriam realizadas em cada teste, com uma matriz L9 como resposta. No entanto, modelos de regressão utilizados foram importantes para selecionar os parâmetros mais significativos, seguidos de análises completas de regressão linear múltipla, que forneceram um modelo para maximizar os parâmetros de acordo com o conjunto de respostas. Percebeu-se que a corrente média afetou quase todas as respostas, com exceção da área de reforço. A velocidade de soldagem não interferiu apenas na penetração e na área de penetração, mas a distância bico de contato-peça influenciou significativamente no reforço.

Palavras-chave: Método de design robusto, Modelos de regressão, Conjunto de respostas, Área de penetração, Distância bico de contato-peça.

STATISTICAL ANALYSIS OF PARAMETERS FOR DEPOSITION OF A COATING BY THE PULSED FCAW PROCESS OF MARTENSITIC STEEL 410 NiMo USING THE TAGUCHI METHOD AND REGRESSION MODELS

Abstract: This study aimed to analyze and optimize deposition welding parameters using a pulsed Flux Cored Arc Welding process (P-FCAW), where the influence variables adopted were the average current, pulsation frequency, welding speed and the contact-tip-workpiece distance, with each variable being tested at three different levels. The geometric characteristics evaluated, that is, the response variables, are width, reinforcement, penetration, reinforcement area, penetration area and dilution. Statistical techniques were used as analysis tools, using the Taguchi method to establish which combinations of parameters would be performed in each test, providing us with an L9 matrix. Used regression models was important to select the most significant parameters, followed by multiple linear regression complete analyzes, which provided a model for maximization the parameters according to the set of responses. It was noticed that the average current affected almost all responses, only with the exception of the reinforcement area, the welding speed only did not interfere with the penetration and the penetration area, but the contact-tip-workpiece distance significantly influenced in the reinforcement.

Keywords: Robust design method, regression models, set of responses, penetration area, contact tip workpiece distance.

1. Introduction

Coatings of materials with high quality and properties of hardness and resistance to wear, as is the case of martensitic steel, have been widely accepted both in the original manufacturing process of components subject to intense demands in relation to these properties, as in the process of recovery sudden or scheduled maintenance of these components damaged. For example, in the case of hydraulic turbines, cavitation erosion is a constant and harmful phenomenon, being responsible for large losses and damages in the electricity sector. However, the replacement of an already installed hydraulic unit would be unfeasible from a technical and economic point of view, with the costs of repairs being significant, and the biggest consequence is the stop of the hydraulic unit for several days, to recover the surfaces eroded by cavitation (KUMAR; BHINGOLE, 2015).

In coating welding the main objective is to obtain a bead with the lowest possible dilution, a small penetration, the largest width and possible reinforcement, for a better process yield. Thus, in the welding segment, the FCAW (Flux Cored Arc Welding) process has been increasingly used. This process is evidenced in the industrial environment because it has a large production capacity, mainly ensured by the high current density, which guarantees a high melting rate, high work factor and automation of the process (SHI; ZHENG; HUANG, 2013). Therefore, it is noted that one of the biggest challenges of this method is to adjust the process parameters so that the deposited material can acquire the desired geometry (PRABHU; ALWARSAMY, 2014).

The used to regression models, analysis of variance and other statistics methods of their data, based on an experimental design by Taguchi method, making it possible to identify which parameters would significantly influence their responses (GHAZALI; MANURUNG, 2015) (PRASAD; RAO; RAO, 2012). Another common approach is based on Response Surface Methodology (RSM), which is a tool that allows to evaluate how the responses are affected when the input variables are adjusted outside the region of interest, to know which input variables when combined they affect the response and also know which values of these variables will have the desired response (maximized or minimized) and which the response surface is closer to this optimum (ACHEBO; SALISU, 2015) (KUMAR et al., 2017).

Since in the welding with tubular wire (FCAW-Flux Cored Arc Welding) with pulsed current, coalescence between metals occurs through an electric arc established between the part to be welded and a continuously fed electrode, variables already well known as width, reinforcement, penetration, reinforcement area, penetration area, contact-tip-workpiece distance (CTWD) and dilution, are specific data fundamental to the efficiency and quality of hardfacing (MORENO; PINTO; ÁVILA, 2019).

However, jointly controlling all these parameters, technically depends on the skill of the welder, the machine, but factorial experiments, regression models and statistical hypothesis testing, where a fraction of the total number of combinations of the input variables is performed, can identify and justify the efficiency reasons of the response variables by Oliveira et al., 2015.

2. Experimental Methods

The samples used for the survey of the technical results were of a substrate in steel SAE 1020 and deposit of the coating in martensitic steel EC410NiMo, where the coatings were performed using the bench shown in Figure 1. During the preparation and testing of deposits beads they were strictly followed important procedures for the best deposition possible with prior preheating of the sheet waiting at 200°C and subsequently decrease for 150°C temperature to eventually apply the following passes.

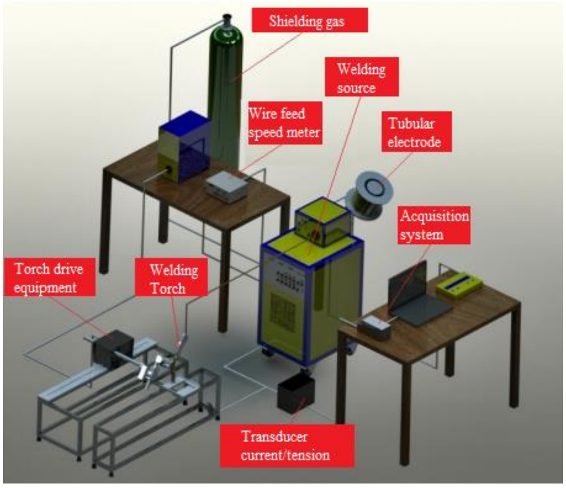

Figure 1 – Welding workbench identifying the main equipment used to carry out the experiments.

Parameters were defined for performing the coating welds as shown in Table 1. The transfer of metal during the welding process when using the pulsed electric arc was achieved by combining the efficiency of the work source with two current levels, where at the high level of current intensity, there is a high current applied in a given time interval, when the drop is detached; and at the lowest level of current with a certain time, there is the formation of the drop, so that it is highlighted at the upper level of current (MONTGOMERY, 2019).

The specimen for measures of responses such as width, penetration, area of penetration, reinforcement and reinforcement area were extracted from the beads and properly prepared macro graphically as shown in Figure 2, which also indicates the respective delimitations of these measures.

Table 1 – Parameters and levels maintained constant during the welding.

Parameters	Level
Electrode polarity	CCEP
Shielding gas	Ar + 2% O
Gas flow	15 L/min
Torch angle	90º
Welding position	Flat
Interpass temperature	150ºC
Wire feed speed	8,5 m/min
Number of passes	1
Peak current (Ip)	350 A
Peak time (tp)	10 m.s

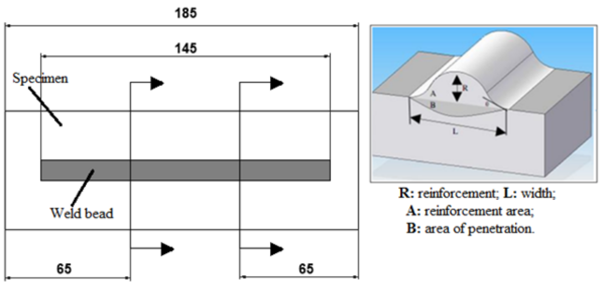

Figure 2 – Representation of the sectioning performed on all weld beads and geometry of the coating weld bead section.

2.1. Experimental Planning

In planning the experiments, care was taken that the input variables were purposely modified at different levels so that is possible to analyze what happens in the response variables. The importance of carrying out a design of the experiments is mainly to obtain satisfactory results and at the same time savings (SIVARAMAN; KULKARNI; DE, 2016). For this work, a common matrix model, where it presents 4 variables and 3 levels, as shown in Table 2, was adopted, resulting in a L9 matrix (3^4) with the best combination of these parameters.

Table 2 – Influence variables and their Levels

Variables / Levels	**-1**	**0**	**1**
Average Welding Current (A)	170	200	230
Pulsation Frequency (Hz)	18.88	20.00	22.22
Welding Speed (mm/min)	300	350	400
Contact tip workpiece distance (mm)	30	35	40

In addition, the method provides other main tools: the P diagram; the ideal function; the quadratic loss function; the signal to noise ration; and orthogonal vectors, also adopted in the analysis of the results. Table 3 shows the parameters combinations provided by the program and applied during the test.

It is necessary to use randomization to perform the tests, thus minimizing errors in the functioning of any instrument, measurement errors, error in the instrumentation system and equipment accuracy. Therefore, the tests carried out for pulsed current followed the sequence: 2, 5, 4, 8, 7, 3, 9, 6, 1. Thus, each test was performed with two repetitions to obtain a satisfactory number of results, and thus enable statistical analysis in L9 matrix.

After obtained of the collected data, was performed statistical analysis using regressions linear multiple models, with first order regression equations, so results exhibition in tables of ANOVA and graphs of effects that interfere in the response variables. In this evaluation and validation of models, when opting for first-order linear regression model methods, it is necessary to check the assumptions about the residuals of the adjusted model (ε_i), to verify their adequacy or lead to a review of the proposed models. Thus, the assumptions of the residues imply homoscedasticity, absence of autocorrelation and that the residues follow a normal probability distribution with zero mean and constant variance. All assumptions were checked using graphs (QQ plot, graph of dispersion of the residuals versus predicted and graph of autocorrelation of the residuals) and hypothesis tests. In all statistical analyzes, a fixed significance level of 5% and computational support from the

MINITAB software were used.

Table 3 – Values of test with pulsed current

Experiment	Average Current (A)	Pulsation Frequency (Hz)	Welding speed (mm/min)	Contact-tip-workpiece distance (mm)
1	170	18.18	300	30
2	200	20.00	300	35
3	230	22.22	300	40
4	230	20.00	350	30
5	170	22.22	350	35
6	200	18.18	350	40
7	200	22.22	400	30
8	230	18.18	400	35
9	170	20.00	400	40

2.2 Statistical analysis

Every procedure for statistical analysis was performed with the support of the MINITAB software. First order regression equations were generated, with tables by the ANOVA software, with graphs of effects and how the influence variables influenced the responses variables. The graphical analysis of residues was adopted, where a normal probability graph was generated, commonly called Normal Q-Q Plot, that is, one that verifies the assumption that the residues are normally distributed. On the other hand, the other diagnostic graphs are presented:

- Graph of the residuals versus the predicted values: verifies the homoscedasticity of the model that is, constant σ^2;
- Graph of the residues versus the order of observation or order of data collection: assesses the hypothesis of data independence, that is, if there is no self-correlation between the residues.

2.3 Hypothesis testing

A statistical hypothesis is an affirmation where the decision-making procedure is called a hypothesis test that must follow the steps: 1. Identify the parameters of interest in the problem context; 2. Establish the null hypothesis (H_0); 3. Specify the alternative hypothesis (H_1); 4. Determine an appropriate statistical test; 5. Applying the criteria for rejection or non-rejection of the null hypothesis; 6. Calculate any required sample quantities and substitute them in the equation for the statistical test to calculate this value; 7. Decide whether or not H_0 should be rejected and report this in the context of the problem (STREIB; DEHMER, 2019).

3. Results and Discussions

The response variables, that is, the intended results at the end of the test, were width, reinforcement, penetration, reinforcement area, penetration area and dilution. The values determined for width, reinforcement, penetration, reinforcement area and penetration area measured using the AUTOCAD software. Table 2 shows a complete survey of data measured at and which will be statistically tabulated. Figure 3 shows the profiles of the geometry of the beads obtained in the experiments.

However, Table 4 presents the results obtained in each experiment for the cord morphology with pulsed current and its respective repetition, where was observed that for lower currents, the reinforcement was very high and, consequently, a small width, when compared to larger currents. Therefore, according to the variables and levels adopted in this work, to meet the conditions of a coating weld, the best results are achieved in practice with the use of higher current values, such as 200 and 230 A. A first highlight is the increase in the width of the cord as the average current and the contact tip workpiece distance increase. Was obtained a minimum width of 7.920 mm for the current of 170 A, and a maximum of 11.510 mm for the current of 230 A.

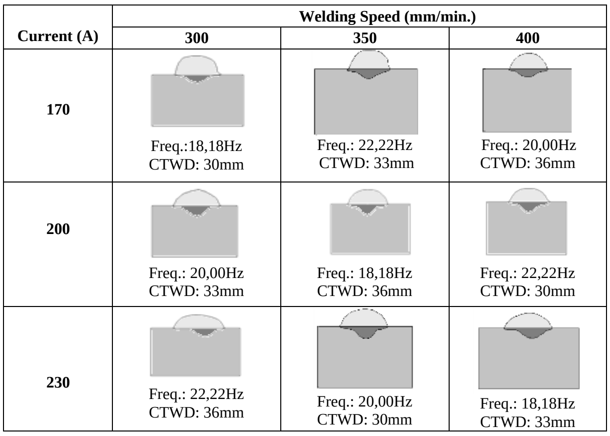

Figure 3 – Geometry of the weld beads obtained in the welding tests.

This result is in accordance with the bibliography (MORENO et al., 2018) (KUMAR, 2014) in the area, because the higher the concentration of head at the tip of the electrode, the greater the heating, causing a greater amount of material to be deposited in the melt pool. In the reinforcement, it is observed a maximum value of 4.750 mm with a current of 170 A, and a minimum value of 3.140 mm for conditions worked with a current of 230 A. On the other hand, was noticed an inverse behavior in width, after all, as the current increases, the reinforcement decreases, considering that there is a reduction in the reinforcement as the welding speed and contact-tip-workpiece distance increase. As for the reinforcement area, was found higher values with the reduction of the welding speed, where in the surveys it was obtained a maximum reinforcement area of 33.140 mm^2 with a welding speed of 300 mm/min and a minimum value of 20.540 mm^2 with a welding speed 400 mm/min. In penetration, was found a minimum value of 1.590 mm at a current of 170 A and a maximum value of 2.820 mm at a current of 200 A. There is an increase in penetration as the current increases. This is also true for the penetration area, where it obtained a minimum value of 7.750 mm^2 in the current of 170 A, and a maximum of 13.970 mm^2 in the current of 200 A.

3.1 Results of the regression models

A regression model was generated for each response variable to analyze the results, as well as generated an interaction graph to understand the maximization of the influence variables in relation to the welding process. From the multiple linear regression models, was obtained ANOVA (QASIM et al., 2015) tables that allowed, from the p-value, to verify which input variables (average current, pulsation frequency, welding speed and contact tip workpiece distance) influence significantly in the process variables directly (width, reinforcement, penetration, reinforcement area, penetration and dilution area).

This decision-making in relation to the p-value was based on the hypothesis test concepts, that is, it can be considered that the input variables have a statistically significant influence on the response variable, when the p-value has lower values at the level of significance (0.05% or 5%), rejecting H_0. Table 5 show the p-value obtained, highlighting those in which there was rejection of H_0, as regression equations were generated for each response variable, as highlighted below.

Table 4 – Results of weld bead morphology with pulsed current.

Tests	Welding Parameters				Results					
	AC	**PF**	**WS**	**CTWD**	**W**	**R**	**P**	**PA**	**RA**	**D**
1	170	18.18	300	30	9.240	4.750	1.970	8.220	33.140	19.874
2	170	18.18	300	30	8.140	4.350	2.050	8.770	27.960	23.877
3	200	20.00	300	33	10.690	4.110	2.340	12.480	32.600	27.684
4	200	20.00	300	33	11.040	4.090	2.690	13.970	29.870	31.866
5	230	22.22	300	36	11.460	3.420	2.230	12.190	30.330	28.669
6	230	22.22	300	36	11.510	3.590	2.150	11.370	30.950	26.867
7	230	20.00	350	30	10.060	3.560	2.540	11.420	26.920	29.786
8	230	20.00	350	30	10.130	3.610	2.550	11.560	26.600	30.294
9	170	22.22	350	33	8.130	4.110	1.880	8.500	23.990	26.162
10	170	22.22	350	33	7.920	4,200	1.860	7.750	25.180	23.535
11	200	18.18	350	36	10.480	3.710	2.820	13.930	28.230	33.041
12	200	18.18	350	36	9.860	3.650	2.500	11.500	26.060	30.618
13	200	22.22	400	30	9.810	3.320	2.070	9.750	23.170	29.617
14	200	22.22	400	30	9.630	3.270	2.480	11.950	22.010	35.188
15	230	18.18	400	33	9.750	3.520	2.080	10.660	23.290	31.399
16	230	18.18	400	33	10.040	3.140	2.130	10.720	22.230	32.534
17	170	20.00	400	36	8.980	3.400	1.980	9.750	20.540	32.189
18	170	20.00	400	36	9.120	3.250	1.590	8.050	20.880	27.826

*AC: Average Current (A); PF: Pulsation Frequency (Hz); WS: Welding Speed (mm/min); CTWD: contact-tip-workpiece distance (mm); W: Width (mm); R: Reinforcement (mm); P: Penetration (mm); PA: Penetration Area (mm2); RA: Reinforcement Area (mm2); D: Dilution (%).

Table 5 – Analysis of Variance (ANOVA) obtained through Regression Analysis for response variables (p-value).

Factor	**W**	**R**	**P**	**PA**	**RA**	**D**
x_1: Average Current (A)	**0.000**	**0.000**	**0.040**	**0.009**	0.103	**0.023**
x_2: Pulsation Frequency (Hz)	0.706	0.094	0.391	0.647	0.308	0.854
x_3: Welding Speed (mm/min)	**0.043**	**0.000**	0.306	0.288	**0.000**	**0.011**
x_4: CTWD (mm)	0.058	**0.014**	0.712	0.371	0.578	0.315

For the statistical generation of each response variable, the following equations for mathematical modeling were carefully formulated.

$$W=1.49 + 0.03172x_1 + 0.0335x_2 - 0.00792x_3 + 0.1222x_4 \text{ [mm]} \quad (1)$$

$$R=10.748 - 0.00894x_1 - 0.0484x_2 - 0.00735x_3 - 0.0511x_4 \text{ [mm]} \quad (2)$$

$$P=10.748 - 0.00894x_1 - 0.0484x_2 - 0.00735x_3 - 0.0511x_4 \text{ [mm]} \quad (3)$$

$$PA=2.34 + 0.0469x_1 - 0.107x_2 - 0.01020x_3 + 0.142x_4 \text{ [mm}^2\text{]} \quad (4)$$

$$RA=59.20 + 0.0240x_1 - 0.215x_2 - 0.08788x_3 - 0.078x_4 \text{ [mm}^2\text{]} \quad (5)$$

$$D=-11.1 + 0.0725x_1 - 0.078x_2 + 0.0499x_3 + 0.294x_4 \text{ [\%]} \quad (6)$$

The effects graphs generated for each response, where its interpretation is simplified, but is associated with the values found in the ANOVA tables, and that mathematically the regression equations and extracted observations came from Table 2. A first aspect to be verified is that every time there is great variation between the lines in the effects graph, this means that input variable is having a determining influence on the response variable studied in question, since it is also observed that the data of p-values were chosen for this same input variable.

In the analysis of the effect of the variables, it is noted that there was great variation in the straight lines, and that there is also a significant p-value, lower than the significance level, rejecting H_0. Therefore, when the lines have a small variation, there is also a p-value grater than the significance level, thus concluding that particular input variable is not having a limitation in the response (ABBAS et al., 2016).

A second aspect for the interpretation of these graphic effects is an association with the regression equations, because when the regression coefficient that multiplies the input variable has a positive sign, it is interpreted that this response variable is positively affected by the input variable, that is, as the levels of the input variable results, thus maximizing the values at the highest level which is the same when the regression coefficient results in a negative sign. Therefore, it appears that the response variable is being negatively affected by the input variable, that is, as the levels of the input variable increase, there will be a reduction in the results of the response variable, thus maximizing the response at the lowest level adopted.

All of these analyzes are recorded in Figures 4(a) and 4(b); Figures 5(a) and 5(b) and Figures 6(a) and 6(b) for all important variables in the work. Figure 4(a) shows that the data average was 9.78 mm (dotted line), where the behavior of the weld cords showed an increase in width with an increase in the average current and the distance between the contact-tip-workpiece-distance. However, with the increase in speed, the opposite happens, that is, the width decreases, because the electric arc remains a shorter time during welding in the melting pool.

The pulsation frequency, on the other hand, obtained a small difference in its lines, since H_0 was not rejected for this variable ($p = 0.706$). The variables that most affected the width were the average current ($p = 0.000$), the welding speed ($p = 0.043$) and to a lesser extent, but very close to the contact-tip-workpiece distance ($p = 0.058$), as shown in Table 5.

In the penetration shown in Figure 5(a), the average of the data was 2.22 mm (dotted line). In this response variable, we have a greater intensity of influence from the variation of the average current ($p = 0.040$), as H_0 was rejected.

However, for the area of penetration shown in Figure 5 (b), the average of the results was

10.70 mm^2 (dotted line). As can be seen, the parameter with the greatest effect was the average current ($p = 0.009$), as it was the straight line with the greatest difference in slope, as well as in penetration, rejecting H_0.

In the reinforcement area, Figure 6 (a), a data average of 26.33 mm^2 was obtained. The parameter with the greatest intensity of effects was the welding speed ($p = 0.000$), rejecting H_0, where there was a decrease in the reinforcement area with its increase, as well as in the reinforcement.

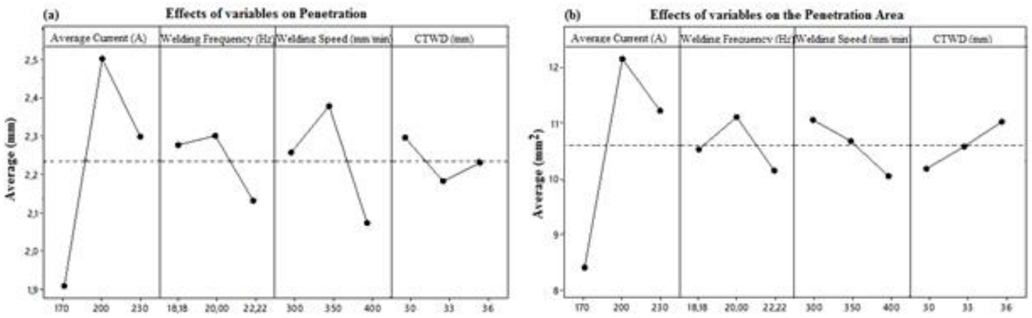

Figure 5 – Effect of welding variables/parameters on (a) Penetration and (b) Penetration Area.

In the dilution, Figure 6 (b), the average of the results was 28.95% (dotted line). By the graphic behavior, the factors with the greatest influence the average current ($p = 0.023$) and the welding speed ($p = 0.011$). The contact-tip-workpiece distance obtained a p-value equal to 0.315, not rejecting H_0.

From the graphical analysis it appears that all the results obtained, from the collected data and the statistical analyzes, are summarized in the simple observation of these figures, where very similar results were obtained by other researchers (KURTULMUS et al., 2015). Emphasizing that, all analyzes to verify the assumptions imposed in the literature for the residuals of the regression equations were also performed and satisfied, which indicates that this regression model is adequate to predict values and analyze the influence on responses (SINDHU; RUBAN. 2016).

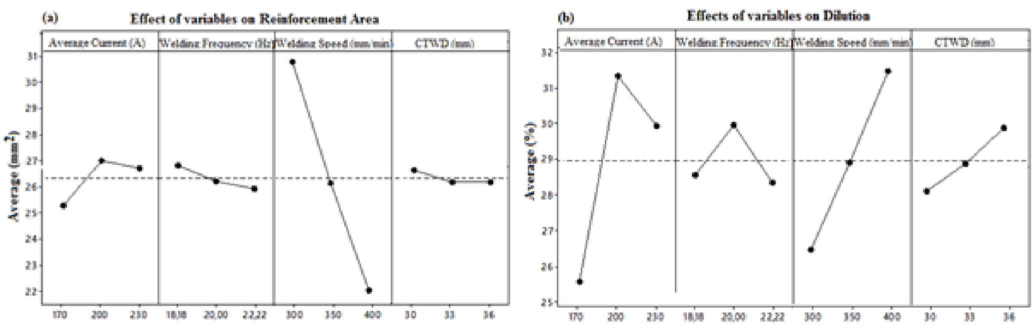

Figure 6 – Effect of welding variables/parameters on (a) Reinforcement and (b) Dilution.

In these graphs of Figure 7, their axes are constructed by contrasting the theoretical quantiles of a normal probability distribution with the observed quantiles of the residues obtained by the model. Which means that if the points approach a 45° straight line (perfect linear pattern), it makes it possible to infer that they approach a standard normal distribution. Therefore, it appears that the registered residues approach the diagonal, without any significant deviation, that is, the normal empirical distribution is verified, as the points approach the line. Still, to show confidence in the use of the equations to predict the results, analyzes were performed calculating the percentage of correctness of these mathematical models (JOSEPH et al., 2019). For this, a calculation of MAPE (Mean Absolute Percentage Error) was applied to the results measured and predicted by the model.

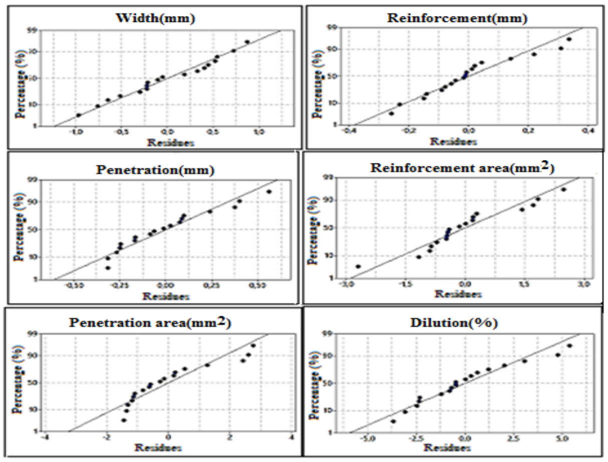

Figure 7 – Normal Probability graph of the residues of the response variables.

Figure 8 shows that this present study is above the cutoff point recommended in the scientific literature, since was obtained an average MAPE of around 6% in the generated models, that is, a good accuracy and extrapolation of the experimental results. Thus, was verified that from all these statistical analyzes of the welding tests carried out, by the statistical regression models (SREERAJ; KANNAN; SUBHASIS, 2013), by analyzes of variance, by the MAPE calculations and other equations employed were satisfactory according to the parameters established for their validation, and allow be used with some confidence to predict the results of a welding process (VELAZQUEZ; ESTRADA; GONZALEZ, 2014).

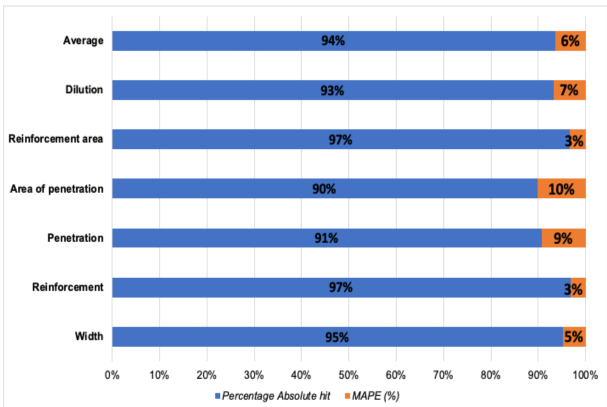

Figure 8 – Results plotted from the percentage absolute H_{it} and MAPE for each response variable.

4. Conclusions

On determining and optimizing the best conditions using regression models for coating welding through the process of welding with pulsed current tubular wire, it is possible to conclude that the variables and their interactions were decisive for the control of the welding process, allowing to find responses with significant effects to improve performance.

Among the adopted methodology of a project of analysis of the experiments with use of robust design, specifically Taguchi method, it provided important and effective data, as well as the analysis of applied statistics that provided the statistical study of the answers, even with a small number of experiments.

Based on the results of the regression models and visualized by the analysis of variance tables, it appears that among the stipulated parameters, the average current (A) affected almost all responses, with the exception of the reinforcement area. The welding speed (mm/min) just did not interfere with the penetration and the penetration area. The contact tip workpiece distance (mm) significantly influences the reinforcement and the pulsation frequency (Hz) did not affect any of the responses.

According to the tests carried out, the largest width (11.51 mm) was obtained at an average current of 230 A, welding speed of 300 mm/min, a pulse frequency of 22.22 Hz and a nozzle contact distance of 36 mm. The statistical regression model produced was effective in studying the responses obtained, demonstrating reliability in the results found, and adequate for predicting and extrapolating the findings according to MAPE vales. The effects graphs generated by the regression model were consistent with the results obtained in the test, after all the influence variable affected positively or negatively according to each response variable, in the same way as observed in the experiments, which may lead to an effective use of these findings, in bench experiments in the welding area.

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