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ANALYSIS OF THE PENETRATION IN ROOT PASS WITHOUT COPPER-JOINT NOR ROOT OPENING, IN FLAT, VERTICAL AND OVERHEAD POSITIONS

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Abstract. *This paper presents an analysis of the penetration effect using the method of groove face inclined in root pass welding, without using copper-joint or root opening and was applied to the three critical welding positions (flat, vertical and overhead), considering the same welding parameters for these positions. The analysis was performed using the MIG / MAG process by derivative short circuit, CMT (Cold Metal Transfer), with AWS ER 70S-6 wires (1.2 mm) and STARGOLD shielding gas. The Central Composite Design was used as a tool for better organization of tests and the analysis of the results was done and optimized using the Desirability theory for multiple answers, carried out in flat sheets of 1020 steel with a narrow-gap in U-shape. The results showed that using a wire of 1.2 mm a full penetration is obtained, besides to get a welding cord with good visual appearance and without internal defects.*

Keywords Full penetration, Root pass, Narrow-gap, CMT, Central Composite Design.

1. INTRODUCTION

The welding process MIG/MAG is one of the most used process in the industry, being in constant technological investment to improve its quality and reduce its cost. The welding processes that make use of transfer short circuit controlled are processes actually derivate from MIG / MAG process using transfer by conventional shorting, in which it use the external control methods to improve the metal transfer (Costa 2011). CMT utilizes an innovative wire feed system integrated to high speed digital control in order to control not only the arc length during welding but also the method of material transfer and amount of thermal input transferred to the work piece (Pickin and Young 2006). The union of two sheets by the welding process begins with the deposition of the root pass, being realized by different joint configurations methodologies. On top of welding, as well as in the external and rootless opening welding the root face height is decisive for full penetration (Aures 2013). By using mechanized narrow gap welding the amount of filler metal in welding process is reduced, which leads to reduction of tensile residual in base metal (Teng and Chang 1997).

In this Paper or objective is to analyze, understand and solve possible problems in performing the root pass welding in narrow gap joints of flat plates and in the three critical welding positions: flat, vertical and overhead, with welding process derivative by CMT. Using central composite design for to organize experiments, also making an optimization of multiple response applying the method Desirability to discover a set of parameters that can perform the weld in three critical position.

(Lamond and Lee 2007) Explains that the interest for a perfect welding process should be one that allows root pass welding without copper-joins or internal systems and produces a root bead with a good weld metal with sufficient accumulation (deposition) to ensure a good thickness cord. This weld should also not present bites, lack of fusion or porosities and should submit appropriate mechanical properties.

2. PROCESS GMAW DERIVATED

GMAW-Gas Metal Arc Welding, also known as MIG/MAG (MIG - Metal Inert Gas and MAG - Metal Active Gas), it is an electric arc welding that serves as a shield from contaminants by the flow of an inert, active or mixed gas. This process uses a continuously fed consumable wire metal electrode, which is melted by the arc from the tip to the weld pool. The welding processes that make use of the transfer by short circuit are actually controlled processes derivatives of conventional GMAW process, in which the external control methods allow an improvement in metal transfer. The development of these processes aims to take advantage of the metal transfer by short circuit (low heat input welding in all positions, etc.) substantially reducing the problems encountered in conventional processes, such as high generation of spatter and smoke, as well irregularities in the metal transfer (Kvasov, 2000).

The cold metal transfer process as we called cold metal transfer (CMT) is a modified MIG welding process which invented by Fronius company. The principal innovation is that the motions of the wire have been integrated into the welding process and into the overall control of the process. Every time the short circuit occurs, the digital process control both interrupts the power supply and controls the retraction of the wire. The wire retraction motion assists droplet detachment during the short circuit, as shown in Fig. 1, thus the metal can transfer into the welding poll without the aid of the electromagnetic force. Then the heat input can be decreased greatly (Zhang, *et al*., 2008).

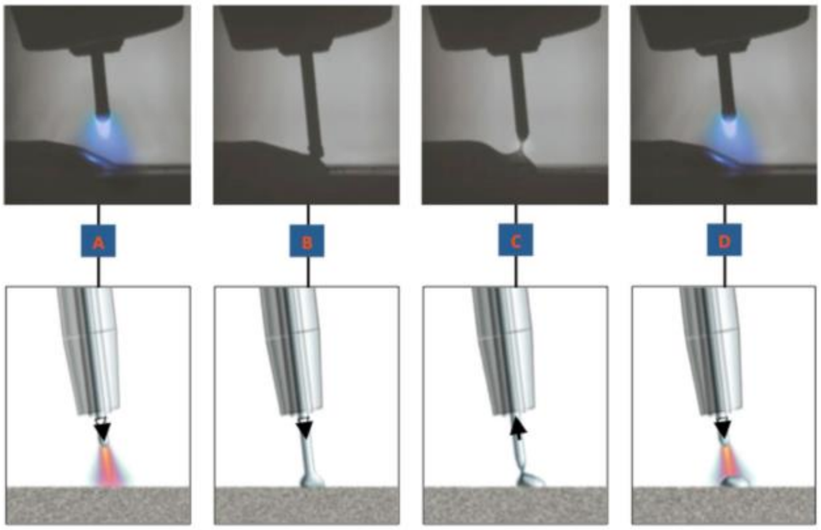

Figure 1. Fronius CMT process operation. Wire advancing in A and B, retracting during the short circuit in C and advancing again when the arc reforms in D. Source: Reprinted with the kind permission of Fronius International.

In Fig. 1 are represented the different phases which characterize the process:

- During the period of the electric arc, the electrode is moved towards the molten bath;
- When the electrode initiates contact with the molten bath the arc is extinguished and the welding current is reduced;
- The electrode backward movement assist the highlight drop during the short circuit, while the short-circuit current is kept small;
- Finally, the wire movement reverses and the process begins again.

2.1. Narrow Gap Welding (NGW)

Although narrow gap welding (NGW) has generated great interest in the welding industry and has been the subject of much investigation in the last twenty years, there is still some controversy around a proper definition for the technique. (Nazarchuk and Steenburgen 1984) agree that narrow gap welding is performed in thick joints using an essentially square butt joint preparation with small gaps. In an attempt to systematize the concept of narrow gap welding, (Malin, 1983) distinguished the following features of NGW:

- NGW is not a welding process, it is a special bead deposition technique.
- NGW features a fixed bead deposition layout that is characterized by a constant number of beads per layer (1-3) deposited one on top of the other.
- NGW requires low or medium heat input.

The development of NGW was intended to reduce weld metal volume in thick plate welding and hence reducing welding cost, time and distortion level. The technique was first described in the USSR (Dudko et al. 1957) and in the United States (Meister and Martin 1966), and it was developed and used mainly in Japan, where several different approaches have been proposed in order to overcome its limitations.

Some of the advantages attributed to NGW processes, when compared with other welding processes for thick joints, are listed below (Modenesi 1990):

- Reduction in welding time,
- Lower consumable costs,
- Reduction in post-weld heat treatment,
- Improved toughness, and
- Reduction in angular distortion.

There are different configurations of chamfers, from traditional together in "V" to the most drawn, all appropriate to the welding conditions and the material to be welded. Decreasing the chamfer angle of a joint in a "V", with a filler will lead to fewer passes, thus increasing productivity. In Fig. 2, are shown some of the various existing settings.

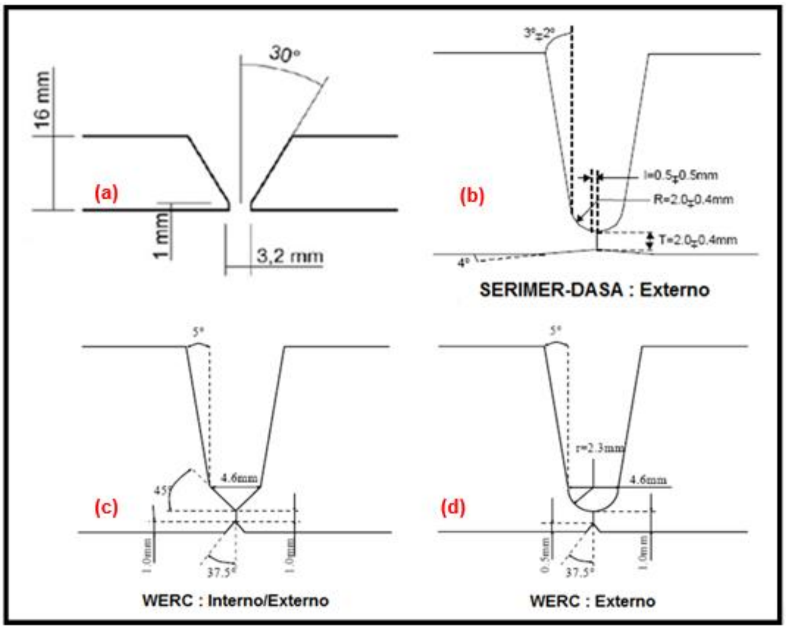

Figure 2 – Some joint configurations: (a) joining in a "V" base, (b), (c) and (d) narrow groove joints (Hudson, 2004)

In applying the welding process MIG/MAG in narrow gap, the main difficulty is to get the wire electrode and the shielding gas arrive at the deepest regions of the chamfer, so as to ensure correct feeding of the material to be deposited, without problems gas protection. Furthermore, it is necessary to achieve an adequate penetration of the weld pool, both the fund channel of welding and in the side margins of the chamfer(Vieira 2012).

2.2. Weld Bead Geometry

Today quality is a vital factor in manufacturing world. The quality of a weld depends on mechanical properties of the weld metal that in turn depends on metallurgical characteristics and chemical composition of the weld (Kannan and Murugan 2006). The mechanical and metallurgical feature of weld depends on bead geometry which is directly related to welding process parameters. The process parameters have a direct influence on bead geometry (Gunaraj and Murugan 2006). Fig 3 shows the clad bead geometry. This is an indication of bead geometry. It mainly depends on wire feed rate, welding speed, arc voltage etc. Therefore it is necessary to study the relationship between in process parameters and bead parameters to study clad bead geometry.

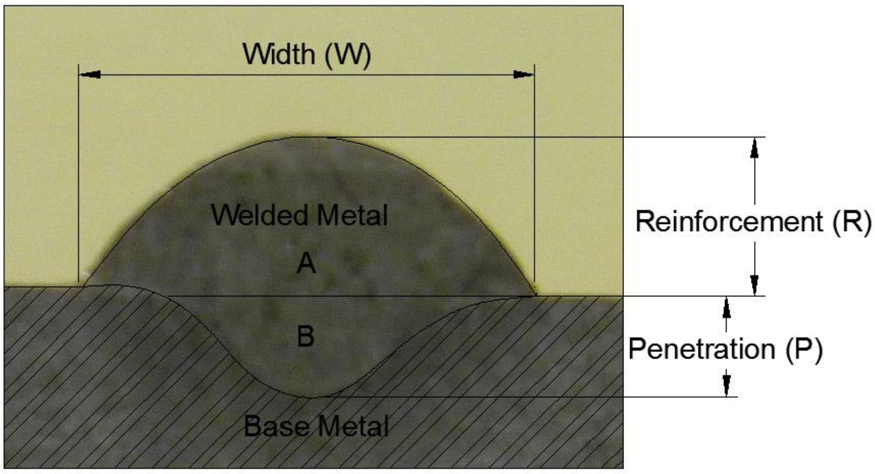

Figure 3. Clad bead geometry. Weld CMT in flat plate

2.2. Modeling

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes (Myers et al 2009) .The most widespread application of the RSM is in situation where input variables potentially influence some quality characteristics of a process. Also is used in this work to achieve second-order models of weld bead penetration. To perform the experiments for three independent input variables this methodology uses a central composite design (CCD) as shown in Fig. 4.

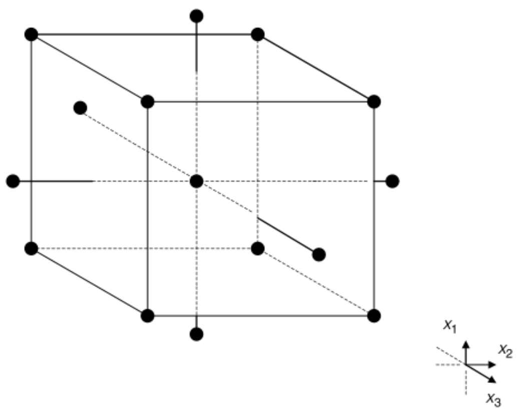

Figure 4. Central composite design in three factors.

Based on experimental design, multiple linear regression technique is used to get second-order models, which can be written as Eq. (1).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} {X_1}^2 + \beta_{22} {X_2}^2 + \beta_{33} {X_3}^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (1)$$

Where Y = predicted response, β_0=constant, β_1,β_2, and β_3= lienear coeficientes, β_{12}, β_{13}, and β_{23}= cross product coefficients, β_{11}, β_{22}, and β_{23} = coefficients quadratics .

Desirability function for multi-response optimization is a useful tool for optimizing problems with multiple simultaneous variables. This technique was popularized by (Derringer and Suich 1980). It is one of the most widely used methods in industry which is based on the idea that the "quality" of a product or process that has multiple quality characteristics, with one of them outside of some "desired" limits, is completely unacceptable. Their procedure makes use of desirability functions. The common approach is to first transform each response $d_i(y_i)$ that varies over the range $0 \leq d_i(y_i) \leq 1$ where it takes a range of between 0 and 1, and increases as the corresponding response value becomes more desirable (Fuller and Scherer 1999).

Depending on whether a particular response y_i is to be maximized, minimized, or assigned to a target value, different desirability functions $d_i(y_i)$ can used. The individual desirability $d_i(y_i)$ will be as follows, it occurs when the response of interest has two constraints: a maximum and minimum another Eq. (2):

$$d_i = \begin{cases} 0 & \hat{Y}_i < L_i \ ou \ \hat{Y}_i > H_i \\ \left[\frac{H_i - \hat{Y}_i}{H_i - T_i}\right]^R & \hat{Y}_i < \hat{Y}_i > H_i \\ \left[\frac{\hat{Y}_{i_i} - L_i}{H_i - L_i}\right]^R & \hat{Y}_i < \hat{Y}_i > H_i \end{cases} \quad (2)$$

Where L_i and T_i, respectively are, the biggest and the lowest acceptable value for i-th response.

In this work will make an optimization with multiple answers, where every answer is the penetration in each critical position, with this we are trying to find a set of parameters to produce a cordon geometry equally in all three positions.

3. METHODOLOGY

Fig. 5. Illustrated the sequence of the methodology to obtain optimal parameters to implement the root pass welding in joints type of narrow gap in flat plates and in the three critical welding positions.

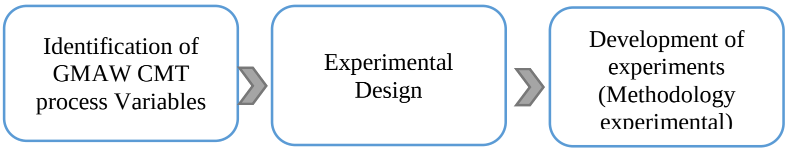

Figure 5. Methodological diagram of the project.

3.1 Identification of GMAW CMT process variables

Welding parameters are the variables that can be changed or modified in the process and can affect the characteristics of the electric arc and modify the shape of the weld deposited. Since measured responses depend on many parameters, in this work are taken in consideration the variables which direct action and interaction have a significant influence on the external geometry of the weld bead (with shielding gas and electrode constant). Then, length arc ,wire feed rate and welding speed were established as input variables. The distance of the axial points to the center (α) was chosen for a rotatable design where $\alpha: 1.682$, the range and level of the investigated factors are shown in the Tab. 1.

Table 1. Ranges and levels of the welding selected the CCD

Welding parameters	Symbol	Ranges and levels				
		-1,682	**-1**	**0**	**1**	**1,682**
Wire feed rate (m/min)	Va	3,82	4,1	4,5	4,9	5,2
Welding speed (mm/s)	Vs	4,25	4,5	5	5,5	5,75
Length Arc	l_a	-30	-15	0	15	30

3.2 Experimental Desing

The materials used in the experimental procedure are:

- Solid wire: AWS A5.18 ER70S-type 6 with a diameter of 1.2 mm.
- Base material: steel AISI 1020.
- Distance from contact tube to the workpiece 12 mm
- Shielding gas: STARGOLD 96% Ar and 4% CO2
- Shielding gas flow rate: 15 liters / min
- Fronius TransPuls Synergic 5000

The Fronius TransPuls Synergic 5000 welding power source is used for depositing beads using GMAW CMT Commercial grade STARGOLD 94% Ar and 6% CO2 is used as shielding gas. The gas flow rate is 15 L/min for steady arc. AWS A5.18 ER70S-type 6 with a diameter of 1.2 mm, with a diameter of 1.2 mm is used to deposit bead on- plate welds. Base material, AISI 1020 steel with flat-plate shaped, 6 mm thickness, 125 mm length, 38,1 mm width. Constant contact tip to work distance (16mm) is maintained throughout the welding operation. The welding torch is at 0°, 90°, 270°, to the work surface. The welding was made with the robot PS 130/6 – 5-P from the company ABB Robotic and the programation for one cord with Interface ROB 5000, controller RCU 5000 and programmation made with the software Sport S3

This work began with the decision to use "narrow groove" as joint configuration to be used for the metallic plates, as shown in Fig.6 . This type of bevel requires less filler metal, which is reflected in lower power requirement, less time spent in completing the joint, reducing of the distortions and the welding time, among others. To be able to machine the 5° slope narrow gap on the plate, was necessary to turn the vise that fix the plate at the time of machining.

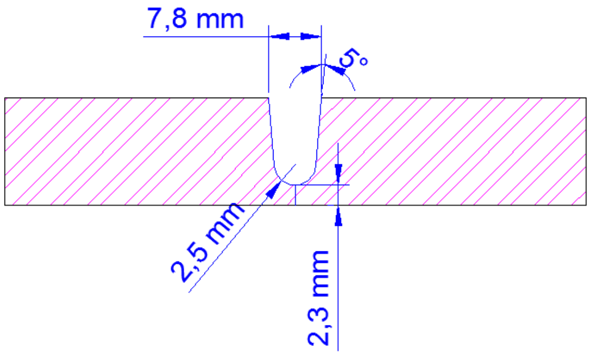

Figure 6. Joint dimensions used in the parameterization.

We propose an approach that allows the construction of a joint configuration, specifically, the thickness of the nose, with which it can perform root pass without the use of gasket-cover, a welding top. It was then understood that the key to the construction of this joint is the thickness of the root face. Thus, considering a specific welding condition (welding parameters), the root face must be thick enough to allow a complete melting, can remain adhered to the liquid weld pool on the base metal without sticking due to leaks or pressure and enables an acceptable strengthening the root after solidification of the bead, and no internal defects present(Aures 2013).

Thus, it was thought that welding should be performed on a joint which has variable thickness nose, with an inclined format to a maximum start value (in this case 4 mm) and end at a minimum value of 0 mm. Consequently this methodology has been called "chamfer method Inclined nose " and is shown in Fig. 7.

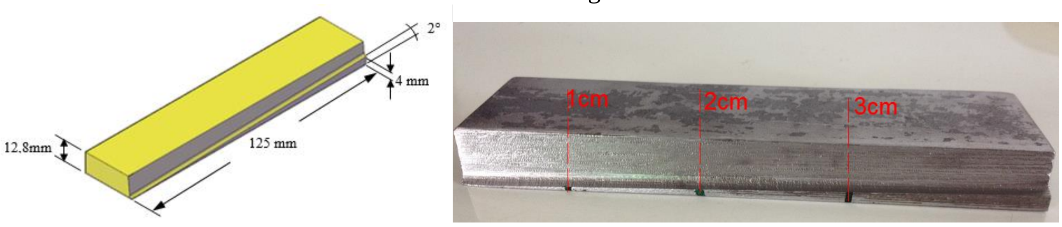

Figure 7. Joint dimensions used in the methodology penetration

These machined plates ready for testing, as shown in Fig. 7, are fixed and positioned on the "support" in such way that the inclined nose coincides with the top face in a perpendicular position to the movement of the torch (Fig.8). This in order to avoid this with the intention of avoid inducing greater slipping or fall of the liquid metal pool, caused by a higher tilt, which causes defects and impedes penetration.

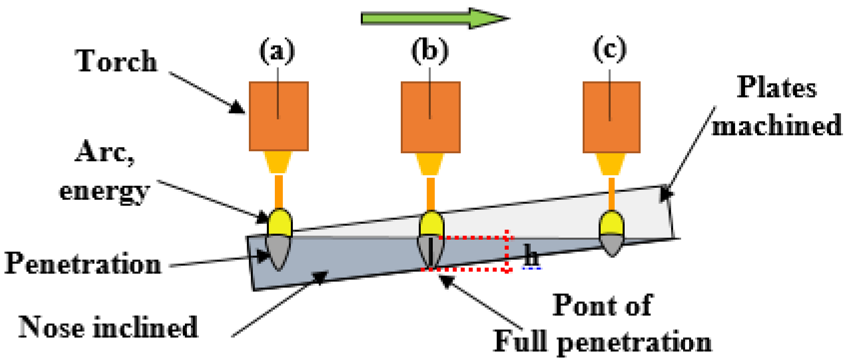

Figure 8. Joint chamfer method weld nose inclined

With the torch positioned at the point (a), assuming a flat weld (Fig. 8), the arc is struck with certain welding parameters. The parameters voltage and current (I and U) provide an energy that originates a certain penetration of the point where the arc operates, in this way the welding process is performed by moving the torch from position (a) to position (c). During this welding process, at some point of the route the total fusion of the nose is achieved, reaching a full penetration.

By the calculation of the distance from B to C and knowing the angle of the inclined nose we can find the completely penetration "p´" using a simple triangles relationship.

The implementation of this procedure in three critical welding positions resulted in three different points of full penetration, which is reflected in three different thickness nose, this due to the effect that the welding position causes in the weld pool and the forces that help to the drop fall, specifically the force of gravity, the Fig 9. schematizes these positions to work.

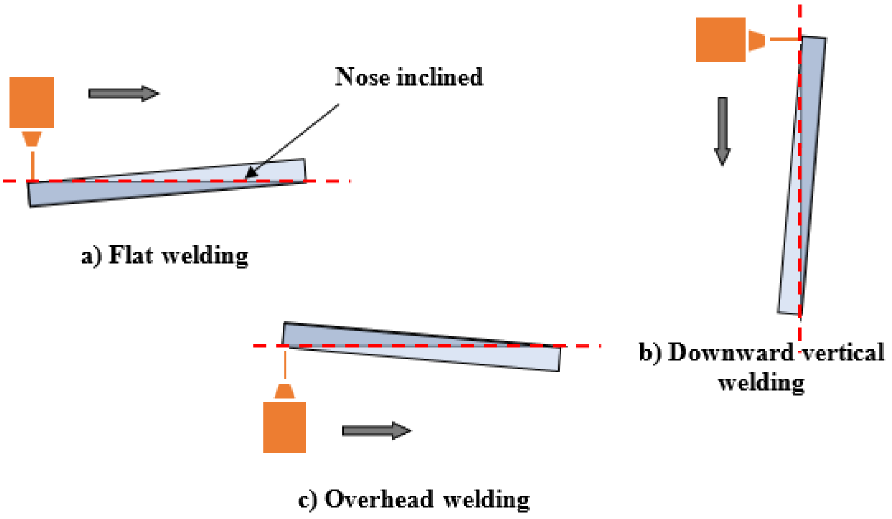

Figure 9. Positioning the test plates with the surface of the "inclined nose" perpendicular to the displacement of the torch

4. RESULT

The geometric parameters for CMT with narrow gap welding method inclined nose, which correspond to the values of the input variables indicated in Tab. 1, are presented in Tab. 2, where p' is encountered at each penetration welding position. Based on the results obtained (Tab. 2) by regression analysis, using the least squares method (Montgomery 2001), the coefficients which are listed in Tab. 3 were determined using the Eq. 1. For obtain the Table was used the software Minitab.

Table 2. Results of the experiments

Exp.	parameters			Variable input			Penetrations p´ (mm)		
	$x1$	$x2$	$x3$	Va (m/min)	Vs (mm/s)	l_a	Flat welding	Vertical welding	Overhead welding
1	-1	-1	-1	4.1	4.5	-15	2.5	2.3	2.2
2	1	-1	-1	4.9	4.5	-15	2.6	2.1	2.8
3	-1	1	-1	4.1	5.5	-15	2.2	2.4	1.8
4	1	1	-1	4.9	5.5	-15	2.6	2.3	2.4
5	-1	-1	1	4.1	4.5	15	2.3	1.9	2.7
6	1	-1	1	4.9	4.5	15	2.6	2.0	2.1
7	-1	1	1	4.1	5.5	15	2.8	1.9	2.2
8	1	1	1	4.9	5.5	15	2.7	2.5	2.1
9	-1.68	0	0	3.82	4.5	0	2.6	2.1	2.2
10	1.68	0	0	5.2	4.5	0	2.7	2.5	2.5
11	0	-1.68	0	4.5	4.25	0	2.4	2.0	2.5
12	0	1.68	0	4.5	5.75	0	2.6	2.2	2.4
13	0	0	-1.68	4.5	5	-30	2.4	2.2	2.1
14	0	0	1.68	4.5	5	30	2.6	2.3	2.3
15	0	0	0	4.5	5	0	2.7	2.3	2.5

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Table 3. Analysis of variance for response variables with full quadratic polynomial

Source	Penetrations					
	Flat welding ($p'f$)		Vertical welding ($p'v$)		Overhead welding ($p'o$)	
	Sum of Squares *(aj)*	*p*	Sum of Squares *(aj)*	*p*	Sum of Squares *(aj)*	*p*
Va	0.067772	0,046	0.10736	0.010	0.07803	0.057
Vs	0.04147	0.102	0.12221	0.007	0.16704	0.010
l_a	0.02890	0.162	*	*	*	*
Va^2	*	*	*	*	*	*
Vs^2	0.03828	0.114	0.04743	0.058	*	*
la^2	0.03353	0.136	*		0.06099	0.086
$Va * Vs$	*	*	0.12773	0.040	*	*
$Va * la$	*	*	0.432450	0.006	0.43610	0.000
$Vs * la$	0.13520	0.010	*	*	*	*

Note: * removed coefficient

For the model of response of penetration ($p'f$), we can see in the Table 3 that the terms of first order are significant in flat welding. Beyond the terms of first order the iteration $Vs* la$ was the one that obtained a better fit with an (R^2) of 60% and with the lowest variance with a value of 0.116. Analogically the same criteria was use for response ($p'v$) with (R^2) equal to 74% and ($p'o$) with (R^2) adjust to 75%. Therefore, vertical and overhead welding showed a better adjustment.

Equation (3), Eq. (4) and Eq. (5) penetration models presented in critical positions with their respective solder and with an adjusted coefficient R^2.

$$\hat{y}\ p'f = -6.39 + 0.1742\,Va + 3.19\,\text{Vs} - 0.0838\,la - 0.308\,Vs^2 - 0.000186\,la^2 + 0.01733\,Vs * la$$
$$R^2 = 76{,}94 \quad (3)$$

$$\hat{y}\ p'v = 2.2739 + 0.1513\,Va + 0.1484\,Vs - 0.1765\,Vs^2 + 0.2199\,Va * Vs + 0.436\,Va * la$$
$$R^2 = 83{,}47 \quad (4)$$

$$\hat{y}\ p'o = 2.3733 + 0.1290\,Va - 0.1734\,Vs - 0.206 - 0.805\,Va * la$$
$$R^2 = 81{,}57 \quad (5)$$

Equation (3) , Eq. (4) and Eq. (5) present the models in a common regression analysis, the covariates (coefficients that multiply the independent variables, their interactions and quadratic terms) may be overestimated if the input variables (or parameters) are correlated. This phenomenon is known as multicollinearity. Through the experiments and response surface design methodologies, designed as CCD arrays (Central Composite Design) used in this work (Table 2) does not suffer from the Multicollinearity, since they are constructed to satisfy an orthogonally restriction, (Montgomery and Runger 2003), in the Eq. 4 having interaction ($V_a * l_a$)was observed as best fit possible (R^2=83,47) and with the lowest variance.

Optimal factor setting can be obtained for each response variable, but when we have more than one response variable, we need to obtain a setting factor that fit to optimize all response variables according to a criteria. Because certain settings factor may yield a high desirability for one response, but desirability for other responses. The criteria to find the best overall setting factor are a desirability function. The overall desirability, D, is a measure of how well a researcher has satisfied the combined goals for all responses. The ‘optimal’ factor settings are a setting that maximizes overall desirability (Fitrianto and Midi 2011).

In this study exist three response variables. The use of the Desirability methodology is in order to obtain a set of welding parameters (V_a, V_s e l_a)) to produce a welding cord with full penetration, with good stability and without deviation on the side walls. Taking as criteria the penetration data obtained in the table 2 and estimating the value of 2.3 mm of penetration as the ideal value for the three welding positions. Using the statistical tool Minitab the objective response values found are $P'p = 2{,}305\ mm$, $P'V = 2{,}287\ mm$ and $P'O = 2{,}301\ mm$, with individual desirability equal to: $0.99, 0.96$ and 0.98 respectively, shown in Fig. 10.

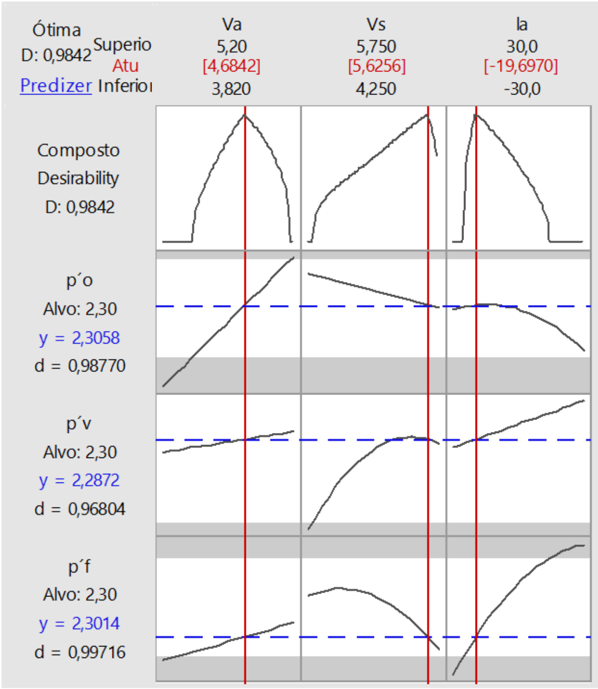

Figure 10: Individual optimization Desirability.

After having determined the value ($D = 0{,}9842$) using the optimization method Desirability composed, the parameters $V_a = 4.68\ m/min$, V_s=5.625 mm/s e $I_a = -19.697$ were revalidated at a joint as shown in Fig. 6, where we have a constant nose. Getting a good cord geometry, appropriate for use in the three critical welding positions as shown in Table 4.

Table 4. Appearance of the face and root of the weld beads obtained optimization without covers-joins the three positions with CMT

Position	Format do Cord
Flat welding face	
Flat welding root	
Vertical welding face	
Vertical welding root	
Overhead welding face	
Overhead welding root	

In the Fig. 11, we can see how in the transversal section two cords have a full load at the joint, with a total penetration reach in all the welding position tested. In addition, the cords not present internal defects and confirm the optimization of the experiment on chamfer inclined nose.

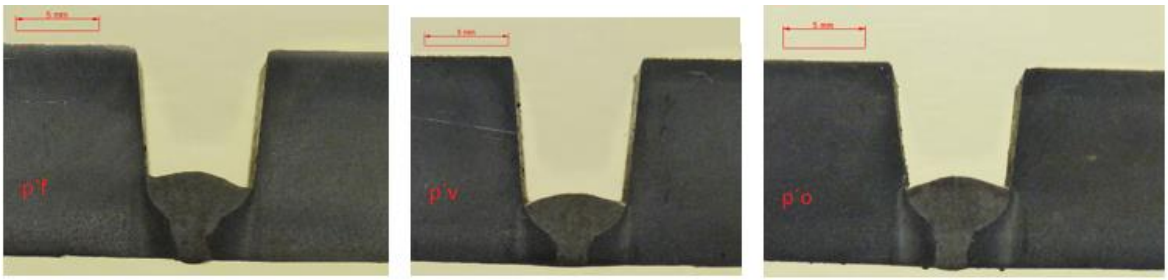

Figure 11: Section cross string, realized with narrow groove joint without covers joint at points where welding the top positions Flat welding (*p´f),* Vertical welding(*p´v*) and Overhead welding (*p´o*) with CMT

5. CONCLUSION

The mathematical models developed through the response surface methodology (Central Composite Design), to control penetration, are statistically adequate and allow to prevent the geometric conditions of the welding cord, being validated by the confirmation of the results.

Using the proposed mathematical models, it was verified that the wire feed rate, the welding speed and the length arc significantly influence the penetration, because the wire feed rate provide a higher intensity.

An adjusted model is used for obtain variables with ideal responses, the optimal range of input variables using the methodology Desirability, being able to obtain a set of results for the full penetration in the three critical positions of welds proposals.

The deposition of weld in the joint with chamfer was performed satisfactorily and the expected results were obtained to find the total penetration and then be validated on a joint with chamfer inclined nose.

6. REFERENCES

Aures, J. V.. 2013. Avaliação de Processos MIG/MAG derivativos utilizando-Se Simulador de Soldagem de Dutos dor Retificação. Tese de Doutorado. Universidade de Brasilia DF. UNB.

Costa, T. F. 2011. Aplicação de processos MAG curto- circuito convencional e controlado na soldagem de dutos de aço carbono. Dissertação. Ed. Universidade federal de uberlândia. Uberlândia – MG. UFU.

Derringer, G., and Suich, R., (1980). Simultaneous Optimization of Several Response Variables,Journal of Quality Technology, 12, 4, 214-219.

Dudko, D. A. et al. 1957. Multi-pass welding of thick metal in the shield of carbon dioxide. Automatic Welding, (3), pp. 58-63.

Fitrianto, Anwar, and Habshah Midi. 2011. “Multi-Response Optimization via Desirability Functionfor the Black Liquor DATA.” Journal of Science and Technology (Ii): 91–102.

Fuller, D and Scherer W. (1999). The desirability function: underlying assumptions and application implications. IEEE International Conference on Systems, Man and Cybernetics, p. 4016-21.

Gunaraj,V.; Murugan,N.2006. Effect Of Flux Cored Arc Welding Process Parameters On Duplex Stainless Steel Clad Quality ,Journal Of Material Processing Technology Vol.176 Pp 230-239.

Hudson, M. G. 2004. Welding of X100 linepipe. Ph.D. Thesis, Cranfield University,.

Kannan,T.; Murugan,N.2006b. Prediction Of Ferrite Number Of Duplex Stainless Steel Clad Metals Using RSM, Welding Journal. Pp. 91 - 99.

Kvasov, F. V. Special Features of Mechanized Welding with Controlled Electrode Metal Transfer. Weld. J., v. 14, p. 158-161, 2000.

Lamond, J., and Lee, K. Y. A cost effective root pass. The 4th International scientific- professional conference. Cost Effective Application of Welding Processes and Welding Related Techniques in Manufacturing of Construction and Products. 335 – 344 p. Slavonski Brod, November 14 – 16, 2007.

Malin, V. Y. The State of the Art of Narrow Gap Welding Part I. Welding Journal, v. 62, Nº 4, 1983,p. 22-30.

Meister, R. P. and Martin, D. C. 1966. Narrow-gap welding process. British Weld. J., pp. 252-257.

Modenesi, P.J. (1990) Statistical Modelling of the Narrow Gap Gas Metal Arc Welding Process, PhD Thesis, Cranfield Institute of Technology.

Montgomery, D.C. e RUNGER, G.C., Estatística Aplicada e Probabilidade para Engenheiros, 2ª ed., LTC Editora, Rio de Janeiro, 2003

Montgomery, D.C., Design and Analysis of Experiments, Fourth ed.,Wiley, New York, 2001.

Myers, R.H.; Montgomery, D.C.; Anderson- cook, C. Response surface methodology: process and prod- uct optimization using designed experiments. 3 ed. New Jersey, USA: John Wiley & Sons, 2009, 680p.

Nazarchuk, A. T., and Sterenbogen, Y. A. Narrow gap gas shielded welding and some of the special features of the process. Automatic Welding, May 1984, pp. 54-58.

Pickin, C. G., and K. Young. 2006. "Evaluation of Cold Metal Transfer (CMT) Process for Welding Aluminium Alloy. Science and Technology of Welding and Joining 11(5): 583–85.

Teng, T. L. and Chang, P. H. 1997. "A study of residual stresses in multi-pass girth-butt welded pipes," International Journal of Pressure Vessels and Piping, vol. 74, no. 1, pp. 59-70,.

Vieira, F. D.. 2012. Desenvolvimento de tocha e de procedimento para a soldagem MIG/MAG em Chanfro Estreito de peças espessas em aço ao carbono. Dissertação. ed. Universidade Federal de Santa Catarina-SC. UFSC.

Zhang, H. T., J. C. Feng, and P. He. 2008. "Interfacial Phenomena of Cold Metal Transfer (CMT) Welding of Zinc Coated Steel and Wrought Aluminium." Materials Science and Technology 24(11): 1346–49).

7. RESPONSIBILITY NOTICE