Statistical Model to Evaluate the Weldability, Mechanical and metallurgical Properties of the Processes GMAW and FCAW

Barbedo, N.D., Corrêa, E. O., Castro, C. A. C.

Abstract— **In recent years, one of the main goals of metalworking industry has been the pursuit of higher productivity with lower manufacturing cost. In this context, two welding processes have been more extensively used: the GMAW (Gas Metal Arc Welding) and the FCAW (Flux Cored Arc Welding). In this work, welds using these processes were carried out in flat position on ASTM A-36 carbon steel plates in order to make a comparative evaluation between them concerning to mechanical and metallurgical properties. A statistical tool based on technical analysis and design of experiments, DOE, from the Minitab software was adopted. For these analyses, the voltage, current, and welding speed, in both processes, were varied. As a result, it was observed that the welds in both processes have different characteristics in relation to the metallurgical properties and performance, but they present good weldability and satisfactory mechanical strength.**

Index Terms— **Flux Cored Arc Welding (FCAW), Gas Metal Arc Welding (GMAW), Design of Experiments (DOE).**

I. Introduction

THe enhancement of welding processes have been widely investigated due to their versatility and the fact of being considered the most important method of metal joining in structure and piece manufacturing [1].

The increase in the use of FCAW and GMAW processes has happened due to the reduction in the use of shielded electrode technique [2]. The FCAW and GMAW have presented a continuous development because they have proven to be flexible, low cost and adequate for mechanical processes. Furthermore, these processes present high productivity, high deposition rate and high quality welding [2]. The FCAW and GMAW processes are widely applied in the oil industry. Both processes may be applied to several types of steel, like low carbon steel, stainless, among others [3]. These two processes are already used industrially; however, studies related to their microstructure and mechanical properties are little explored scientifically.

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Aiming to meet the demands for quality welding, the optimization of the variable in the welding processes is necessary: voltage, current and speed [4]. For this purpose, the use of methodologies based on the statistical analysis has become invaluable to cover the analyses of the parameter influence isolatedly or through interactions [5].

Studies show that the rise in welding voltage leads to a reduction of the weld bead width and the increase in welding speed leads to a reduction of the bead width. The increase in voltage also leads to a reduction of the bead height and the increase in current rises the bead height. In terms of penetration, the most influent parameter is the current, where the higher the current, the higher the penetration [6].

The design of experiment (DOE) enables the definition of which factors, their quantities and conditions must be collected and controlled during a particular experiment, for a higher statistical accurateness of the response, with a lower operational cost [7]. This tool provides more reliable, time and money saving results. [8]. The DOE technique is an economical experiment programming method which identifies the most influencing variables in the result of the process by carrying out a reduced number of experiments [9].

II. Objectives

The objectives of this work are:

Verify the influence of the variables on the metallurgical properties of the weld bead;

Verify the mechanical behavior, that is, the mechanical resistance of the GMAW and FCAW processes in welded joints;

Analyze the microhardness profile on the base metal, the heat affected zone (HAZ), and the weld metal, in both processes.

III. Materials and Methods

Two types of wires were used in this work. Their names are: ER70S-6 and E71T-1 with 1.0 and 1.2 mm of diameter. It was used one source of 400 ampere.

The material used for the sample was steel ASTM A-36, with 200 x 160 x 3 mm. The chemical composition of steel A-36 may be seen in Table 1.

TABLE I
TYPICAL CHEMICAL COMPOSITION OF ASTM A-36

C (%)	Si (%)	Mn (%)	Ni (%)	Mo (%)	P (%)	S (%)
0.17	0.23	0.62	0.01	0.013	<0.027	<0.018

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Bead on plate (BOP) and groove weld were carried out. The plate was milled along its length (200 mm) to make a groove of approximately 30°. The tests were based on a complete factorial planning [10].

The tests were divided into two steps. Voltage, current and welding speed were assessed in both phases. In the first step, where the welding was done on plates, the geometric properties of the welded steel were assessed in both GMAW and FCAW processes. In the second step, where the welding was done in groove, metallurgical properties and mechanical resistance of the welded steel were verified.

The BOP welding was carried out as illustrated in Figure 1. The geometrical properties of the beads were assessed as shown in Figure 2.

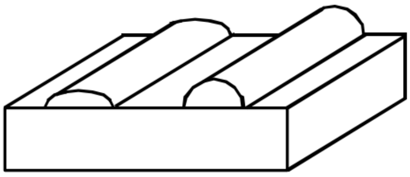

Fig. 1. Welding on plates

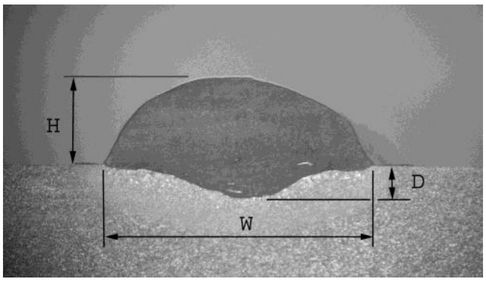

Fig. 2. Geometrical features on the bead: Width, Height and Depth.

The variables were selected from values recommended by the manufacturer, shown in Tables 2, 3 and 4.

TABLE II
SUMMARY OF THE TESTS WITH WIRE ER70S-6.

ER70S-6					
Diameter (mm)	Variables	Below	Reference	Above	Factorial Planning
1.0	Voltage (V)	22.5	25	27.5	2^3 8 tests
	Current (A)	171	190	209	
	Weld. Speed (cm/min)	31.9	46.5	62.3	
1.2	Voltage (V)	23.85	26.5	29.15	2^3 8 tests
	Current (A)	225	250	275	
	Weld. Speed (cm/min)	31.9	46.5	62.3	
Total tests					16 tests

TABLE III
SUMMARY OF THE TESTS WITH WIRE E71T-1

E71T-1					
Diameter (mm)	Variables	Below	Reference	Above	Factorial Planning
1.0	Voltage (V)	26.1	29	31.9	2^3 8 tests
	Current (A)	207	230	253	
	Weld. Speed (cm/min)	31.9	46.5	62.3	
1.2	Voltage (V)	31.05	34.5	37.95	2^3 8 tests
	Current (A)	310.5	345	379.5	
	Weld. Speed (cm/min)	31.9	46.5	62.3	
Total tests					16 tests

The fixed parameters used in the welding process will be shown in Table 4.

TABLE IV
FIXED WELDING PARAMETERS

Shielding gas:	95% Ar + 5% O_2
Gas flow:	18 l/min
Distance between tip/piece:	17 mm
Polarity:	CC^+
Feeding Speed:	4,4 – 18 m/min

The scheme for joint welding follows in accordance to Figure 3. It presents two plates with specific geometry and angle. The joint welding was carried out when the best welding parameters were known, that is, when the welds were obtained on the plates.

The welding was carried out with a mechanized system that moves the torch.

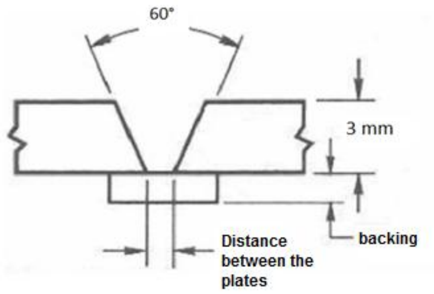

Fig. 3. Scheme for groove weld

A. Preparation of the test sample for the mechanical tests

After the groove welding, the samples were prepared for the mechanical tests of microhardness, tensile test and metallographic analysis.

The microhardness assessment was done through the Vickers method with a 0,5 N applied on the transversal surface of the sample in several equally spaced points along it, from the metal base to the center of the weld, thus obtaining the microhardness profile, as can be seen in Figure 4.

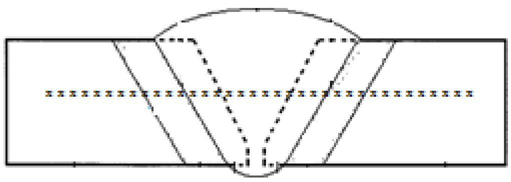

Fig. 4. Micro hardness test scheme.

The tensile test was accomplished in the sample with transversal section, in which the longitudinal axis is perpendicular to the longitudinal axis of the weld. The samples were taken from the GMAW and FCAW processes. Three samples were tested in each situation. Figure 5 illustrates a sample for the tensile test.

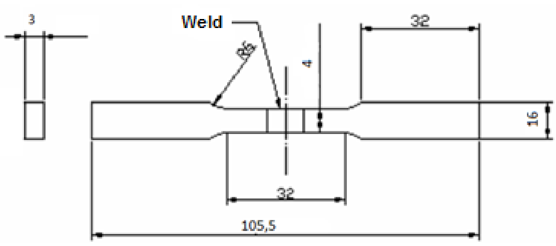

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Fig. 5. Dimensions (mm) of sample with transversal section.

For the microstructural analysis, the welded samples were cut transversally and reagent HNO_3 4% was added. The results obtained were compared with other of the filled metal.

IV. Results and Remarks

A. Optimum Parameters

The optimum geometrical parameters found through the microscope are represented in Table 5.

TABLE V
OPTIMUM PARAMETERS OF WELDING ON PLATES.

Wire diameter	Voltage (V)	Current (A)	Welding Speed (cm/min)	Height (mm)	Width (mm)	Depth (mm)
ER70S-6 1.2 mm	19.4	190	31.9	3.84	9.1	2.38
ER70S-6 1.0 mm	21.5	183	31.9	3.2	8.2	2.77
E71T-1 1.2 mm	19	220.3	62.3	3.01	5.57	1.04
E71T-1 1.0 mm	17.1	223	62.3	3.00	4.89	1.63

Data from Table 5 were inserted Response Optimizer in Minitab software to check the influence of the parameters in the geometry of the weld bead.

B. Statistical Tool DOE

The statistical tool DOE enabled the determination of the influence of the welding parameters in the geometry of the weld bead. Figures 6, 7, 8 and 9 display the most influencing parameters in the weldability of the weld bead for each electrode.

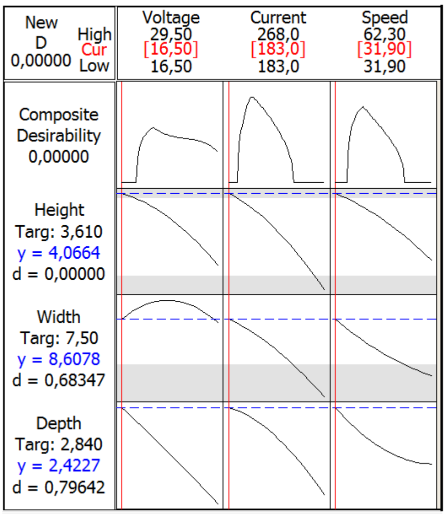

Fig. 6. - Influence of welding parameters in the weldability of steel ASTM A-36 for ER70S-6 (1.2 mm).

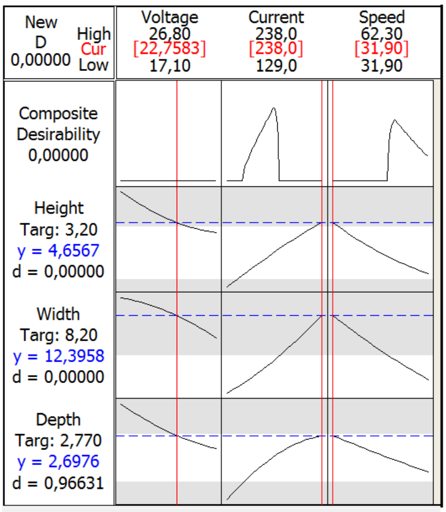

Fig.7. Influence of welding parameters in the weldability of steel ASTM A-36 for ER70S-6 (1.0 mm).

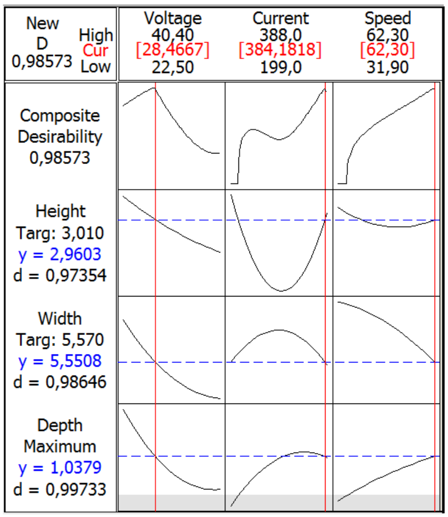

Fig. 8. Influence of welding parameters in the weldability of steel ASTM A-36 for E71T-1 (1.2 mm).

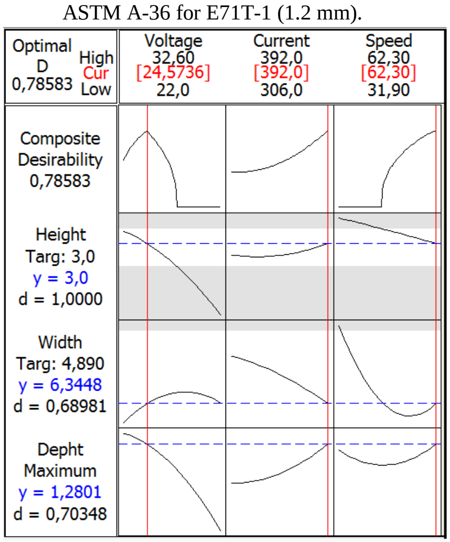

Fig. 9. Influence of welding parameters in the weldability of steel ASTM A-36 for E71T-1 (1.0 mm).

Figures 6, 7, 8 and 9 represent what is desirable in each response and *D* is the combined value of the desirabilities of all responses. The closest *d* is to 1, also *D* is closest to 1 and so all responses will be near the optimum in the bands specified acceptable.

In this work, where you want maximum penetration, the

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individual desirabilities in the bands are acceptable.

Influence of welding parameters on the bead geometry is discussed below:

Figure 6 - ER70S-6 (1.2 mm): The height of the bead decreases as the voltage, current and welding speed increase. The width also decreases with increase in welding parameters. However, its relation with voltage variation is parabolic. Penetration decreases as the voltage, current and welding speed increases.

Figure 7 - ER70S-6 (1.0 mm): The height of the bead and penetration decrease with the increase of the voltage the welding speed.

Figure 8 - E71T-1 (1.2 mm): Influence of the current in the geometry of the bead varies parabolic shape. However, the individual desirabilities have been achieved, since d = 1 reaches the geometry of the weld bead. Penetration decreases when the voltage increases and it increases when the current and speed increase.

Figure 9 - E71T-1 (1.0 mm) height reaches the desirability, *d = 1*. The bead width is outside the desirability. Penetration decreases with the increase of voltage and it increases with increasing current.

C. Groove Welds

Figure 10 shows the groove welds using the optimum parameters of each electrode found in the first phase.

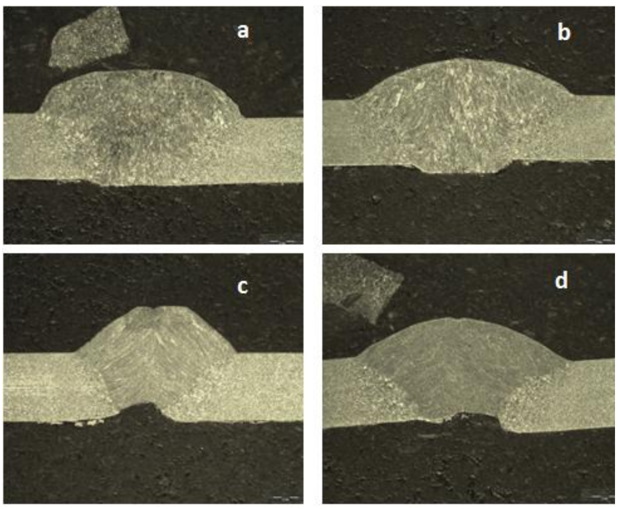

Fig. 10. Grove weld carried out with optimum parameters for each electrode used. a) ER70S-6 (1.2 mm); b) ER70S-6 (1.0 mm); c) E71T-1 (1.2 mm); d) E71T-1 (1.0 mm).

Welds made with GMAW - ER70S-6, occur complete penetration and fusion. This demonstrates the arc stability during welding.

The use of backing FCAW - E71T-1, retained slag causing lack of penetration.

D. Microhardness Test

The graphic with the microhardness test results may be observed in Figure 11.

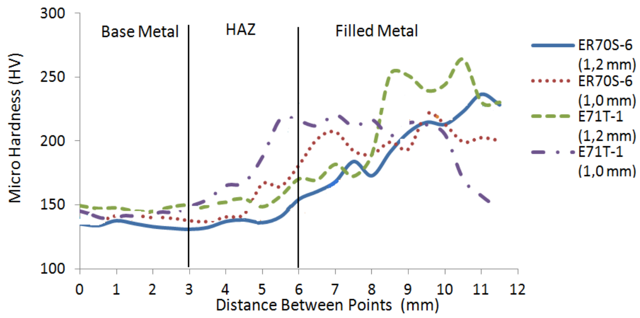

Fig.11. Comparison between micro Vickers hardness profile for each electrode used.

This graphic displays that the microhardness increases from the Base Metal to the Filled Metal, because the addition of materials increases the hardness at the weld zone.

Along the transversal section, the welds in the FCAW process present greater microhardness profile than those carried out in the GMAW process. Due to this, the process with solid electrode may be used in situation where a maximum microhardness is required.

E. Tensile Test

The tensile test proved the integrity of the welded joints, because all the samples fractured in the metal base or the HAZ, with maximum strain above the minimum value of 400 MPa according to expected.

The maximum strains were greater in the welds accomplished with electrode of 1.2 mm of diameter – E71T-1. However, the joint welded with the same electrode of 1.0 mm of diameter presented lower strain due to the lack of penetration.

F. Metallographic Analysis

The metalographic analysis may be observed in Figure 12, with magnification of 50μm.

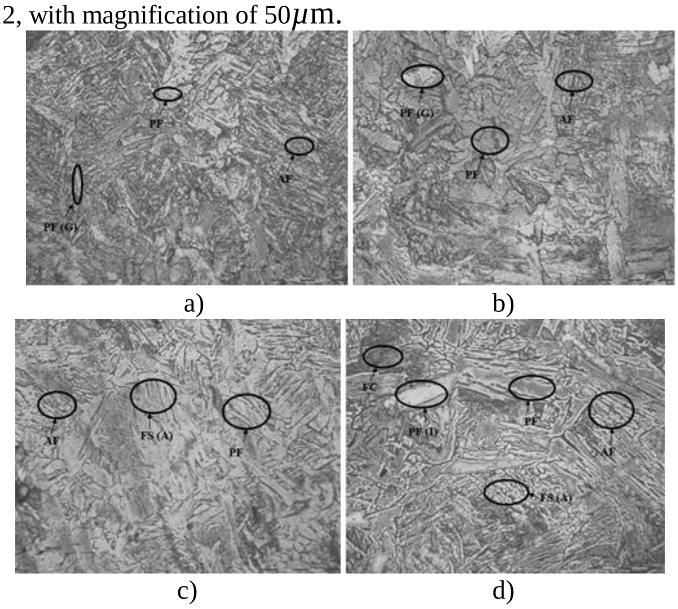

Fig.12. Metalographic analysis of each electrode used. The images are organized in: a) ER70S-6 (1.2 mm), b) ER70S-6 (1.0mm), c) E71T-1 (1.2 mm), d) E71T-1 (1.0 mm) in weld metal.

Fused zones were found in the following phases:

a) ER70S-6 (1.2 mm): Grains of primary ferrite (PF), acicular ferrite (AF) and grain boundaries of ferrite (PF (G)).

b) ER70S-6 (1.0 mm): primary ferrite (PF), acicular ferrite (AF) and grain boundaries ferrite (PF (G)).

c) E71T-1 (1.2 mm): acicular ferrite (AF), ferrite aligned second phase (FS (A)) and primary ferrite (PF).

d) E71T-1 (1.0 mm): acicular ferrite (AF), polygonal ferrite intergranular (PF (I)), primary ferrite (PF), and ferrite aligned second phase (FS (A)).

V. CONCLUSIONS

The statistical tool DOE enabled the determination of the influence of the welding parameters in the geometry of the weld bead.

The GMAW process presented a more stable behavior, generating excellent finishing and satisfactory penetration welding. The weld carried out through the FCAW process presents the formation of slag with E71T-1.

The welding speed and current are the factors that most influence the penetration of the weld. Higher speeds generate lower penetration welds and higher currents increase the penetration of the bead.

The use of backing for the FCAW process with E71T-1 motivated the retention of slag in the root of weld, causing lack of penetration, reducing the maximum strain applied in the tensile test.

Refinements in the microstructure of the weld metal can be verified in all the processes.

The GMAW process produces welds with a lower microhardness profile. Its use is recommended for situations where maximum limits of microhardness are established.

The FCAW process presented a higher micro hardness profile. This is attributed to its higher cooling rate and to its greater amount of AF in the welded zone, due to its welding energy.

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