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Optimization and Influence of GMAW Parameters for Weld Geometrical and Mechanical Properties Using the Taguchi Method and Variance Analysis

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Abstract

Gas metal arc welding is one of the arc fusion processes that is widely used in industry due to its high efficiency. The correct selection of the input parameters has direct influence on the weld quality and, with the control of those parameters, it is possible to reduce the amount of weld material, improve its properties and then increase the productivity of the process. This study intends to take a group of weld parameters and submit them to the optimization by the Taguchi Method and check the influence of those through a Variance Analysis (ANOVA). An L9 orthogonal array gathered three parameters (weld voltage, weld speed and weld torch angle) into three levels, then, with all combinations set and performed, the macrography and the transversal tensile strength test provided, respectively, the geometrical and the mechanical properties. The signal-to-noise ratios enable the optimization and the ANOVA provided the influence of the input parameters on the response parameters. The weld speed appeared as the most influent parameter for the weld geometry, contributing 63.54% to reinforcement, 66.36% to width and 66.94% to penetration, and the weld torch angle the most influent to the ultimate transversal tensile strength (41.39%). The optimum levels to the reinforcement are 22.4 [V], 400 [mm/min] and 30 [°], to the width 22.4 [V], 300 [mm/min], 0 [°], to the penetration 23.3 [V], 400 [mm/min], 0 [°] and, lastly, to the ultimate transversal tensile strength 24.1 [V], 200 [mm/min], 15 [°]. The Taguchi method showed to be suitable for this kind of problem and giving an efficient experiment design and good results.

Keywords: Taguchi method, Optimization, GMAW

1. Introduction

The Gas Metal Arc Welding (GMAW) is a weld procedure that follows the industry development since the 20th century. This kind of process was created to reach high production levels due to advantages such as high reliability, all position capability, low cost, high deposition rate, ease of use, absence of fluxes, cleanliness and ease of

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mechanization [1]. Manufacturing industry had steel as the base of most part of the processes. This material provides high productivity with low manufacturing costs, great weldability and, moreover, high-strength steels can provide a better weight to strength ratio [2].

Nowadays, the steel properties are well accepted for some processes, but in order to enhance the performance of the final manufactured products, materials like aluminum and its alloys brings improvements such as light weight and considerable strength.

About twenty years ago, the weld performed by a human is getting in disuse and the robot weld is constantly growing in modern manufacturing industry, where the application of the arc welding technology is wide [3], e.g. the automotive industry depends, most of all, on weld robots to keep its production line always operational.

Welding is not a cheap procedure, on its cost the time to prepare a joint, oil removal, preheating, positioning, welding, slag and spatter removal, inspection, transportation time, machine setup time, repair and rework must be included [4]. To reduce the expenses, optimization procedures like the Design of Experiments (DOE) [5], Taguchi method [6] and an ANOVA parameter influence analysis [7] are applied, thus it is possible to greatly reduce product development cycle time for both design and production, therefore reaching a good cost-quality ratio and increasing profits.

Based on the welding input parameters it is possible to design a series of experiments [8] that leads to the best configuration for the chosen response parameter. The Taguchi method works as a powerful optimization tool to design experimental orthogonal array [9] composed with process control parameters.

Achebo [10] proposed to optimize the GMAW parameters to improve the weld ultimate tensile strength (UTS) applying the Taguchi method and also discover the level of contribution of each input weld parameters (voltage, current, weld time and weld speed) on the UTS response parameter. Sarfcar and Das [11] optimized the weld metal hardness, bending load at a bend angle of 10°, geometry of weld bead reinforcement and depth of penetration of GMAW on stainless steel specimens through Taguchi's orthogonal experiment array design, signal-to-noise ratio and Grey relational analysis.

Rizvi, Tewari and Ali [12] applied the Taguchi technique into the process parameter of the MIG Welding on IS2062 steel. The L_{16} orthogonal array was set and the signal-to-noise functions were responsible for the optimization. Also, an ANOVA indicated the level of contribution of the input welding parameters. Yousefieh, Shamanian and Saatchi [13], as a DOE technique, used the Taguchi method to optimize the pulsed current gas tungsten arc welding (PCGTAW) parameters for the corrosion resistance of super duplex stainless steel (UNS S32760) welds.

Yao, Zhou, Lin, Xu and Yue [14], through the double-pulsed GMAW technique, employed the grey relational based process to explore the weld bead forming rule and check the weld parameters effects, so a new method for the weld bead forming was set. Waqas, Qin, Xiong, Wang and Zheng [15] made an optimization of the effective area of deposition based on the GMAW additive manufacturing process parameters and the mechanical and microstructural of a multi-layer weld were analyzed.

Zhang and Xue [16] studied the weld bead and its formation mechanism. By the gas metal arc welding method, each test carried a different level of current and the weld profile was measured. Yao, Zhou and Huang [17] also applied a optimization process based on the imput parameters of a welding robot. Those parameters were organized into an orthogonal experimental design with nine experiments of three levels. Then the mechanical weld properties were evaluated.

Kurt, Oduncuoglu, Yilmaz, Ergul and Asmatulu [18] using an arc stud welding method, studied the effects of the weld parameters through two methods, one based on a Taguchi approach and the other using an artificial neural network, after that, they made a comparison between those methods based on the experimental results. Schneider, Lisboa, Silva and Lermen [19] studied the weld bead geometry, the optimization was based on the Taguchi method of 27 experiments but, in this case, the welding process was TIG.

This work plans to find the contribution and the optimal levels from the weld voltage [V], weld speed [mm/min] and weld torch angle [°] on the weld reinforcement [mm], width [mm], depth penetration [mm] and the ultimate transversal tensile weld strength [MPa]. Thus, the experiment was designed by the Taguchi method where the group of parameters were organized into the L_9 orthogonal array. Those welding parameter combinations were performed and tested with macrography technique and tensile strength test. With the tests results, the signal-to-noise ratios calculation provided the optimum levels and an analysis of variance (ANOVA) showed the most influent input parameter on the output (response) parameters.

2. Material and Methods

The Gas Metal Arc Welding (GMAW) process was used, in this study, to make weld deposits on plates joints. This welding process has been used for over half a century to join several types of materials. Steel wire electrodes with 0.8 [mm] diameter were used to make welding deposits over a plate top joint with an experimental apparatus controlled by numerical commands used with a GMAW machine that can adjust to

the desirable weld input parameters. The Taguchi method was chosen to conduct the experiments, the method works with the selection of an orthogonal matrix that organizes the experiment parameters in optimal combinations to characterize the entire study in fewer interactions.

The selected input parameters for this study were the voltage [V], the welding speed [mm/min] and the angle of the welding torch [°]. For each parameter three levels were assigned (see Table 1) and that information were organized into a L_9 orthogonal array (shown in Table 2). There is a L8 array in this method, but this matrix only works with two levels and, in this study, three levels were used, and then a L_9 array is recommended.

TABLE 1: Study parameters and their levels

Levels	Parameters		
	Voltage [V]	Welding Speed [mm/min]	Torch Angle [°]
Level 1	22.4	200	0
Level 2	23.3	300	15
Level 3	24.1	400	30

TABLE 2: Taguchi L9 array with the study parameters

Experiment Number	Voltage [V]	Welding Speed [mm/min]	Torch Angle [°]
1	22.4	200	0
2	22.4	300	15
3	22.4	400	30
4	23.3	200	15
5	23.3	300	30
6	23.3	400	0
7	24.1	200	30
8	24.1	300	0
9	24.1	400	15

With the experiment combinations set, the welding deposits could be made on steel plates DIN C20 of 3 [mm] thickness top joints, the steel chemical properties are listed in Table 3.

TABLE 3: Chemical composition of DIN C20

C	Mn	P max.	S max.
0.18 - 0.23	0.30 - 0.60	0.04	0.05

Those plates had the dimensions based on the test specimen, to design the specimen, the European Standards ISO 4136:2012 [20] and ISO 6892-1:2009 [21] were used to determinate the dimensions, the proper preparation of the test specimen and the tensile test conditions. The specimen final design is shown in Figure 1.
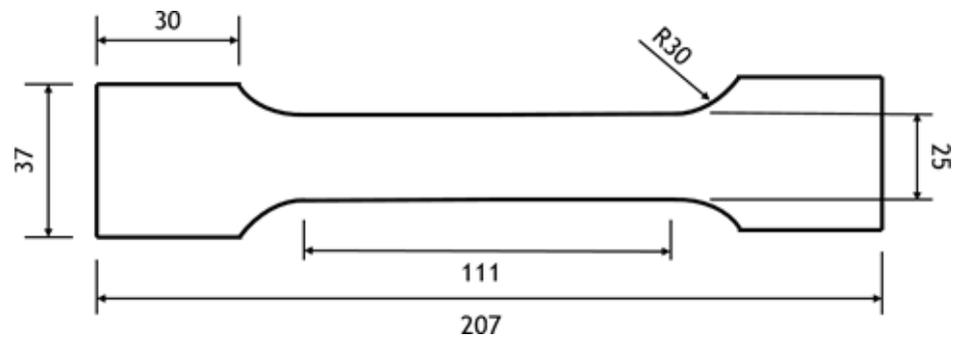

Figure 1: Tensile test specimen [mm]

The machining conditions, such as milling tool of 12 [mm] diameter, milling trajectory and the fixing screws size, were considered to determinate the final dimension of the plates. From each plate, six test specimens were extracted, so the plates had 420 [mm] x 285 [mm] x 3 [mm]. The Taguchi method requires nine tests, but for statistical purpose, there will be at least two tests for each combination. In that case, three plates will be necessary to totalize those 18 specimens to be tested. The plates were cut in half on its width and then three welds were made to join the two parts, each weld has a different combination of parameters set by the method and from each weld two specimens were extracted. The welded plates can be seen in Figure 2.

Figure 2: Plates welded with all the Taguchi experiment parameters

The test specimens were extracted with machining and after that it was necessary to grind them to remove the excess metal. The specimens are shown in Figure 3.

To optimize the use of the plates, the spaces between the similar test specimens were also extracted with the purpose to obtain weld samples (Figure 4). Those samples enable the study of the geometry of the weld. The geometry can be measured and checked with the macrography technique.

Figure 3: Tensile test specimens

Figure 4: Weld samples for macrography inspection

With the objective to optimize the processes, the Taguchi method requires the calculation of a signal to noise function. This function allows to check which process had more disturbances and then the one with the highest signal to noise value is the optimal parameter. There are four cases based on what is the focus of the optimization,

the "larger is better", "nominal is best", "nominal is best (default)" and "smaller is better". In this work, parameters like weld penetration, width, reinforcement and the ultimate tensile strength in transversal tensile test were optimized. For weld penetration and width, the "nominal is best" function was used aiming that both had the same dimension of the plate thickness, for the weld reinforcement the "smaller is better" function and for the ultimate tensile strength the "larger is better" function were used. Those expressions are listed on Table 4.

TABLE 4: Signal to noise Taguchi expressions

Signal to Noise Expressions		
Smaller is best	Nominal is best	Larger is best
$S/N_S = -10 * \log\left(\dfrac{1}{n}\sum_{i=1}^{n} y_i^2\right)$	$S/N_t = -10 * \log\left(s_y^2\right)$	$S/N_L = -10 * \log\left(\dfrac{1}{n}\sum_{i=1}^{n} \dfrac{1}{y_i^2}\right)$

Where the parameter "y" corresponds to the data obtained of the test, "Sy^2" to the variance of "y" data and "n" means the number of measurements made in the study.

Another goal of the project was finding the influence of the input welding parameters on the output or response parameters. A statistical tool commonly used to verify the level of contribution is the Analysis of Variance (ANOVA), in this case the ANOVA method provides the influence of the voltage, welding speed and torch angle on the weld geometrical parameters and on the ultimate tensile strength.

2.1. Tensile Strenght Test

The entire transverse tensile strength test in welded joints was based on the European Standard ISO 4136:2012 and ISO 6892-1:2009. Those standards are used to design the test specimen, set the test parameters and enables to the properties of the material that was tested. A machine that applies a tensile load performs this kind of test; the load varies with time until the specimen rupture. To set the correct parameter, the ISO 6892-1:2009 recommends a variable load based on the elastic modulus of the material. The elastic modulus of the steel DIN C20 is E = 210 GPa, so the standard says that the stress rate must have a value between 6 and 60 MPa/s. However, the machine system is based on the displacement of the machine claws and then this stress rate was converted into a displacement rate of 0.0026 [mm/s]. Thus, the displacement was increased until the rupture. In Figure 5, it is possible to see the tensile strength test setup.

Figure 5: Tensile strength test setup

2.2. Macrography Inspection

In order to check and measure the weld geometry, a macrography was made. This technique involves several steps that enable the visualization of the weld profile. For this part, the samples pieces shown in Figure 4 were cut in such a way that it was possible to obtain another two samples from each piece. Those samples had to be embedded into a thermosetting Bakelite resin that provides more stability during the metallography preparation. This preparation consists of sanding the embedded steel piece into water sandpapers from lower to higher granulometry. At the end, the piece is polished and a chemical attack with Nital (HNO_3) 7% reveals the weld on the steel piece surface. One of the embedded samples can be seen in Figure 6(a).

Using Newtec IRIS software in conjunction with macroscope equipment, images of the weld bead profiles were acquired. These images (Figure 6(b)) were treated with an image software called "ImageJ" that allows making the measurements of the weld bead geometry using the conversion of pixels length into millimeters.
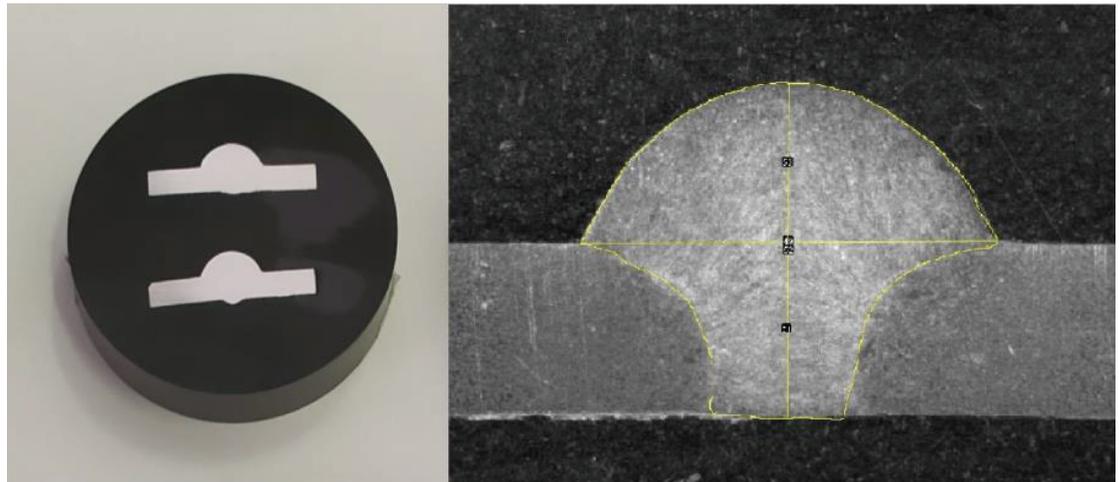
Figure 6: Macrography (a) embedded samples and (b) treated image of weld bead.

3. Results and Discussion

After all the procedures made, the results of the transversal tensile test and the macrography were used to make the optimization and to check the level of contribution of the input welding parameters through the ANOVA test.

3.1. Transverse Tensile Strength Test

During the tensile strength test, the data of the experiment was stored on the machine computer, then after the rupture of the specimen, the same computer reunites all the data into a Force [kN] x Displacement [mm] graph. Each parameter combination set by L_9 array provided two transversal tensile strength test specimens, therefore the nine tests could be done twice. That information was exported through a hard disk to another computer and with the MS Excel and MathWorks MATLAB software, all the 18 Stress [MPa] x Displacement [mm] graphs were plotted. In Figure 7, the result of the first group of tests are associated with their corresponding test of the second group.

With the ultimate tensile strength (UTS) from each test, an average value between the two groups was calculated and organized in Table 5.

3.2. Macrography Measurements

The weld piece samples obtained for the macrography procedure enabled to produce another two samples from each piece. Like the tensile test, two test samples derive
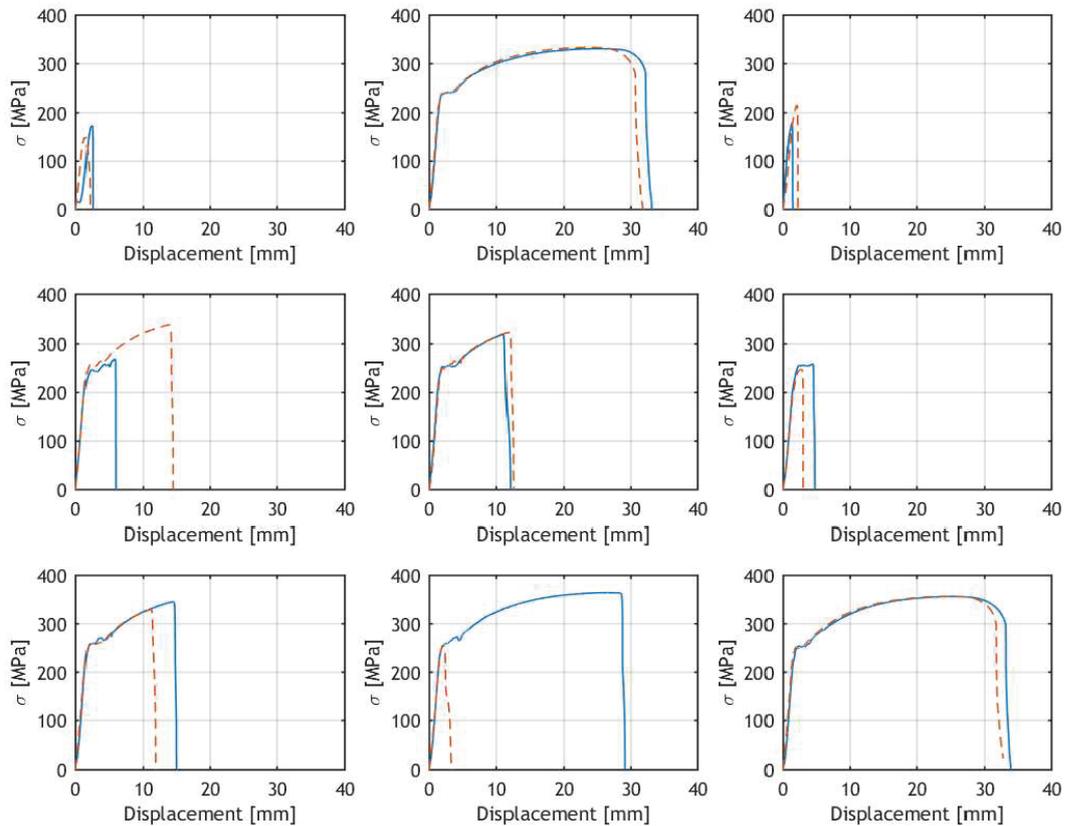
Figure 7: Ultimate tensile strength from both test groups

TABLE 5: The ultimate tensile strength results

Experiment Number	Ultimate Tensile Strength [MPa]
1	309.79
2	321.51
3	161.73
4	356.73
5	197.53
6	252.82
7	331.97
8	337.60
9	304.21

from each parameter combination and then it is possible to calculate an average value for the weld dimensions. The average from the measurements are shown in Table 6.

TABLE 6: Average values from the weld geometry parameters

Experiment Number	Reinforcement [mm]	Width [mm]	Penetration [mm]
1	2.389	6.240	1.878
2	2.759	5.729	1.690
3	1.711	4.284	1.430
4	2.904	7.450	3.012
5	2.387	5.261	1.254
6	2.024	5.164	1.441
7	2.584	7.072	3.013
8	2.216	6.174	1.946
9	2.170	5.930	1.651

3.3. Analisys of Variance (ANOVA)

The ANOVA is responsible to give the level of contribution of the welding voltage [V], welding speed [mm/min] and welding torch angle [°] on the geometrical parameters (reinforcement, width and penetration) and ultimate tensile strength. This method was performed with the Minitab 17 software. For each response parameter, a different ANOVA was made and then the results were gathered in Table 7.

TABLE 7: Level of contribution of the input welding parameters

Parameter	Reinforcement [mm]	Width [mm]	Penetration [mm]	Ultimate Tensile Strength [MPa]
Voltage	3.45 %	18.94 %	12.69 %	18.56 %
Speed	63.54 %	66.36 %	66.94 %	35.93 %
Angle	28.17 %	13.94 %	5.84 %	41.39 %

3.4. Signal to Noise Ratio

In order to make the optimization process, the signal to noise ratio must be computed for each response parameter, based on every experimental input welding parameter combination. For the weld reinforcement the focus was to minimize it, so the "smaller is best" formula was applied. For the penetration and width the objective was control it in such a way that both reached the same dimension of the plate thickness of 3 [mm], so for these two parameters the "nominal is best" formula was necessary. In addition, for the ultimate transversal tensile strength the "larger is better" expression provided the best ratio to obtain the highest value of weld strength. The signal to noise ratio of each response parameter is associated with an input parameter combination, and then

an average value is calculated for each level of those input parameters in order to find the best for the optimization. Figure 8 shows the average signal to noise values from each weld parameter for each study response parameters.
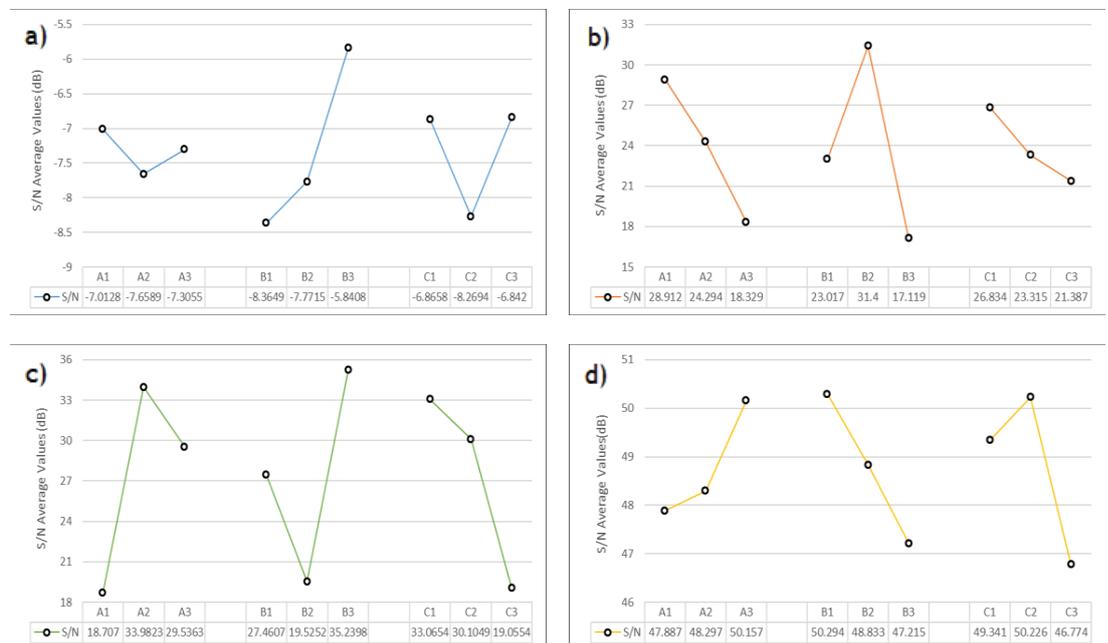
Figure 8: Signal to noise average values for (a) reinforcement, (b) width, (c) penetration and (d) ultimate tensile strength

Based on the results of the graphical signal to noise average values, the welding parameters combination to reach the best performance for the reinforcement is A1B3C3, for width is A1B2C1, for penetration is A2B2C1 and for the ultimate transversal tensile strength is A3B1C2. In terms of weld parameters, the lowest reinforcement height is obtained with a weld of 22.4 [V], 400 [mm/min] and 30 [°], the width closer to 3 [mm] with 22.4 [V], 300 [mm/min], 0 [°], the penetration with dimension closer to the plate thickness with 23.3 [V], 400 [mm/min], 0 [°] and, lastly, the ultimate transversal tensile strength with 24.1 [V], 200 [mm/min], 15 [°].

4. Conclusion

In this research, the Taguchi method is presented to perform a welding GMAW experiment and optimize the process based on the weld parameters. An array of three levels was used to study the relationships between the weld input parameters (voltage [V], weld speed [mm/min] and weld torch angle [°]) and the response parameters such as weld ultimate transversal tensile strength [MPa] and the geometrical parameters

(reinforcement [mm], width [mm] and penetration [mm]). Some conclusions can be made based on the experimental results from this work:

1. The robust orthogonal Taguchi method is well suitable as a first approximation to characterize and analyze the proposed problem.

2. For the optimization of the GMAW parameters, the Taguchi method provides an efficient and simple experiment design.

3. The welding speed is the most influent parameter related with the geometrical parameters of the weld, but for the ultimate transversal tensile strength, the angle of the weld torch became the most significant.

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