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Wire Arc Additive Manufacturing of Mn4Ni2CrMo Steel: Comparison of Mechanical and Metallographic Properties of PAW and GMAW

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Abstract

Wire arc additive manufacturing, WAAM, is a popular wire-feed additive manufacturing technology that creates components through the deposition of material layer-by-layer. WAAM has become a promising alternative to conventional machining due to its high deposition rate, environmental friendliness and cost competitiveness. In this research work, a comparison is made between two different WAAM technologies, GMAW (gas metal arc welding) and PAW (plasma arc welding). Comparative between processes is centered in the main variations while manufacturing Mn4Ni2CrMo steel walls concerning geometry and process parameters maintaining the same deposition ratio as well as the mechanical and metallographic properties obtained in the walls with both processes, in which the applied energy is significantly different. This study shows that acceptable mechanical characteristics are obtained in both processes compared to the corresponding forging standard for the tested material, values are 23% higher for UTS and 56% for elongation in vertical direction in the PAW process compared to GMAW (no differences in UTS and elongation results for horizontal direction and in Charpy for both directions) and without significant directional effects of the additive manufacturing technology used.

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1. Introduction

Additive manufacturing of 3D printing is an emerging technology that offers a variety of opportunities to the manufacturing industry [1]. This technology creates components depositing material layer-by-layer depending on the feedstock and energy source [2]. Among these, wire arc additive manufacturing (WAAM) is a wire-feed additive manufacturing technology that employs metallic wire as a feedstock and an electric arc as an energy source [3]. The wire is deposited using a predefined deposition rate and welded by the electric arc in a substrate or in a previously deposited layer [4]. WAAM has become a promising alternative to conventional manufacturing processes due to high deposition rate (1-4 kg/h) [5], environmental friendliness and cost competitiveness [6], as the cost of a part manufactured by WAAM is lower in comparison to other technologies based on powder laser [4]. There are different kind of WAAM technologies, that depending on employed electrogenic welding can be classified as a gas tunsteng arc welding (GTAW), gas metal arc welding (GMAW) [7,8] and plasma arc welding (PAW).

Aerospace applications are the most challenging ones because of the high performance that need to be achieved by the parts [9]. For this reason, the recent focus is on manufacturing complex geometry parts including nickel and titanium alloys [4]. One of the main limitations of these technologies is the lack of control related to defects, such as pores and lack of fusion, and the repeatability and reproducibility of a part [10]. Therefore, monitoring and control of the process take on special relevance [11]. Developments carried out in process control have triggered improvements to additive manufacturing, mainly in the material properties and surface roughness [12].

Regarding to control process in WAAM, Xiong and Zhang [13] proposed an adaptive height control system for GMAW, developing a passive vision monitoring system. This system allows to control the cumulative errors in the layers, maintaining constant distance between the workpiece and the torch. In a similar way, 3D scanner was used to detect perturbations during additive manufacturing process in [12]. In the same investigation, a control algorithm for adjusting each layer height by iterative learning was developed using the data acquires with laser scanner. In the current investigation, a height control system is used in the case of PAW, and a monitoring of the process is carried out in both PAW and GMAW technologies.

Svoboda and Nadale carried out an investigation [14] to compare fatigue life of GMAW and PAW of boron micro alloyed steels. It was detected that PAW welded parts present higher fatigue life than those welded by GMAW. In a similar investigation [15], the parts manufactured by PAW exhibited a higher fatigue life than the parts manufactured by GMAW. This fact was related to lower and wider beads obtained by PAW, resulting a lower stress generation.

Closely related to this, the hardness and mechanical properties of 10Ni5CrMoV were analyzed in a GMAW process [16]. It was found a maximum hardness of 350 HV, and no hardening tendency was discovered in the welding joints. Regarding to mechanical properties, the welded parts met the following demands: yield strength (461 MPa), ultimate tensile strength (709 MPa), elongation (34%) and percentage reduction of area (48%). In the same direction, metallographic investigation [17] of AISI 304 and 316 employing GMAW showed typical solidification structures and homogeneity of the microhardness profile. The hardness values were similar to ones in the material base.

Piccini and Svoboda [18] analyzed the effect of PAW on the microstructural evolution and mechanical properties of dual phase steels. It was shown full penetration of the material, as well as small fusion zone and heat affected zone. In an investigation [15] related to high strength dual phase steel, a higher acicular ferrite content was found for the parts manufactured by PAW than for the parts manufactured by GMAW. The highest hardness was located at the fusion zone for both technologies and the base material hardness was also similar in both cases.

The composition of shielding gases in the process of welding affect to the morphology and microstructure of the welded parts [19, 20]. In an investigation [19] related to metal active gas welding, increasing CO_2 concentration in the shielding gas resulted in an increase on the ferrite content in the material. It was also shown increasing CO_2 raise the weld width and weld penetration. Zong, Chen, Wu et al. showed [20] that CO_2 has influence on the size of undercutting defects such as width, length and volume. Also, the presence of welding spatters was decreased significantly with higher CO_2 quantity. An increase of CO_2 improves the drop transfer and enhance productivity, allowing to increment the welding speed.

This article aims to study the principal differences between mechanical and metallographic properties of Mn4Ni2CrMo steel in GMAW and PAW additive manufacturing processes. For that purpose, a comparison in tensile testing and Charpy test is carried out between walls manufactured using both technologies. Moreover, an analysis of the macrostructure and microstructure obtained is performed for PAW and GMAW.

2. Materials and methods

Two steel (AWS A-5.28 ER 120S-G) walls of dimensions 200 x 100 x20 mm were manufactured by PAW and GMAW technologies (Fig. 1). For that purpose, a steel (S235JR) substrate of 10 mm thickness was employed. Table 1 shows the chemical composition of the employed material.

To achieve the desired geometry, more beads were required for GMAW technology than for PAW technology. The overlapping percentage considered was 65% regarding to GMAW, compared to 60% that was required for PAW as recommended in other investigations [21-22].

Table 1. Chemical composition of the employed material (%wt)

C	Si	Mn	Cr	Ni	Mo
0.09	0.8	1.8	0.31	2.2	0.55

Fig. 1 (a) Test wall manufactured by PAW; (b) Test wall manufactured by GMAW.

A specific 5-axis machine developed by Addilan for WAAM technology with a PAW welding system was used to manufacture one of the walls (Fig. 1). Compressed Argon (concentration of 99.997%) was used as pilot gas and as protective gas. For the GMAW process, a specific FANUC Arc Mate 100-iC robot for welding was used equipped with a KempArc Pulse 450 welding machine and the wire feeder Kempi DT400. In this process, Stargon gas (82% Argon and 18% CO2) was employed.

The maximum deposition rate achieved for this material in PAW is 2.8 kg/h, that corresponds to 5.2 m/min wire speed. In the case of PAW, the process parameters are wire speed, feed rate and intensity, whereas the voltage is an output process parameter. As this technology limits the deposition rate, the same rate will be used for the wall manufactured by GMAW. In this technology, the input parameters are the wire speed and feed rate, as the welding machine performs the measurements for intensity and voltage. Although the deposition rate is equal for both technologies, the energy employed is much higher for PAW than for GMAW. Table 2 summarizes the main differences between both technologies. In the case of GMAW, 60 layers were needed to achieve the desired geometry, however 55 layers were enough for PAW.

Table 2. Summary of the main differences between both processes.

Technology	Number of layers	Time [h]	Wire speed [m/min]	Gas
GMAW	60	4.8	5.2	Ar (82%) – CO_2 (18%)
PAW	55	4.15	5.2	Ar (99.997%)

3. Results

3.1. Mechanical testing

As the WAAM process is a quite directional fabrication technique with a marked solidification directionality, several mechanical samples have been machined, 6 samples in vertical direction of the wall and other 6 samples in horizontal direction, to check the possible variation of the mechanical properties according to ISO 6892-1 standard [23], according to the width of the manufactured walls, mechanical samples were machined at 4 mm diameter and tested at strain rate of <0.002 s^{-1}. Likewise, 8 samples have been machined for Charpy toughness testing according to standard ISO 148-1 both in vertical and horizontal direction of the wall and with the notch in different positions. Fig. 2 shows a schema of the distribution of the mentioned samples in the walls.

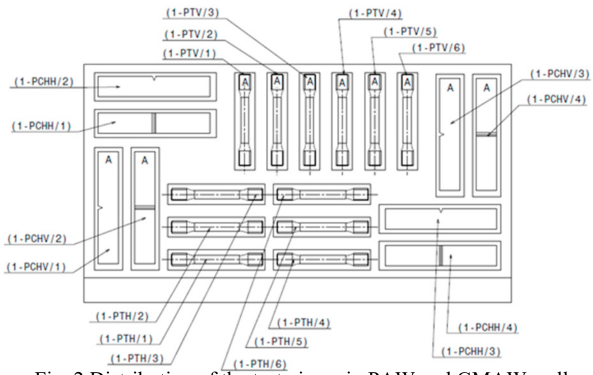

Fig. 2 Distribution of the test pieces in PAW and GMAW wall.

The obtained results for ultimate tensile strength, yield strength and elongation for PAW are shown in **¡Error! No se encuentra el origen de la referencia.** for horizontal and vertical directions. As it can be observed better results were obtained in PAW for the vertical direction than for the horizontal direction for tensile and yield strength.

Table 3. Results of tensile testing of PAW and GMAW

	PAW						*GMAW*					
Probe	Vertical (PTV)			Horizontal (PTH)			Vertical (PTV)			Horizontal (PTH)		
	UTS [MPa]	YS [MPa]	Elong [%]	UTS [MPa]	YS [MPa]	Elong [%]	UTS [MPa]	YS [MPa]	Elong [%]	UTS [MPa]	YS [MPa]	Elong [%]
1	1181	777	17	1124	750	16.5	1008	690	20.5	1029	707	21
2	1183	771	18	1171	742	17	931	681	6	1054	824	18.5
3	1191	786	17.5	1157	749	17.5	966	738	8.5	1005	644	19.5
4	1186	788	16.5	1155	733	22	1012	705	8	1059	688	13.5
5	1188	778	17.5	1141	739	12	1008	689	18	1032	**805**	16
6	1187	786	16.5	1102	708	18	847	695	5	1006	353	18
Mean	1186	781	17.2	1141.7	736.8	17.2	962	699.7	11	1030.8	720.2	17.8
Dev.	3.6	6.7	0.6	25.1	15.5	3.3	64.7	20.4	6.6	22.9	76.8	2.7

The mean values for tensile strength, yield strength and elongation are 1186 MPa, 781 MPa and 17.2% for vertical test pieces, and 1141.7 MPa, 736.8 MPa and 17.2% for the horizontal ones. In addition, the 6 samples values are also more similar among them in the vertical direction, as the standard deviation is lower in this case (3.6 MPA over 25.1 MPa, 6.7 MPa over 15.5 MPa and 0.6% over 3.2%).

In contrast to PAW, in the case of GMAW, better results were obtained for the horizontal test pieces than for vertical test pieces. The mean values for tensile strength, yield strength and elongation for vertical samples are respectively 962 MPa, 699.7 MPa and 11%, whereas 1030.8 MPa, 720.2 MPa and 17.8% are achieved for horizontal ones. Regarding to tensile and yield strength, those values agree with the results obtained by Li et al. [16]. However, the obtained elongation (11% for horizontal and 17.8% for vertical) is lower than the one achieved by Li et al. (34%).

As the tensile values decrease slightly for the GMAW process, it can be expected a certain increase in elongation, but GMAW vertical samples show a decrease in elongation compared to the others. This can be due to small inner defects in the mechanical samples, that can be observed in Table 3, where a quite variability in the elongation values are reached, ranging from 20.5 to 5 so the average is reduced. The presence of small defects (lack of fusion) shown in Fig. 3 and identified as red arrows, has a deleterious effect on the elongation as for this small diameter samples the elongation is very sensitive to the internal state of the material.

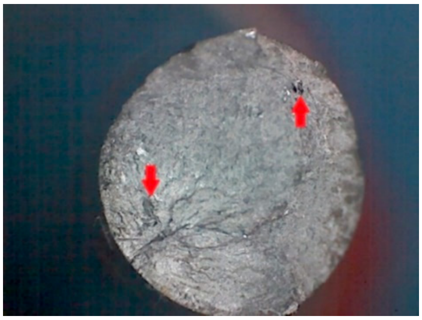

Fig. 3. Small defects (lack of fusion type) observed in the fracture surface of GMAW samples with low elongation values (sample PTV-4)

In Charpy testing, accordingly to tensile tests the vertical samples both for PAW and GMAW present higher impact values than horizontal samples (74.5 J over than 57.5 J in average for PAW and 73.3 J over than 50.5 J in average for GMAW) as can be observed in Table 4.

Table 4 Results of impact testing in samples obtained from PAW and GMAW walls at ambient temperature

Charpy Testing							
PAW				GMAW			
Horizontal		Vertical		Horizontal		Vertical	
	Energy (J)		Energy (J)		Energy (J)		Energy (J)
PCHV-1	80	PCHH-1	57	PCHV-1	75	PCHH-1	37
PCHV-2	85	PCHH-2	50	PCHV-2	73	PCHH-2	43
PCHV-3	63	PCHH-3	50	PCHV-3	71	PCHH-3	59
PCHV-4	70	PCHH-4	73	PCHV-4	74	PCHH-4	63
Mean	74.5	Mean	57.5	Mean	73.3	Mean	50.5
Dev.	9.9	Dev.	10.8	Dev.	1.7	Dev.	12.5

Fig. represents the results obtained in Tables [3-4]. All the test pieces manufactured by PAW show higher values in tensile testing and sharping than parts manufactured by GMAW, except for horizontal test pieces in elongation.

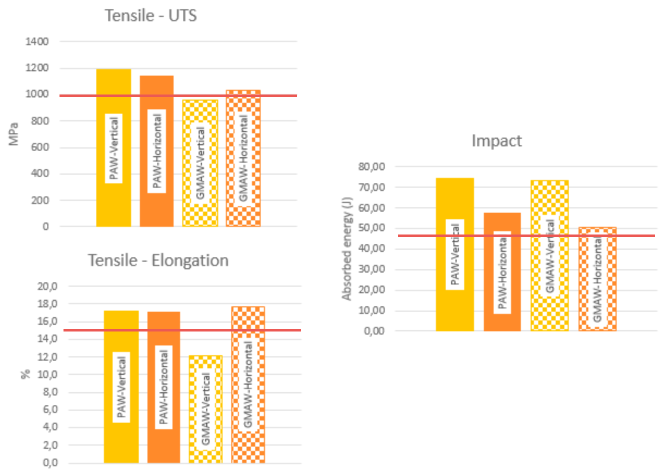

Fig. 4 Comparison of the results obtained for tensile and Charpy testing for PAW and GMAW technologies.

The obtained results can be compared to the ones provided by the material supplier according to which YS should be higher than 960 MPa, the UTS should be also higher than 1000 MPa, elongations should above 15% and impact values should be higher than 47 J (marked with a red line in Fig. 4). Compared the obtained results, ultimate tensile strength is always above 1000 MPa except from the vertical probes obtained by GMAW, this also happens in the case of the elongation. Considering the impact, all the results are higher than 47 J. The only result that is under the reference value in all the tests is the yield strength.

3.2. Metallography

Metallographic samples were extracted out from the manufactured walls approximately in the center of wall length, width and height to analyze the internal structure of the material. Test pieces on different planes XY, XZ and YZ were prepared, being “x” the length, “y” the width and “z” the height of the wall, as can be seen in Fig. Also, when needed microhardness has been measured according to standard UNE-EN ISO 6507-1 [24]. The applied load was 49.03 N applied for 15 s in a flat and polished surface.

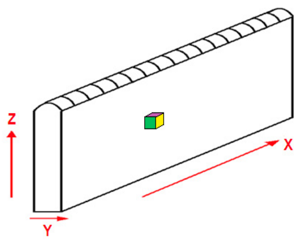

Fig. 5 Schema of the defined directions in the manufactured walls. Metallographic sample is shown as a cube in the center of the wall (colors mean plane observed: Green YZ, yellow XZ and purple XY)

A preliminary observation at low magnification does not show the presence of noticeable dendritic solidification structures.

Once the surface has been metallographically prepared (polished and etched with Nital solution) in the mentioned planes, structures at higher magnification were observed. Fig. 6 (a) shows a micrograph of the internal structure of the material. This structure is basically constituted by tempered martensite needles or tempered bainite. The observed structure is coherent with the microhardness obtained (346 HV5) for this sample. This tempering is probably due to the heat provided by the repetitive material deposition cycles. As stated in the previous paragraph, there is no particularly directional structure with dendrites, neither pores nor lack of fusion are observed on these surfaces.

similar analysis has been performed for the GMAW manufacturing process maintaining the same references for the wall directions. At low magnification no clear directionality was observed in the different planes.

At higher magnification, Fig.6 (b), the observed structure is similar to the previous one in PAW process, primarily constituted by tempered martensite/bainite. The microhardness measured in this case was 339 HV5 similar to the one obtained for PAW.

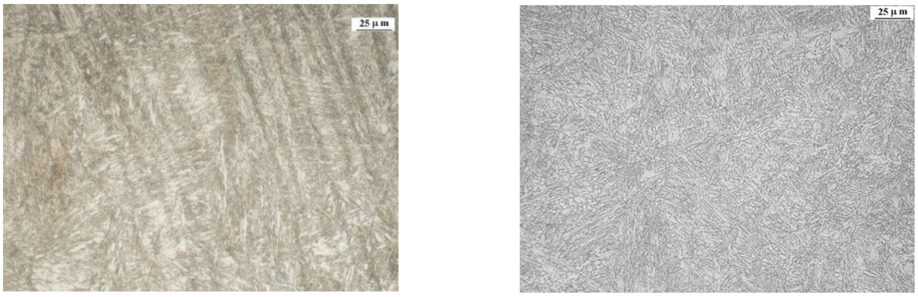

Fig. 6 (a) Microstructure observed in the YZ plane (x400) of the PAW manufactured wall and (b) microstructure observed in the YZ plane (x400) of the GMAW manufactured wall (both structures constituted by tempered martensite/bainite)

4. Discussion

Geometric differences are observed between both WAAM processes, mainly due to the employed quantity of energy, as GMAW introduces 30% less energy than PAW. For this reason, it is necessary to use 3 beads per layer in the case of PAW and 5 beads in the case of GMAW, as well as, 5 more layers in the case of PAW to reach the same wall height.

Regarding to mechanical and structural properties, similar values are obtained for both manufacturing processes. The WAAM process is considered a fast solidification process, thus, for steels, a martensite or bainite structures could be expected, as well as, dendritic or columnar structures oriented across the heat dissipation direction. The structure obtained in this study is like the expected, but no clear directional features are observed.

A characteristic detected in PAW process is a coarser structure on the periphery of the wall observed in plane YZ, indicating a faster solidification. This fact is also expected as the border is cooled by the surrounding atmosphere.

A slight lower tensile and yield strength are obtained for the GMAW wall suggesting that the input energy, three times higher in the PAW process, shall introduce some influence on the mechanical properties. Nevertheless, as the observed structure is similar, the tempering effect of the successive material deposition promotes a cyclic heat treatment of heating when the liquid metal arrives the top of the wall and cooling when the heat input moves along the length of the wall, this cyclic treatment is equivalent to a tempering process and apparent in the tempered structure and microhardness values.

In relation to directionality, the main differences are observed in impact Charpy values as the horizontal samples show a lower impact energy.

Higher elongation values were expected for GMAW samples considering the decrease of the tensile values obtained. Nevertheless, elongation values obtained for GMAW vertical samples are very variable probably due to defects found due to a lack of fusion in the probes that caused an early breakage.

5. Conclusions

Mn4Ni2CrMo Steel has resulted suitable to be manufactured by WAAM in both GMAW and PAW technologies, being able to deposit 2.8 kg material per hour. This study revealed some geometric differences related to the quantity of beads and layers to manufacture two 200 x 100 x20 mm^3 dimension walls with GMAW and PAW processes. These differences are caused by the quantity of energy employed with both WAAM technologies.

Slightly better mechanical results were achieved for the PAW manufactured wall, in comparison to GMAW manufactured wall. The energy impact has significantly penalized the horizontal samples in both processes and more noticeable for the GMAW process. Regarding to metallography, expected structures such as tempered martensite and bainite were achieved. It should be noted that no particularly directional structure with grains or dendrites, neither visible pores nor lack of fusion were founded. This study has revealed the necessity of expanding research on heat treatments to improve the material's performance in mechanical testing. Also, it would be interesting to investigate in machining techniques to create a final part.

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References

[1] A. Thornton, Additive manufacturing (AM): Emerging Technologies, Applications and Economic Implications, Nova Science Publishers: New York, United States, 2015; 9781634826570 1634826574.

[2] D. Ding, Z. Pan, D. Cuiuri et al., Adaptive path planning for wire-feed additive manufacturing using medial axis transformation, Journal of Cleaner Production 2016, Volume 133, 942-952.

[3] D. Ding, Z. Pan, D. Cuiuri et al., Wire-feed additive manufacturing of metal components: technologies, developments and future interests, International Journal of Advanced Manufacturing Technology 2015, Volume 81,465-481, 10.1007/s001070-015-7077-3.

[4] F. Wang, S. Williams, P. Colegrove et al., Microstructure and Mechanical Properties of Wire Arc Additive Manufacturing Ti6Al4V, Metallurgical and Materials Transactions A. 2013, Volume 44, Issue 2, 968-977, 10.1007/s11661-012-1444-6.

[5] S. W. Williams, F. Martina, A. Addison et al., Wire + arc additive manufacturing, Materials Science and Technology, 2016, Volume 32, 641-647, 10.1179/1743284715Y.0000000073.

[6] D. Ding, Z. Pan, D. Cuiuri et al., Bead modelling and implementation of adaptive MAT path in wire arc additive manufacturing, Robotics and Computer-Integrated Manufacturing, 2016, Volume 39, 32-42.

[7] E. Karadeniz, U. Ozsarac, C.Yildiz, The effect of process parameters on penetration in gas metal arc welding processes, Materials and Design, 2007, Volume 28, Issue, 649-656.

[8] D.S. Nagesh, G.L. Datta, Prediction of weld bead geometry and penetration in shielded metal-arc welding using artificial neural networks, Journal of Materials Processing Technology, 2002, Volume 123, Issue 2, 303-312.

[9] S. Guessasma, W.Zhang, J. Zhu et al., Challenges of additive manufacturing technologies from an optimization perspective, International Journal for Simulation and Multidisciplinary Design Optimization, 2015, 6, A9.

[10] A. Antonysamy, Microstructure, texture and mechanical property evolution during additive manufacturing of Ti6Al4V aaloy for aerospace applications, PhD Thesis, University of Manchester, England, 2012.

[11] T. Artaza, A. Alberdi, M. Murua et al., Design and integration of WAAM technology and in situ monitoring system in a gantry machine, Procedia Manufacturing, 2017, Volume 13, 778-785.

[12] Sk. Everton, M. Hirsch, P. Stravroulakis et al., Review of in-situ monitoring and in-situ metrology for metal additive manufacturing, Materials and Science, 2016, Volume 95, 431-445.

[13] J. Xiong, G. Zhang, Adaptive control of deposited height in GMAW- based layer additive manufacturing, Journal of Materials processing Technology, 2014, Volume 214, Issue2, 962-968.

[14] H.G. Svoboda, H.C. Nadale, Fatigue life of GMAW and PAW welding joints of boron microalloyed stells, Procedia Materials Science, 2015, Volume 9, 419-427.

[15] G.K. Ahiale, Y.J. Oh, W.D. Choi et al., Microstructure and Fatigue Resistance of high Strength Dual Phase Steel Welded with Gas Metal Arc Welding and Plasma Arc Welding Processes, Met. Mater. Int, 2013, Volume 19, Issue 5, 933-939, 10.1007/s12540-013-5005-3.

[16] D.Li, D. Yang, X. Luo et al., Effects of shielding gas on GMAW of 10Ni5CrMoV HSLA Steel using high Cr-Ni austenitic wire, Journal of Materials Processing Tech, 2018, Volume 259, 116-125.

[17] G. Constanza, A. Sili and M.E. Tata, Weldability of austenitic stainless steel by metal arc welding with different shielding gas, Procedia Structural Integrity, 2016, Volume 2, 3508-3514.

[18] J. Piccini, H. Svoboda, Effect of the plasma arc welding procedure on mechanical properties of DP700 steel, Procedia Materials Science, 2012, Volume 1, 50-57.

[19] Y. Zhao, X. Shi, K. Yan et al., Effect of shielding gas on metal transfer and weld morphology in pulsed current MAG welding of carbon steel, Journal of Materials Processing Tech., 2018, Volume 262,382-391.

[20] R. Zong, J. Chen, C.Wu et al., Influence of shielding gas on undercutting formation in gas metal arc welding, Journal of Materials Processing Technology, 2016, Volume 234, 169-176.

[21] D. Ding, Z. Pan, D. Cuiuri et al., Bead modelling and implementation of adaptive MAT path in wire arc additive manufacturing, Robotics and Computer-integrated Manufacturing, 2016, Volume 39, 32-42.

[22] D.Ding, Z. Pan, D. Cuiuri et al., A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM), Robotics and Computer- Integrated Manufacturing, 2015, Volume 31, 101-110.

[23] Normalización Española, Materiales Metálicos. Ensayo de tracción. Parte 1: Método de ensayo a temperatura ambiente, UNE-EN ISO 6892-1, February 2017.

[24] Normalización Española, Materiales Metálicos. Ensayo de dureza Vickers. Parte 1: Método de ensayo, UNE- EN ISO 6507-1, October 2018.