23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

MODELING AND CONTROL OF WELD HEIGHT REINFORCEMENT IN THE GMAW PROCESS

Jorge Andrés Girón Cruz, jorgeandres@unb.br
Edna Margarita Moncayo Torres
University of Brasília, Department of Mechanical Engineering, Brasília, D.F., 70.910-900, Brazil
emmoncayo@unb.br

Sadek C. Absi Alfaro
University of Brasília, Department of Mechanical Engineering, Brasília, D.F., 70.910-900, Brazil
sadek@unb.br

Abstract. *In recent research related to technological application in the real-time monitoring and control of the welding, is observed the use of various approaches to improve the productivity and quality through the development of techniques and automatic control systems. This paper presents a methodology for modeling and control of the weld height reinforcement, allowing adjusting the process parameters in real time. Was developed for the geometric characteristic studied an integrated system of images acquisition, modeling and control system. The weld bead formation is measured through an acquisition system and processing of images using a low cost web cam. The wire feed speed, welding speed and voltage are predicted using artificial neural based on the desired weld height reinforcement. The control system is based on fuzzy logic.*

Keywords: *Gas metal arc welding (GMAW), Digital image processing, Artificial Neural Networks, Fuzzy Logic.*

1. INTRODUCTION

The joining of metal pieces by electric arc welding with shielding gas is one of the manufacturing processes most frequently used in the metal construction industry. In recent years, many new applications and welding processes were developed based on technological innovation and market demands.

Monitoring of physical variables generated by the electric arc, monitoring of the weld pool, analysis operational of the process parameters, visual inspection and the definition of strategies of control for the process and the weld bead geometric characteristics has been considered important factors in the efforts for monitoring and controlling of the welding process, as well as improving weld quality.

This paper proposes a monitoring of some physical variables generated by the electric arc and the weld bead geometric parameters in the gas metal arc welding (GMAW) process, to the analysis of their potential to use as manipulated and measured variables in a feedback control system. The purpose of the research is to present a methodology that serves as a guide to modeling and control of the weld height reinforcement and the possibility of real time monitoring of weld bead formation. A study is made to determine the appropriate process parameters to generate weld beads with good appearance and quality. In order to find the best parameters setting, artificial neural networks have been used for the design of models that represent the relationship between certain responses based on different input variables.

Empirical rules - used by specialized operator for analysis and modification of weld bead characteristics - are used to develop fuzzy logic controllers for the weld height reinforcement based on the measurement of the images acquired from the weld bead formation (through web camera) with the desired measurements in the weld bead. According to the control strategies adopted in the controllers it is necessary to change the wire feed speed in order to keep the dimensions of weld height reinforcement and the stability of the electric arc. This fact offers the possibility of developing a control strategy similar to that used by the specialized operator, giving a degree of realism to the process automation and the increase quality.

2. GAS METAL ARC WELDING (GMAW)

The Gas Metal Arc Welding (GMAW) is an arc welding process that produces the coalescence of metals by heating them with an arc between a continuously fed filler metal electrode and the work. The arc and the weld pool are protected from atmospheric contamination by a shield of inert gas, which is delivered through a nozzle simultaneously with the welding wire. There are two main methods for this process: depending on the type of shielding gas, a) MIG (Metal Inert Gas) and b) MAG (Metal Active Gas) (Villani et al, 2005). Due to its characteristics, the GMAW process allows welding arc and weld pool clearly visible; workability in all positions - depending on the type of wire diameter and the process variables; high welding speed; little slag generation, obtaining excellent welding in almost all types of metals and alloys used in industry.

2.1. Weld bead geometry

The width, reinforcement, and penetration are the most important variables to explain the weld bead geometry. Cortés, et al, 2011 establishes a series of concepts to define geometry, dividing them into two groups: Weld appearance and weld morphology. The appearance is related to the visual perception of the weld bead. Due to the subjective nature of this definition, these authors determined some quantitative and qualitative parameters to define the appearance. The morphology defines the profile of the weld bead contour that includes the variables: weld width (L), height reinforcement (R), wetting angle (α), fusion angle (ɵ) and depth of penetration (P).

2.1.1. Height reinforcement

The reinforcement is the maximum distance between the base metal level and the top point of the deposited metal. Gives an idea of the number of filling passes that are required to fill the gap and the convexity has a direct correlation with the strength of welded joint and welding wire consumption. The reinforcement increases with increase in welding wire feed. It is indirectly proportional to voltage, welding speed and electrode diameter. (Gunaraj and Murugan, 1999).

2.2 INTELLIGENT SYSTEMS

Artificial Intelligence (AI) is a multidisciplinary area in the field of mathematics and computer science. IA is historically the most common term for the science whose objective is to development of artificial intelligent systems. Thanks to its versatility and great advantages, this technology offers robust and effective solutions to problems present in the industry. Artificial Intelligent Systems can implement some features and processing mechanisms of biological systems. Between intelligent systems are highlighted: Artificial Neural Networks, Fuzzy Logic and Evolutionary Computation. (Cruz, 2014).

2.2.1 Artificial Neural Networks

Artificial neural networks (ANN) are part of computer science related to artificial intelligence, seeking to implement mathematical models that resembles to neuronal structure of intelligent organisms, with the ability to adjust its parameters as a result from the environment interaction, improving the ability to solve problems (Ferneda, 2006). Artificial neural networks are used to solve problems where is not possible to obtain an analytical model or analytical models are very complex. The main advantage is that this type of algorithm can be generated with little or no human intervention, creating autonomous systems that can make their own decisions based on experience.

2.2.2 *Fuzzy logic*

Fuzzy logic proposed by Zadeh (1965) is an alternative to traditional logic and as an attempt to model the human information processing and the understanding of how humans represent decisions with linguistic concepts. The arrival of fuzzy logic was caused by the need for a method capable of expressing in a systematic manner amounts inaccurate, vague and ill defined. For example, instead of using a complex mathematical model, industrial controllers based on fuzzy logic can be related to the experimental knowledge of trained human operators doing as the control action as efficiently and effectively as more experienced operators (Godoy and Shaw, 2007).

3. METHODOLOGY

Fig. 1 shows the outline for the proposed methodology for the control of the weld bead reinforcement.

3.1 Modeling of weld height reinforcement using artificial neural networks

3.1.1 Identification of GMAW Parameters and process response

GMAW is the most complicated process in terms of selecting and adjusting of parameters for the quantity and the strong interrelation between the variables, a small change in one parameter will affect all the other parameters, what makes it hard to design a table of values showing the optimum welding parameters for a wide range of industrial applications. In this paper were selected process parameters such as voltage, wire feed speed and welding speed for control of weld bead reinforcement, due to literature recognizes that these parameters allow to find relations between electric arc behavior, mass transfer process, appearance and weld bead geometry. The variables that were kept constant are contact-tip-to-work distance (CTWD) of 15 mm, shielding gas flow rate of 15 lt/min and torch inclination angle of 90°. Was used Solid wire AWS A5.18 ER70S-type 6 with a diameter of 1 mm and Metal-cored wire: 410NiMo MC with a diameter of 1.2 mm

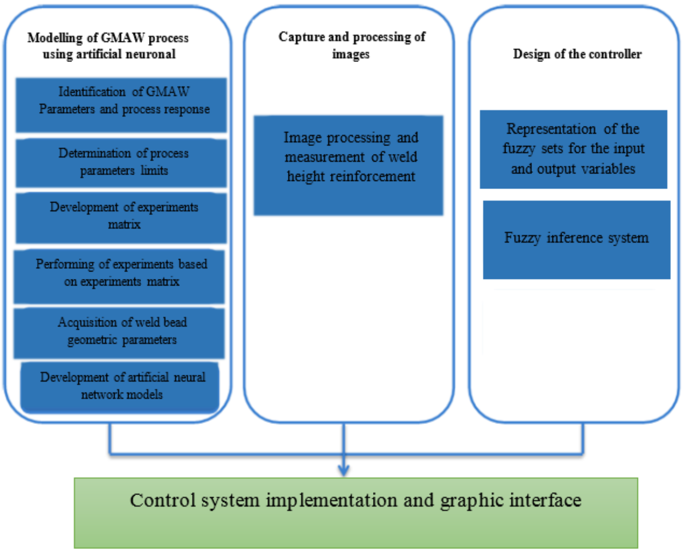


Figure 1: Scheme of the proposed methodology.

3.1.2 Determination of process parameters limits

The working limits of selected parameters was based on numerous trial runs. This was done to vary only one of the factors by keeping the rest of them at constant values. The levels of each parameter were finalized by inspecting the resulting bead on plate carefully and only those beads were accepted which did not show any visible welding defects during trial experiments (spatter, undercutting, poor appearance, etc.). The limiting values of parameters are shown in Tab. 1.

Table 1: Working limits of selected welding parameters.

	Wire feed speed (m/min)	Voltage (V)	Welding speed (mm/s)
MIN	4.5	16	6
MAX	8.5	30	14

3.1.3 Development of experiments matrix

As there is no defined a methodology to choose the number of trial runs, in this study made use of Central Composite Design (CCD) in order to examine the behavior of the response variables in the experimental runs. The CCD counts with a factorial design 2^3 increased with six axial points and a central point. Experiments were carried out with the variations in the process parameters based on experimental design CCD to evaluate the influence on the weld bead geometry. Table 2 shows the coded factor levels and their corresponding values to each selected process parameters.

Table 2: Coded factor levels and their corresponding values to each selected process parameters.

Welding parameters	Symbol	levels				
		-1.682	**-1**	**0**	**1**	**1.682**
Wire feed speed (m/min)	x_1	4.8	5.5	6.5	7.5	8.2
Voltage (V)	x_2	16.2	19	23	27	29.7
Welding speed (mm/s)	x_3	6.6	8	10	12	13.4

With the combination of the values of the variables listed in the Tab. 1 was realized the experimental matrix that is displayed in Tab. 3, wherein are indicated the selected experiments and the values for each variable.

Table 3: Experimental matrix.

	Codified variables			Natural variables				Codified variables			Natural variables		
No Exp	x_1	x_2	x_3	x_1	x_2	x_3	**No Exp**	x_1	x_2	x_3	x_1	x_2	x_3
1	-1	-1	-1	5.5	19	8	**9**	-1.682	0	0	4.8	23	10
2	1	-1	-1	7.5	19	8	**10**	1.682	0	0	8.2	23	10
3	-1	1	-1	5.5	27	8	**11**	0	-1.682	0	6.5	16.3	10
4	1	1	-1	7.5	27	8	**12**	0	1.682	0	6.5	29.7	10
5	-1	-1	1	5.5	19	12	**13**	0	0	-1.682	6.5	23	6.6
6	1	-1	1	7.5	19	12	**14**	0	0	1.682	6.5	23	13.4
7	-1	1	1	5.5	27	12	**15**	0	0	0	6.5	23	10
8	1	1	1	7.5	27	12							

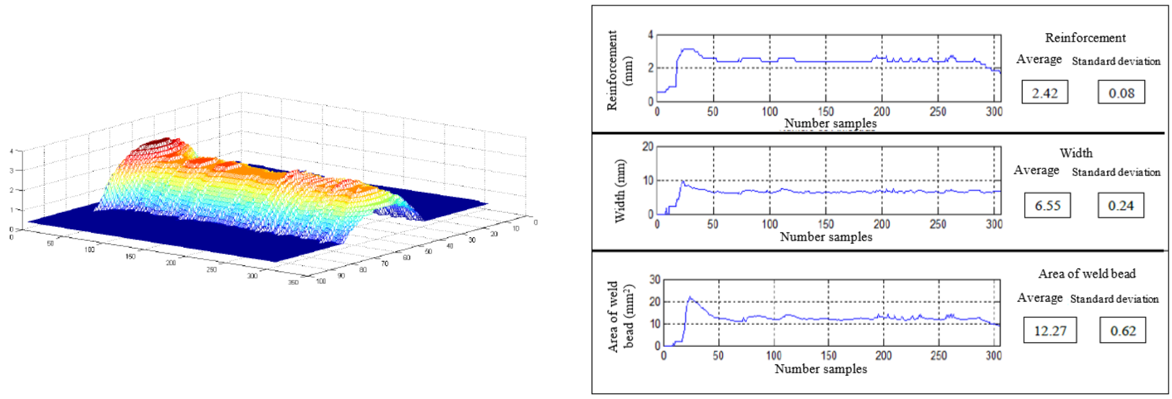
3.1.4 Performing of experiments based on experimental matrix

The experimental runs were performed with each combination of values listed in Tab. 3. To check the repeatability and reproducibility of the proposed methodology to changes in process conditions were repeated the same tests indicated in the experimental matrix for the metal-cored and solid wire.

3.1.5 Acquisition of weld bead geometric parameters

For measurement the geometrical parameters is use a scanning system developed in in Torres, et al., 2011.

A three-dimensional (3D) profile of the weld surface reconstructed after digital image processing sequence is shown in Fig. 2a. Using the scanning system is obtained two measures for each output variable (reinforcement, width and the area of weld bead). The first being the average measure, regardless the limits of the bead, and the second is a measure of the error with respect to the non-uniformity of the weld bead (standard deviation of measure). Measurements of reinforcement, width and area of weld bead are obtained as shown in the Fig. 2b.



(a) (b)

Figure 2: Acquisition of weld bead geometric parameters. a) Three-dimensional profile of the weld surface. b) Measurements of weld bead geometric parameters.

3.1.6 Development of artificial neural network models to estimate the process parameters

Experimental identification is used to develop the models for the reinforcement height taking into account the previously selected process parameters. The average measure and the measure of the error with respect to the non-uniformity of the weld bead (standard deviation of measure) were chosen as inputs for neural network. The network exits are welding speed, arc voltage and wire feed speed. For developed the models, the MATLAB Neural networks Toolbox was used.

The appropriate neural networks structure was chosen by the trial and error method. Feed forward artificial neural network structure was established by keeping 2 neurons in the input layer, three hidden layers formed by 80, 60 and 40 neurons, respectively, and an output layer formed by three neurons. It was trained with help of the mean square error (MSE). The training time consisted of 10.000 iterations using the algorithm back propagation.

3.2 Capture and processing of images

An image acquisition system is used for the measurement of weld bead width; it consists of a web camera with a resolution of 16 megapixels and with USB 2.0 connection, besides a dark filter number 10 (used in the welding helmets) for the decrease of the radiation generated by the electric arc.

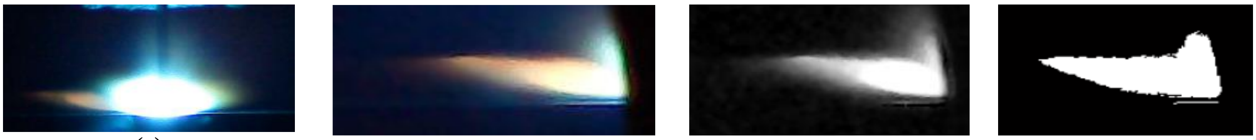
3.2.1 Image processing and measurement of weld height reinforcement

The measurement of weld height reinforcement has the inherent problem of viewing a very bright welding arc, making it difficult to correct treatment, as shown in Fig. 3a. Therefore it became necessary to cover the nozzle trying to reduce the interferences from arc light. An image acquired, cropped and ready for image processing can be seen in Fig. 3b.

Techniques of digital image processing were used to reduce the noise effects, to improve the contrast and to select the work area. Furthermore, a transformation of the image to gray scale was made and a median filter was applied to eliminate isolated pixels, finally the image is binarized as shown in Fig. 3c and Fig. 3d.

The techniques used for the height reinforcement measurement basically searching the image pixels that represent the weld pool, the workpiece and the weld bead.

Once the image is binarized, proceed to find the row of pixels where the base metal is located. See Fig. 4a. When the process for localization of the base metal in the image location has been completed, can be found the columns of the horizontal limits that delimiting the zone in which the reinforcement will be measured (Fig. 4b). In order to avoid the region that has the highest interference by the arc light is chosen a point at a considerable distance from the weld pool as shown in Fig. 4c.



(a) (b) (c) (d)

Figure 3: Image acquired by the webcam. a) With strong influence of the arc light. b) Image acquired and cropped. c) Image in grayscale and median filter. d) Image binarized.

Once located the column where it will measure the reinforcement, proceed to count the number of pixels between the borders of the weld bead and the line that delimits the workpiece. The difference between the two points (borders of the weld bead and workpiece) in the column represents the weld height reinforcement in pixels. A representation of the expressed above is shown in Fig. 4d. The last step is the conversion from pixels to millimeters, using a model obtained stage positional camera calibration.

(a) (b) (c) (d)

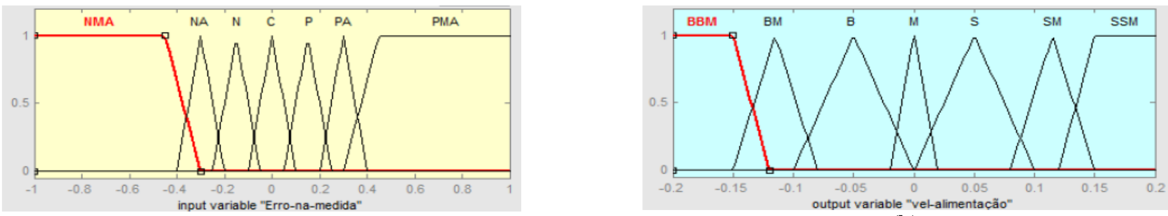
Figure 4: Image processing. a) Delimitation of wokpiece. b) Horizontal Limits. c) Zone for measurement of weld bread reinforcement. d) Reinforcement measure.

3.3 Design of the controller

For the implementation of a fuzzy controller based on the *Mamdani* inference system, it was necessary to define some parameters from experience, literature search and experiments design. For real-time control, the control action is carried out preferably at wire feed speed, a parameter that has the greatest influence on the height reinforcement. The fuzzy controller was projected in the MATLAB fuzzy logic toolbox. The general process can be characterized by the steps described as follows.

3.3.1 Representation of the fuzzy sets for the input and output variables

The input variable that is generated in the measurement of weld bead starts from the difference between the reference sign (desired height reinforcement) and the output (measured height reinforcement). The output variable (manipulated variable) is the wire feed speed. For the input variable, seven pertinence functions were used (Fig. 5a). The parameters of each function are based on the experience generated from the different experimental tests. For the output variable, seven pertinence functions were used (Fig. 5b).



(a) (b)

Figure 5: Fuzzy control and pertinence functions. a) Input variable. b) Output variable.

3.3.2 Fuzzy inference system

A group of linguistic rules describes the control strategy, where, one input is considered for one output. The group of rules comes in Fig. 6. The method of the selected defuzzification was the centroid method, where the obtained numeric value represents the center of gravity of the probability distribution of fuzzy system output.

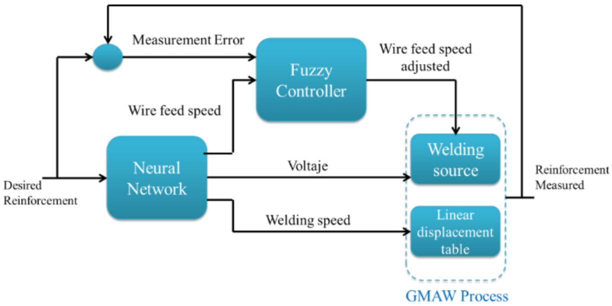
1.	If (Erro-na-medida is NMA) then (Vel-alimentação is BBM)
2.	If (Erro-na-medida is NA) then (Vel-alimentação is BM)
3.	If (Erro-na-medida is N) then (Vel-alimentação is B)
4.	If (Erro-na-medida is C) then (Vel-alimentação is M)
5.	If (Erro-na-medida is P) then (Vel-alimentação is S)
6.	If (Erro-na-medida is PA) then (Vel-alimentação is SM)
7.	If (Erro-na-medida is PMA) then (Vel-alimentação is SSM)

Figure 6: Rules for the control strategy.

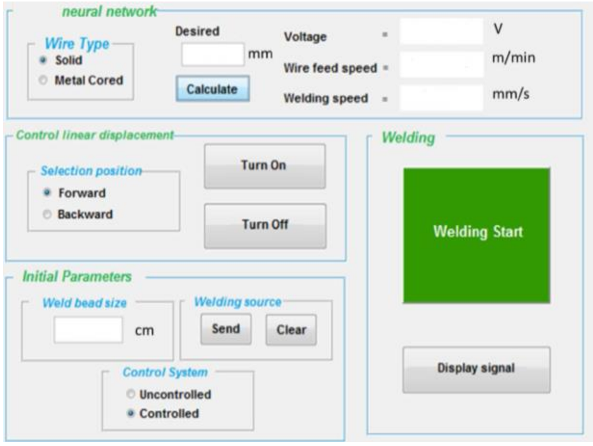
3.4 Control system implementation

Finally, with the network trained and evaluated, the images processed and the fuzzy controller are integrated in an operating environment system of the application. For the real-time control strategy implementation, a feedback system is implemented, where the output signal has a direct effect on the control action, as evidenced in Fig. 7a.

Figure 7b show the graphical interface developed to facilitate user interaction.



(a)



(b)

Figure 7: Control system implementation: a) Architecture of the developed system. b) Graphic interface for the control of the weld height reinforcement.

4. RESULTS

4.1 Project results

To model reinforcement height were extracted - using the scanning system - profiles related to weld bead geometric parameters. The weld bead were obtained from the tests previously indicated in the experimental matrix shown in Tab. 3. The training data for the neural network are derived from test measurements as shown in Tab. 4. The measure of height reinforcement and the measure standard deviation are taken as input, and wire feed speed (Valim), Voltage (V) and welding speed (Vsol) as output (Fig. 8).

Table 4: Results of the Central Composite Design (CCD) for weld height reinforcement.

No Exp	Codified variables			Solid Wire weld height reinforcement (mm)		Metal-Cored Wire weld height reinforcement (mm)	
	x_1	x_2	x_3	μ	δ	μ	δ
1	-1	-1	-1	2.09	0.09	3.56	0.18
2	1	-1	-1	2.56	0.08	4.04	0.25
3	-1	1	-1	1.62	0.10	2.63	0.14
4	1	1	-1	2.22	0.11	3.08	0.09
5	-1	-1	1	1.76	0.08	2.74	0.11
6	1	-1	1	2.08	0.13	3.11	0.16
7	-1	1	1	1.40	0.14	2.32	0.13
8	1	1	1	1.89	0.13	2.67	0.11
9	-1.682	0	0	1.57	0.12	2.31	0.12
10	1.682	0	0	2.21	0.12	3.20	0.11
11	0	-1.682	0	2.07	0.34	3.52	0.17
12	0	1.682	0	1.71	0.10	2.71	0.14
13	0	0	-1.682	2.31	0.09	3.17	0.13
14	0	0	1.682	1.60	0.09	2.44	0.11
15	0	0	0	1.82	0.10	2.76	0.17

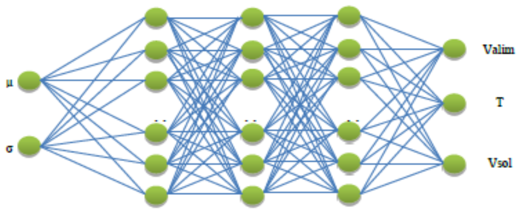
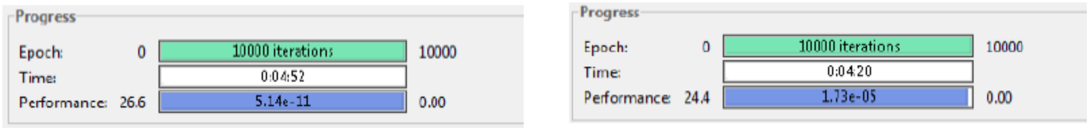


Figure 8: Schematic diagram of neural networks used in this methodology

As the training errors and simulation values greatly change with the function of neurons number, the network topology that presented the smallest simulation errors was chosen. Figure 9 presents the network training for both solid and metal-cored wires with their respective iterations, time of training and validation error. As shown in Fig. 9, it is possible to grasp that by using the same network topology few errors occur, which makes it suitable for modelling.



(a) (b)

Figure 9: Training of the neural network (a) For solid wire, (b) For metal-cored wire

Table 5 show the values of voltage, wire feed speed and welding speed determined by neural networks for different heights reinforcement with solid and metal-cored wires.

Table 5: Welding Parameters for different heights reinforcement in solid and Metal-cored wire.

	Solid wire			**Metal-cored wire**		
Weld height reinforcement (mm)	Wire feed speed (m/min)	Voltage (V)	Welding speed (mm/s)	Wire feed speed (m/min)	Voltage (V)	Welding speed (mm/s)
2	5,86	20,36	8,93	4,63	20,67	13,47
2,5	7,34	19,84	7,13	6,71	23,26	13,29
3	10,09	20,85	9,42	8,88	22,23	10,69
3,5	11,25	21,17	8,23	5,65	18,89	8,24

4.2 Implementation results

Once described and developed, the set of steps that comprise the system are proposed and the evaluation was performed. The control system was implemented in MATLAB, which allows controlling the weld height reinforcement in real time – the system adapts itself for variations during the process. Figure 10 shows the graphical interface developed to facilitate user interaction.

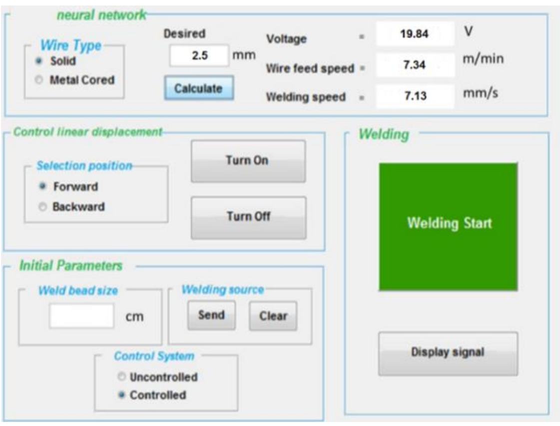
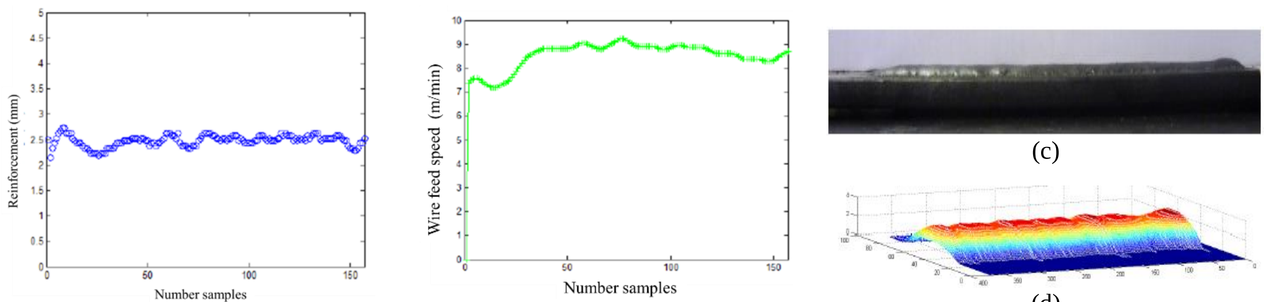


Figure 10: Graphic interface for the control of the weld height reinforcement.

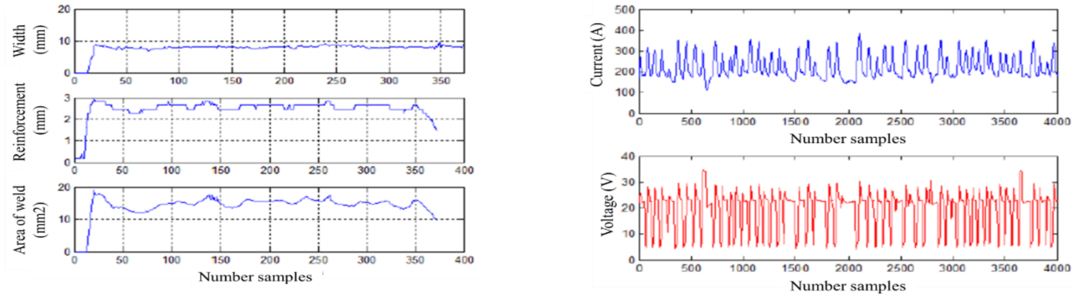
Figure 11a shows the set of height reinforcement measurements obtained from the image processing. The control action exerted on the welding wire feed for the weld height reinforcement of 2.5 mm is presented in Fig. 11b. The weld bead obtained is shown in Fig. 11c. Figure 11d shows the 3D reconstruction of the weld bead.

Figure 12a presents the measurements of the weld bead geometric characteristics. The result was an average height reinforcement of 2.59 mm with a standard deviation of 0.092 mm, width of 8.11 mm with a standard deviation of 0.324 mm and weld bead area of 15.34 mm^2 with a standard deviation of 0.842 mm^2. Figure 12b shows the voltage and current signals obtained from the welding process. In this sense, it can be observed that the transfer mass occurred in short circuit mode with an average current value of approximately 219 A and an average voltage value of approximately 19.28 V.



(a) (b) (c) (d)

Figure 11: Measures and actions for the weld bead with height reinforcement of 2.5 mm in solid wire. a) Measures. b) Behavior of wire feed speed during the control of height reinforcement. c) Weld Bead obtained after controlling. d) 3D reconstruction of the weld bead.



(a) (b)

Figure 12: Measures and signals for the weld bead with height reinforcement of 2.5 mm in solid wire. a) Geometric characteristic measurements of weld bead. b) Measurements of welding process signals.

5. CONCLUSIONS

Given the difficulty of establishing the relationship between the weld bead geometric parameters and the process parameters, an approach based on artificial neural networks is used to model the process. In this line, using experimental data and artificial intelligence techniques have been developed to establish relationships between the process parameters and any weld height reinforcing desired.

Image processing and proper filtering were used to effectively reduce the strong interference of arc light, metal transfer, spatter and other sources in the welding process. A low-cost image acquisition system was developed to measure the weld height reinforcement in real time by using a webcam for the GMAW process. The images obtained allowed the height reinforcement to be identified quite accurately. The system proved to be efficient, practical, inexpensive and adaptable for industrial applications and for research purposes.

The proposed control of weld height reinforcement showed applicability in both types of wire. The fuzzy logic control showed that the system control is adaptable and works even with changes in the welding process conditions.

The results show that the proposed methodology using artificial neural networks for the estimation and optimization of process parameters and the subsequent real-time control through digital image processing and fuzzy logic control is efficient.

The proposed methodology with few tests of training and validation get excellent results and showing up as a good option in control of weld bead geometry in GMAW Process.

6. REFERENCES

Cortés, P.A., Gómez, D.A. and Posada, D. Giraldo, J.E., 2011. Efecto de la oscilación en la geometría de soldaduras superficiales aplicadas con GMAW cortocircuito, Trabalho de Conclusão de Curso. Universidad Nacional de Colombia, Medellín.

Cruz, J. A. G., 2014. Uma metodologia para modelagem e controle da altura do reforço e da largura do cordão de solda no processo GMAW. Dissertação de Mestrado em Sistemas Mecatrônicos, Departamento de Engenharia Mecânica, Universidade de Brasília, Brasília, DF.

Ferneda, E., 2006. "Redes neurais e sua aplicação em sistemas de recuperação de informação". *Jornal Ciência da Informação*, 35(1), p25-30.

Godoy M. and Shaw I. S., 2007. "Controle e Modelagem Fuzzy." *Revista e Ampliada*. Editora Blucher, Ed. 2, p.200-201.

Gunaraj, V. and Murugan, N., 1999. "Application of response surface methodology for predicting weld bead quality in submerged arc welding of pipes. *Journal of Materials Processing Technology*, 88(1-3), p.266 – 275.

Torres, E.M.M., Cruz, J.A.G., Lopera, J.E.P. and Alfaro, S., 2013. "Parameter optimization in GMAW process with solid and metal-cored wires". In *22nd International Congress of Mechanical Engineering (COBEM 2013)*. Ribeirão Preto, Brazil.

Villani, P., Modenesi, P. and Bracarense, A., 2005. "Soldagem Fundamentos e Tecnologia", Editora UFMG, 1.ed., Belo Horizonte, Brasil.

Zadeh, L., 1965. "Fuzzy Sets". *Information and Control*, 8, p.338-353.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.