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Preliminary development of a Wire and Arc Additive Manufacturing system (WAAM)

J.L. Prado-Cerqueira[a], J.L. Diéguez[b], A.M. Camacho[a]

[a]*Department of Manufacturing Engineering, Universidad Nacional de Educación a Distancia (UNED), C/Juan del Rosal 12, Madrid 28040, Spain*

[b]*Department of Design in Engineering, University of Vigo, C/ Torrecedeira 86, Vigo (Pontevedra) 36208, Spain*

Abstract

Additive manufacturing has experienced a remarkably growth over the last few years, making possible not only to make prototypes, but also to produce final products, so nowadays most of recent works are focused in metal additive manufacturing. The main objective of this work is to show the first experiences in the development of a cost effective metal additive manufacturing system on the basis of gas metal arc welding (GMAW). The proposed system, wire and arc additive manufacturing (WAAM), integrates a cold metal transfer (CMT) welding equipment patented by Fronius®, and a CNC milling machine Optimus with three axis and it presents the advantages to reduce the heat accumulation originated using a conventional GMAW equipment and the possibility to implement surface finish operations by milling. Preliminary results are also presented.

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Keywords: WAAM; Metal Additive Manufacturing; Hybrid Manufacturing; CMT

1. Introduction

As a result of the development of additive manufacturing techniques, the direct formation of metal products has gained the attention of the scientific and industrial community. These techniques have experienced a remarkably growth over the last few years, making possible not only to make prototypes, but also to produce final products [1], so nowadays most of recent works are focused in metal additive manufacturing [2]. The final metal part is usually fabricated from wire or powder material transformed to the semi-solid state by means of a "layer by layer" process. The additive manufacture of metallic materials can be classified into three main groups according to the energy source being used in the process: laser, electron beam (EB) or electric arc. According to Santos et al. [3] and

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Wanjara et al. [4], laser and EB energy sources use very high energy densities, resulting in good dimensional properties in the shaping of parts. However, this entails a very low material deposition rate, a high cost of equipment and a limitation on the dimensional scope of prototyping. The researchers Munghal et al. [5] have determined that additive manufacture with electric arc has a high material deposition ratio, low cost of production at the expense of low surface quality and dimensional accuracy. In a welding-based additive manufacturing process by GMAW (gas metal arc welding), the accumulation of heat is important in successive layers and it must be taken into account when making thin thicknesses. Zhang et al. [6] have investigated the heat transfer control system in order to improve accuracy by controlling the frequency and size of the weld drops. Song and Park [7] have presented a hybrid solution called "3D welding and milling" using GMAW as an additive solution and a milling head as extractive process, in order to increase the geometric quality of the product. Xiong et al. [8] investigated the width of the weld bead in multi-layer deposition, increasing dimensional accuracy by adjusting the wire speed through a passive vision system. In order to stabilize the process, the height of the gap between the nozzle and the surface has been investigated by Xiang and Zhang [9]. Yang et al. [10] have proposed the use of gas-welding and double-electrode (DE-GMAW) in order to minimize energy transfer to the base metal by studying the formation of the bead. To solve the disadvantages of heat accumulation, the present work shows the development of a wire and arc additive manufacturing (WAAM) system to manufacture metallic parts by combining CMT (cold metal transfer) technology patented by FRONIUS in 2005 and a numerical control milling machine. The first experiences obtained with this device are presented.

2. Equipment development

2.1. Motivation

In WAAM processes, the final product is manufactured by melting a wire using an electric arc. The dimensional accuracy of the pieces obtained by this process is in the order of +/- 1 mm, while the deposition of the material rate is much higher with respect to other metallic additive manufacturing methods. In addition, for higher working speeds it allows higher workload and a significantly lower price than other methods [5].

Fig. 1. Examples of geometries obtained by WAAM.

This system presents the advantages of a hybrid system, including a material removal process, so that the indicated deficient surface finishes can be improved. Thus, a hybrid system composed by two processes is proposed in order to obtain the required geometry: first, the 3D welding-based process as an additive technology, and second, the milling as a material removal process to improve the surface finish. Some of the main advantages of this system are the following [11]: a) more efficient use of the material; b) higher automation; c) manufacture of parts composed by different materials or parts with metals that are difficult to machine; d) higher speed than other metal additive manufacturing methods; f) direct production of metallic parts with no need of tools manufacture.

2.2. Operating principle and preliminary setup

This hybrid system works on the basis of the layers deposition of metallic wire melted by using a GMAW equipment, a currently low cost method to melt the wire. The positioning required in the deposition is obtained by means of a computerized numerical control (CNC) milling machine. When necessary, this milling machine will also do the post-machining to comply with the dimensional requirements.

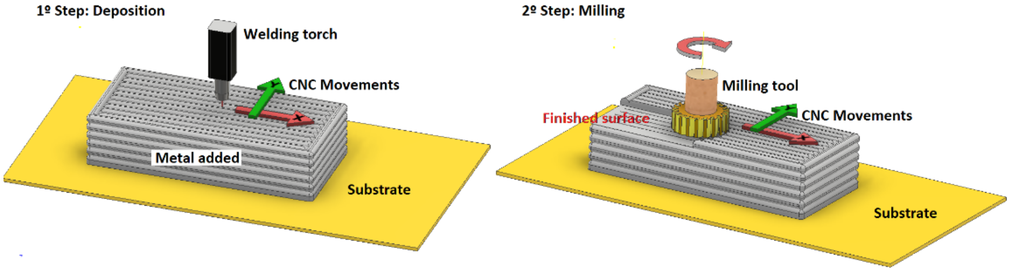

Fig. 2. Steps in the hybrid process of metal additive manufacturing combining 3D welding-based process and milling.

During deposition, the material is fed continuously from a coil and melted in a protective atmosphere of argon gas (Fig. 3). The equipment necessary to carry out the deposition process consists of an energy source, a system to feed the wire automatically, a gas source for protection and a welding gun.

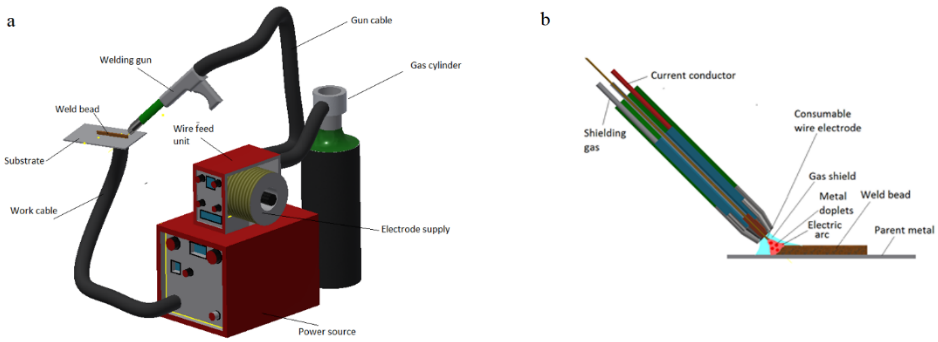

Fig. 3. (a) Equipment necessary to carry out the deposition process; (b) Sketch of deposition process based on GMAW technique.

The voltage and current intensity are the fundamental parameters to set in the GMAW equipment. An important problem derived from the use of a GMAW equipment is the great thermal input received by both the obtained part and the substrate. This excessive thermal input produces deformations in both the substrate and the weld beads, resulting in parts with dimensional tolerances in the order of +/- 1 mm, as well as surface finishes not suitable in many industrial applications. In order to overcome this important issue, the new CMT (Cold Metal Transfer) welding technique patented and manufactured by the company FRONIUS GmbH in 2002 was used [12].

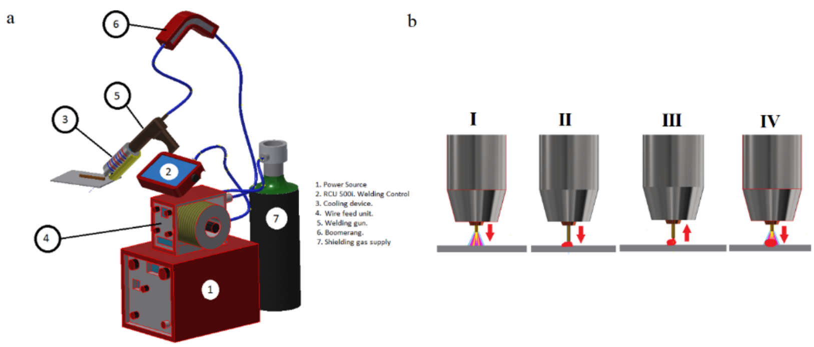

Fig. 4. (a) Description of cold metal transfer equipment [15] ; (b) Stages of CMT process.

The CMT process is basically arisen from the GMAW technology, where the intensity and voltage are controlled. The transfer of the metal to the weld pool is carried out without applying voltage or current. The electrode is constantly retracted at very short intervals, thus achieving a clean, splatter-free deposition and controlling the detachment of the drop [13]. A CMT device is shown in Fig. 4a. The process directly integrates the movement of the wire in its regulation and is composed by four phases (Fig. 4b): I) arc ignition, II) immersion in the molten bath and arc quenching, III) retraction movement in short-circuit, IV) inversion of movement.

The wire movement takes place at a very high frequency; about 70 drops of material are deposited per second. To integrate the movement of the wire, a special gun equipped with an ac-servomotor without gears is required, which provides accurate wire transport and constant clamping pressure. For the positioning of the gun, the controlled Z-axis of an Optimum BF30 Vario milling machine was used. Fig. 5 shows the integration of all elements in the additive manufacturing system developed.

Fig. 5. Setup of the integrated WAAM system in the positioning table.

As the CMT equipment can operate at intensities up to 400 A, while the motors that control the positioning table use intensities that do not exceed 5 A, it was necessary to electrically isolate both means as a safety measure. To this aim, two CELOTEX® bars were installed between the deposition and the milling tables. The evacuation of the heat produced during the deposition process is of vital importance. Two independent cooling systems have been developed: an air-cooling system for the deposition table and a hydraulic cooling system for the gun (Fig. 6). It is composed by a set of two pieces of aluminum with double helical groove through which water circulates driven by a pump to a cooler tank.

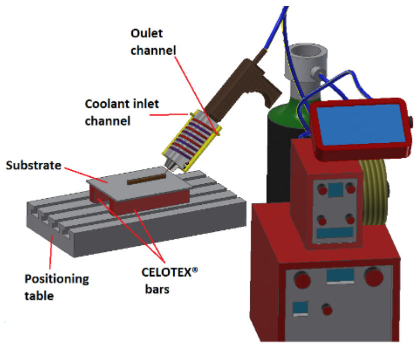

Fig. 6. Torch refrigerant assembly and electrical insulation system.

2.3. Integration of deposition and positioning equipment

As a work table, an aluminum plate is used because of its good thermal and electrical conductive properties (Fig.7). Taking into account that the torch will not have to support stress during the deposition operation, it has been decided to hold it to the same structure as the head, positioned on the Z-axis of the milling machine. In order to avoid damaging the welding torch against shocks with the deposited material, a magnetic fastening system was devised. To develop the process, the positioning and deposition equipment must be integrated, so that the desired part will be manufactured by the CNC code of the system.

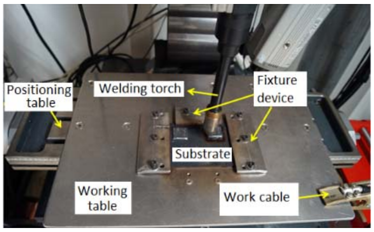

Fig. 7. Work-table.

Fig. 8. Integration cabinet.

To make this possible, an integration cabinet (Fig. 8) has been prepared where the variables are configured (the connections of the RCU remote control of the CMT equipment, the power source of the deposition equipment and of the controller of the stepper motors of the axes). The main objective is to integrate functions to turn on and turn off the electric arc, so the system can interpret them properly.

2.4. Programming strategies and trajectories

By means of a CNC code, the welding system can position the welding torch in the correct positions, and depositing the successive drops of molten metal, then the required part is obtained. The CNC code can be developed by manual programming or by CAD/CAM software. The programming language used was DIN 66025. Once obtained the code, it is introduced in NCdrive control software to be post-processed and communicated to the CNC machine.

3. Experimental methodology and results

Fig. 9 shows the steps to create a part by the hybrid additive manufacturing system proposed in this paper.

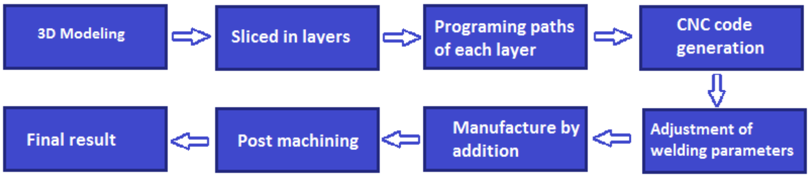

Fig. 9. Methodology followed with the hybrid additive manufacturing system.

Experiments have been carried out on a substrate of a S235 JR steel sheet of 3 mm thickness, 150 mm long and 100 mm wide. This substrate has two main functions: as a support for the deposited metal and as a heat dissipation system for the heat generated during the process by conduction transfer through the aluminum work table. The wire material is a 0.8 mm diameter mild steel wire with an AWS ER70S-6 copper coating supplied on a 15 kg coil. The properties of the base material and the deposited material are shown in Table 1.

Table 1. Properties of the substrate and the welding wire.

Mechanical properties	S235 JR	AWS ER70S-6
Density (kg/m^3)	7800	7833
Elastic limit (MPa)	235	420
Tensile strength (MPa)	370-510	6

The density of both materials is the same, while the mechanical properties are better for the case of the deposited material. A commercial gas mixture called CORGON® 15, supplied by the company LINDE, and composed of 15% CO2 and 85% Ar according to ISO 14175 is used to isolate the deposition area from the atmosphere.

3.1. First experiences

The first step was to adjust the welding parameters. These parameters depend on the thickness and height of the weld bead to be obtained and the feed rate of the CNC table. In order to identify the optimal deposition parameters and their relationships with layer height and cord width, 115 experiments were carried out on 8 different substrates. In them, different combinations of welding parameters were experimented (Table 2). Some of them are presented in Fig. 10. During this stage, different results were produced that allowed to identify the appropriate combinations of variables in order to obtain the desired results.

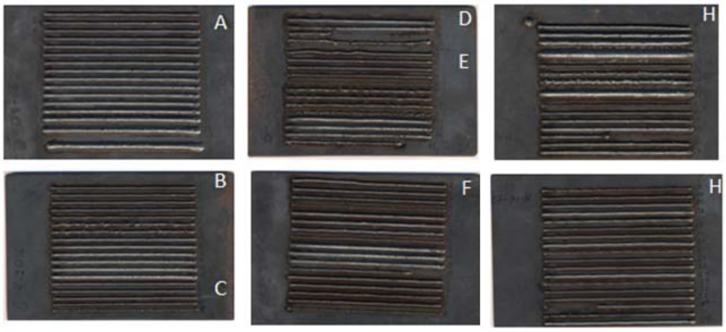

Fig. 10. Results of the metal deposition experiments.

Table 2. Properties of the substrate and the welding wire.

Series	A	B	C	D	E	F	H
Welding speed (m/s)	0.4	0.4	0.4	0.4	0.4	0.4	0.1
Intensity (A)	40-110	40, 60, 80	40, 60, 80	40, 60, 80	40, 60, 80	40, 60, 80	27-80
Arc correction (%)	0	-30, -15, 0, 15, -30	0	-30	-15	15	0
Dynamic correction	0	0	-5, -2.5, 0, 2.5, 5	-5, -2.5, 0, 2.5, 5	-5, -2.5, 0, 2.5, 5	-5, -2.5, 0, 2.5, 5	0

3.2. Analysis of results

3.2.1. Interrelation between welding parameters

In these first experiments, the relationships between the welding and positioning parameters were analysed: wire speed / intensity, wire speed / voltage, dynamic correction / voltage, dynamic correction / intensity, arc correction / voltage, arc correction / intensity. From the results, a clear direct relation between the wire feed rate and the intensity was identified, considering the strong linear correlation ($R = 0.9634$) between the studied parameters. This relationship is independent of the welding speed and the used corrections. As a result of the data obtained in the experiments, first it was analysed the behaviour of welding system with the input parameters. For this purpose, the behaviour of the voltage (V) and intensity (A) as a function of the wire feed rate (Fw) has been studied (Fig. 11). As it is a synergic process there is a slight difference between the theoretical and the real values. The first ones are programmed while the second ones are the real obtained during the process. From the analysis of the parameters, it was identified that, when high wire feed speeds are programmed; the system uses a higher intensity to melt the material transported by the rollers of the torch towards the outlet nozzle. Experimentally it has been found that, at a welding speed of 0.4 m/min, with a null value of the corrections and with an intensity over 60 A, the system is not able to reach the programmed wire feed speeds.

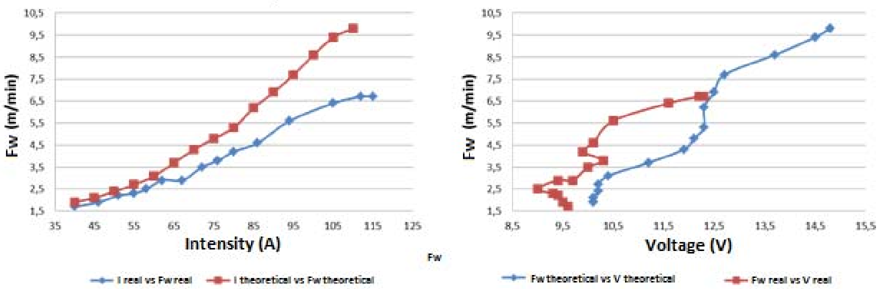

Fig. 11. Relationship between the intensity and the voltage with the wire feed speed in the experimental tests.

The relationship between the voltage and the theoretical wire speed is totally different from that obtained experimentally. In the theoretical case the voltage will increase as we increase the wire feed rate. However, in practice the voltage provided during the process varies between 9 and 12 V as a function of the wire speed, and since it does not reach the programmed values, the theoretically calculated voltages will not be reached.

3.2.2. Influence of the intensity on the bead geometry

Using a stereomicroscope Nikon SMZ800N and the NIS-Elements image processing software, the height and width of the beads were analysed according to the intensity and the welding speed. Experiments were performed by varying the welding speed between 100 and 800 mm / min and subsequently measuring the widths and heights for each intensity range (Fig. 12).

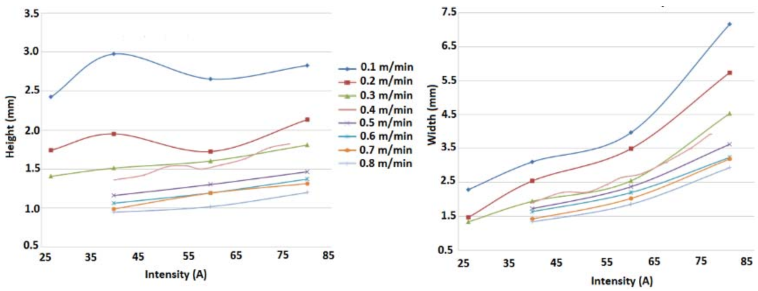

Fig. 12. Height and width of beads as a function of intensity for each welding speed.

It is observed that the height and width of the beads grows more smoothly and with a clearer trend as the intensity increases for welding speeds higher than 200 mm /min.

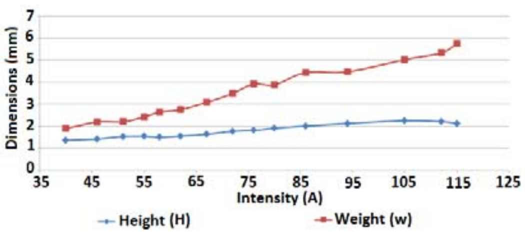

Fig. 13. Relationship between the current intensity and the height and width of the beads for a welding speed of 400 mm/min.

When the experiments were performed at a speed of 400 mm / min it can be observed that the curve present intermediate features that are very attractive, considering that they offer a good penetration and a relationship between height and width of the bead that can be very interesting to make walls. The results observed in Fig. 13 show the relationships between the intensity and the width and height of the beads for the optimum deposition rate (400 mm / min). Whenever the wire feed rate increases, the amount of material deposited and the bead dimensions increase. In addition, as the height grows very smoothly (stabilizing from 85 A), the width has to grow much more steeply because of the greater amount of material supplied with the increased intensity.

4. Conclusions

A low cost metal additive manufacturing system has been developed compared to other laser or electron beam based technologies by integrating a CMT welding equipment and a CNC milling machine. This hybrid manufacturing system allows the manufacture of metallic elements regardless of their geometric shape and it presents the advantages to reduce the heat accumulation originated using a conventional GMAW equipment and the possibility to implement surface finish operations by milling after the additive process. In the paper the integration of the different parts of the equipment is presented. Previous experimentation has shown that the optimum welding speed is 400 mm / m for the used material to be deposited, and that the welding intensity will condition the dimensions of the manufactured beads. Welding speeds below 400mm / min take up too much time for the manufacture of test pieces, while those above this value reduce the dimensional accuracy and surface quality of the results. In this way, the geometric results obtained at this speed show that there is an almost linear relationship between the intensity and the height and width of the bead in which a 100% increase of the intensity supposes a growth of 35% of the height and 106% of the width.

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