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COBEM2021-1752 WELDING BEADS OVERLAPPING ALGORITHM DEDICATED TO WAAM

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***Abstract**: The wire and arc additive manufacturing (WAAM) is an additive manufacturing route in which the part is fabricated by layers composed by multiple arc weld beads side-by-side. One of the current challenges for the actual implementation of this DED-type additive manufacturing, with its full capabilities, to revolutionize state-of-the-art manufacturing is the geometric prediction of the layers during deposition. One of the alternatives that help in this prediction is the use of several coupled optical sensors that read the conditions online. However, this method can have disadvantages such as a decrease in the degrees of orientation material deposition freedom as well as an increase in the capital cost of equipment. Another way to predict layer geometry is by creating a geometric results database and developing mathematical equations to represent the most interesting depositing conditions and use it to simulate and predict future deposits geometries with a dedicated algorithm integrated in the deposition trajectory generation CAE software. This paper demonstrates a methodology for creating this database from hands-on experiments to optimize weld bead overlap based on measuring and comparing overlapped deposition areas between weld beads and their center points. The generated algorithm calculates the optimal offset between passes to result in a layer with homogeneous height. The algorithm was fed with data obtained in the single weld bead deposition, subsequently using the algorithm was calculated the ideal distance in function of the overlap area. In addition, it was variated adding and decreasing 10% in the calculated distante in order to evaluate the algorithm precision and accuracy. The overlap beads were built with a CMT power source with a ER70S6 wire feedstock under conventional deposition conditions. The results showed that the algorithm is a reliable approximation of the real geometry, presenting low error. With the second-degree equation used as model it was possible to create a method to define the optimal overlap condition and mitigate welding defects like under cut, lack of fusion and other common to these depositions.*

***Keywords**: Additive manufacturing; Simulation; WAAM; Directed Energy Deposition; MIG; TIG.*

1. INTRODUCTION

Introduction

Additive Manufacturing (AM) has made possible to manufacture objects with complex shapes using a layer-by-layer deposition of a defined feedstock material, which when compared to starting with over dimensioned raw block of material, presents a higher buy-to-fly ratio, thus making viable the usage of this process to build titanium and nickel components to industries such as the aerospace [1]. Through all the different techniques used for AM, the Direct Energy Deposit (DED) excels between the other ones due to its effectiveness in building medium complexity metallic materials components, due to its substantially higher deposition rates [2], and it has a higher material efficiency in the case of the DED wire feedstock methods [1].

Wire Arc Additive Manufacturing (WAAM) has been widely explored because of its advantages such as being able to construct large metallic components, offering a low system cost and a decreased material cost of wire in comparison to powder[3], thus corroborating to Ding, et al., [5]. The more common welding process used in WAAM are the Gas

Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), and Gas Metal Arc Welding (GMAW), which the last one presents the benefit of having a simplified tool path programming for the construction of complex components and structures. Modified GMAW process, called Cold Metal Transfer (CMT), has enabled welding methods with lower heat input and less splatter [3].

This variant of GMAW bases its mechanism on a controlled dip transfer mode mechanism, this is possible due to the incorporation of the motion from the wire into the electrical process control. This system works by synchronizing the wire feedstock system with a high speed digital control that senses the arc length, short circuiting phase, and thermal input transferred to the weld pool. It occurs that, when the wire moves forward and dips the molten pool, the digital control senses the drop of the voltage to nearly zero value, and that a short circuiting phase occurs, simultaneously with a decrease of the current. Then the motion of the wire is reversed, this assists in the breaking of the liquid bridge, and thus the droplet detachment takes place. This leads to the metal transfer occurring by surface tension at nearly zero current. After this the arc is reignited, and the process restarts [4].

One of the main challenges that WAAM faces during the process of building components is the necessity of an algorithm responsible for the creation and construction of the trajectory patterns. Uneven weld bead geometry may lead to the accumulation of errors in the vertical direction after the deposition of several layers [5], which when is not in consonance with the thermal gradient, the heat input, and many others parameters involved during the welding process, can lead to huge effects in the geometry of the welding bead. When projecting structures where the welding beads are overlapping each other, the necessity for the development of tool paths that can predict the width, and height of the welding bead, and with this, guarantee a trajectory pattern that creates a structure with most of its surface regular.

It is important to understand the mechanisms that are involved in the formation and variation of the welding bead geometry, for the development and planning of the trajectory that the tool path must have. Thus leads to the fact that experimentation is a vital part for the development of such an algorithm. Especially because the trajectory planned doesn't always represent the real behavior of a system composed of multi welding beads in a vertical/horizontal direction. This makes necessary the comprehension of these conditions so it can help to better programm the desired trajectories.

In this logic, mathematical modeling shows itself as an alternative for defining optimal overlap conditions, Ding, et al., [6] present curve fitting methods based on the width and height of the weld beads. Experimental results show that the parabola and cosine functions accurately represent the cross-section profile of a weld bead. Furthermore, for the horizontal overlap, the authors taking into consideration the behavior observed experimentally, verified a tangency effect of the overlap seam's crest along the base bead and a relationship between the overlap areas, where the distance between the centers of the beads must have a distance that corresponds to a condition where the overlap area is equal or very close to the valley area (bead crest). Figure 1 graphically illustrates the described method.

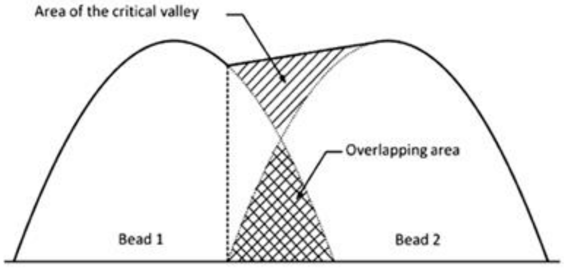

Figure 1- Schematic of an overlapped welding bead system [6].

Thus, Ding, et al., [6] conclude that the use of the method considering a representation based on second degree functions along with the tangential behavior accurately represents the typical geometric profile and the ideal distance between the beads. However, if the same method is applied, but without using the tangent, the error is small enough to ignore. In this sense, any value between 67% and 73% of overlap is already sufficient for an adequate overlap, provided that the bead has a wettability greater than 90° and the geometric conditions of the deposited bead are kept the same along the longitudinal section.

Analogously, Suryakumara, et al., [8] and Xiong, et al., [9, 10] also present the modeling of the horizontal overlap of multiple beads, based on second degree functions (parabolas) and cosine function, where the best performance results were those with the second degree function corroborating with Ding, et al., [6]. However, unlike Ding, et al., [5], the authors focus on keeping the area equal between the overlap and the valley without taking into consideration the slope of the overlap bead. However, practical results for both Suryakumara, et al., [8] and Xiong, et al., [9, 10] show a suitable overlap profile (distance among centers) from 65% to 70% of the weld bead base width.

In continuity, Ding, et al., [7] presents the concatenation of the trajectory optimization method allied to the tangential overlap method. In this work aiming to reduce over metal, as well as unnecessary paths and allied to minimum overlap, the authors performed the analysis of thin-wall deposition, horizontally overlapping two beads. For comparison, a conventional path creation method was used, which is quite efficient for single contour patterns (single bead). This method creates contour patterns from outside to inside, taking the perimeter into consideration. When building compound trajectories (with overlapping), the method ends up offsetting the boundary curves recursively towards the inside, not respecting the distance between the paths, thus leaving internal gaps that can generate unfilled problems, for example. The results presented show a significant difference between the samples, where it is possible to verify in Figure 2c a complete filling in relation to another method in Figure 2d that presented a lack of fusion between the overlaps. However, the conventional method could have been corrected if the welding process had used a higher deposition rate or lower welding speed to increase the deposit width. In this sense, it can be reaffirmed that the path creation method should be in line with the welding process.

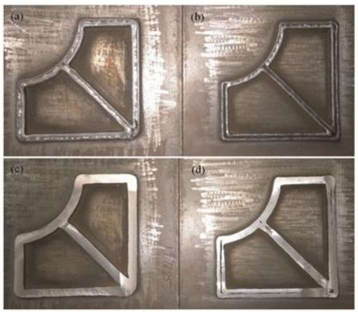

Figure 2 - Experimental comparison between the described methods, where: a) Deposition using optimized method; b) Deposition using conventional method; c) Machined surface of optimized method; d) Machined surface of conventional method [7].

In parallel, Li, et al., [11] developed a mathematical model of horizontal overlap taking the beads scattering into consideration, which shifts the centroid of the overlapped bead due to the dynamics of anchoring and solidification of the melt pool during deposition near or over another bead. The method employed was to empirically correct an existing model. The results of Li, et al., [11] corroborate with the tangential method of Ding, et al., [6] where it was found that overlap values of 73% of the base deposit width is sufficient for an overlap with low defect probability. In practice, using the proposed model, a reduction in lack of fusion problems was found, as well as slight attenuation in the surface profile of the overlaps, as illustrated in Figure 3.

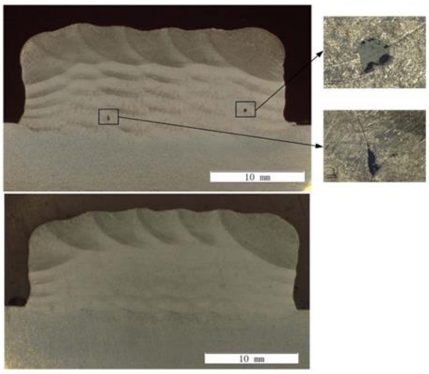

Figure 3 - Cross section of manufactured specimens using a model without considering scattering and considering scattering, optimized method, adapted from Li, et al., [11].

It has been observed so far that the process of planning and creating an overlap concatenated to the welding process is not trivial, due to the infinite possibilities of relationships and interactions between welding parameters and paths. However, it is possible to observe a pattern among the best overlap conditions, where in the verified methods values between centers of 63% to 73% of the base weld bead width is sufficient for a defect-free overlap.

Aiming to test a simple method of simulation without taking into account complex algebraic techniques. In this sense, this article was developed to present a method based on second degree functions considering the equality between the overlap area and the valley area formed by the intersection of the curves created from the width and height of the base weld bead. To test and validate the method, practical experiments were performed, and further tests adding and subtracting 10% of the simulated value were also performed. In order to evaluate the efficiency and precision of the method and the effect of varying the distance between centers on the quality of the weld beads made.

2. EXPERIMENTAL PROCEDURE

An algorithm based on a second-degree equation was developed to optimize overlapping among weld beads dedicated to WAAM. Matlab was used for implementation and virtual tests. Initially two inputs are necessary, height and width of the weld bead.

From these inputs, assuming that the weld bead width represents the intersection of the abscissa axis and the height represents the maximum value of the parabola, a regression analysis is performed and a quadratic function is created. After that, a second equal function is created, but with a x-axis offset. The offset is done as a function of overlap area between the curves, which must be equal for both the valley area and the overlap area, so the algorithm tests n distances until the difference between the areas (valley and overlap) has the lowest error. From that conditional loop, a center distance among the maximum values of the parabolas is defined. Figure 4 shows schematically the overlapping structure.

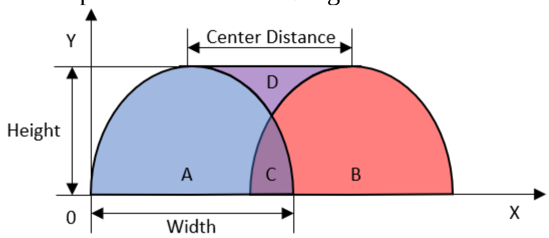

Figure 4 - Schematic overlapping structure. A - Base weld bead; B - Overlap weld bead; C - Overlap area; D - Valley area.

In order to clarify the understatement about algorithm structure the fluxogram described in Figure 5 was elaborated.

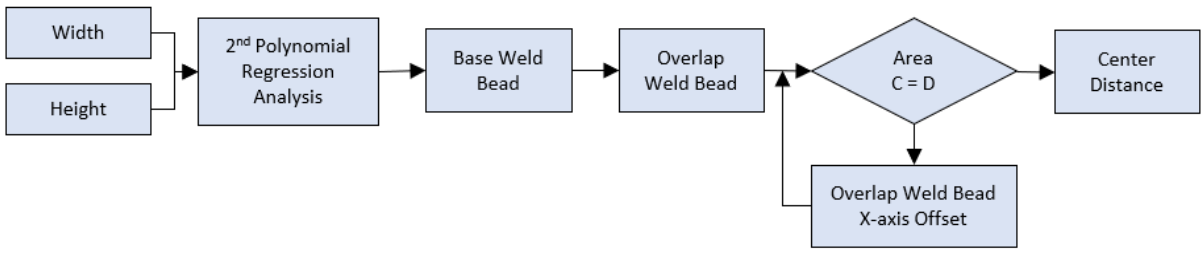

Figure 5 - Algorithm fluxogram.

For practical tests an ASTM A36 carbon steel plates of 9,53 x 37,50 x 250 mm were used as substrate in the experiment. For the WAAM technique it used an anthropomorphic robot with 6 axes of motion from Motoman Yaskawa model HP20D as a motion system, and a CMT Advanced 4000R with an interface configuration module RCU5000i from Fronius as a power source. For all depositions was used a synergetic G3Si1 – CMT 1220 (V2.3.8.4) program, the wire feed speed was 5.0 m/min, welding speed 30 cm/min, contact tip-to-work distance 15 mm and gas flow 13 L/min. The wire feedstock used was a ER70S6 of 1.2 mm diameter and 75% Ar + 25% CO_2 (C25) as gas mixture.

Initially, it was realized as single bead welds in order to preliminary characterize the weld bead geometrical profile as height, width and surface appearance by means of macrographic analysis. From this geometric information, as well as input data in overlapping algorithm and center distance calculation was performed overlap weld beads to verify the accuracy of the simulation method. In order to explore center distance effects overlap quality, experiments changing the center distance were realized. The first experiment was to decrease the center distance, i.e. through the simulated center distance value was decreased 10% of the nominal value. The second experiment was against the first, i.e., increasing 10% of the center distance. Figure 6 shows schematically the experimental procedure.

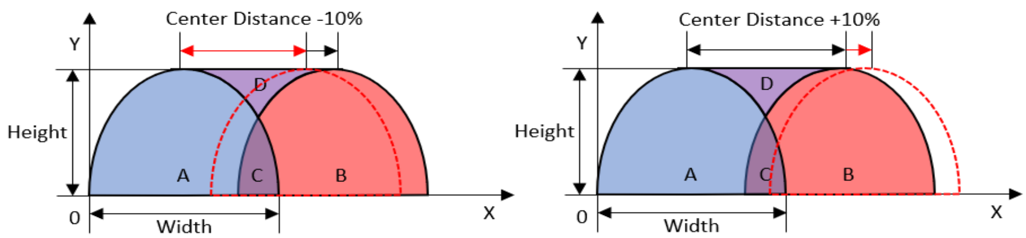

Figure 6 - Schematic overlapping experimental procedure distance variation.

By means of the overlapping experiments, macrographics was realized to observe weld defect incidences. In addition, a measurement process was performed to verify the influence of each center distance in material usage.

3. RESULTS AND DISCUSSIONS

The geometric profile obtained from the single weld bead deposition shows a regular profile with width of 7.4 mm and 3.04 mm height. Using this dimension on the developed algorithm generated the function that represents the cross-section weld profile which is described in the Figure 7.

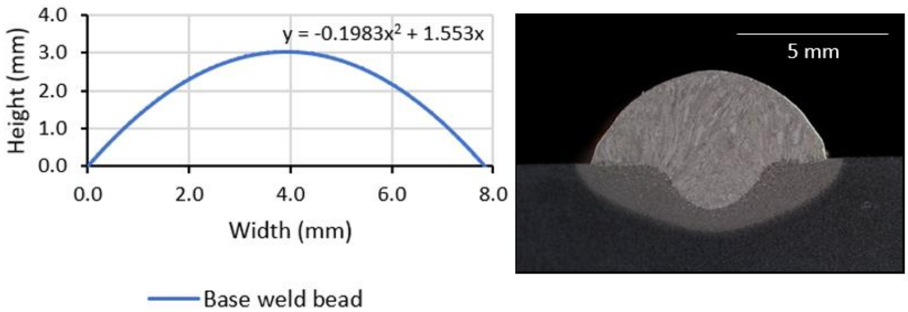

Figure 7 - Function obtained based on the cross-section profile of the weld bead.

From this profile the overlap function was generated and the offset (center distance) was calculated. The value obtained with 1.2% error was 5.22 mm. Both function and overlapping profile are described in Figure 8. It was noted that the total width between the simulated and realized overlaps was 0.25 mm, about 2%, where it was read in the simulation a value of 13 mm and measured a value of 12.75 mm. The average height measure was 3.05 mm, with variation of 0.2 mm among beads, very similar to base weld bead. These results show a good accuracy of the algorithm corroborating with Ding et al. [6, 7] who also described a similar method with second degree functions. However, it's possible to observe a lack of fusion in the weld bead interface, this problem can be in function of the center distance.

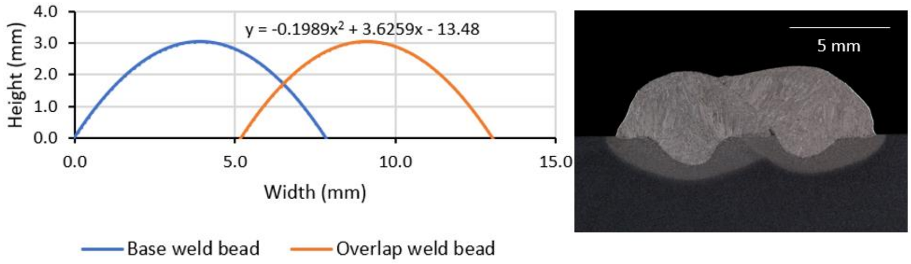

Figure 8 - Overlapping function obtained and overlap weld bead deposited.

Decreasing the overlap offset in 10% (about 4.70 mm) was possible to mitigate the lack of fusion observed in the previous experiment as shown in Figure 9. The measure from the cross-section profile noted a variation of 0.9 mm in the overlap weld bead height. However, the width presented a difference between the simulated and the realized of less than 1%, where it was read in the simulation a value of 12.5 mm and measured a value of 12.48 mm, showing once again good precision in the calculation.

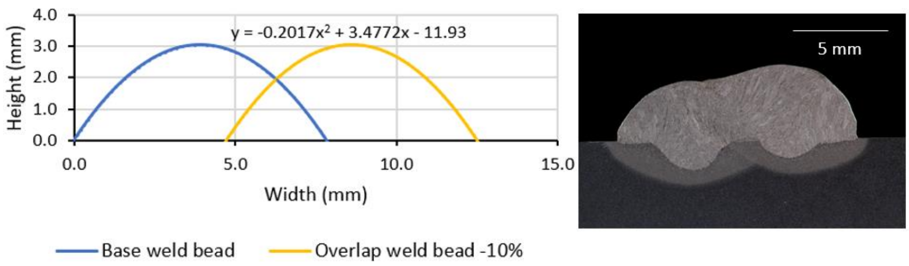

Figure 9 - Overlapping function obtained for -10% offset and overlap weld bead deposited.

Increasing the overlap offset in 10% (about 5.74 mm), illustrate in Figure 10, noted again the lack of fusion like the first experiment, this result shows a relationship between the increase of the distance and the formation of this defect, possibly influenced by the way of anchoring of the weld pool of the overlapped bead on the base bead. The measure from the cross-section profile noted a variation of 0.3 mm in the overlap weld bead height. The width measured was 13.35 mm while the simulated value was 13.30 mm, less than 1% difference.

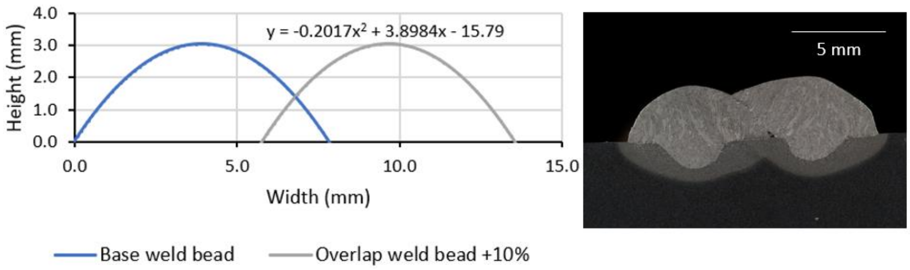

Figure 10 - Overlapping function obtained for +10% offset and overlap weld bead deposited.

Analyzing the proposed method was verified a good approximation among simulation and performed experiments, with error less than 1% for width and 2% for height. However, for a good weld quality is necessary a reduction of 10% in the center distance.

In general, the optimal center distance calculated using the propose method corroborate with Ding et al., [6, 7], Suryakumara, et al., [8] and Xiong, et al., [9, 10] that also found center distances values around 67% to 73% of the base weld bead width. This fact shows that it is possible to accurately and precisely use second degree functions to represent weld seams, even though that in some real cases the overlap bead height may vary somewhat.

In addition, to verify the accuracy of overlap, three overlapping weld beads were deposited as described in Figure 11. The results corroborate with the previous experiments, where for the case A and C was notice lack of fusion in both, which was performed with nominal calculated distance (area valley equal overlap area) and nominal distance plus 10%. In Case B, using the nominal distance less 10%, it was not verified the lack of fusion. Observing the height deviation was noted for all cases the same value, about 15% or 0.45 mm. However, in case A and C a higher valley is seen in the top of the weld bead, which is not verified in Case B.

Figure 11 - Experiments for three overlap weld beads. A - Nominal center calculated distance; B - Nominal center distance less 10%; C - Nominal center distance plus 10%.

4. CONCLUSION

Based on the results presented, it is possible to draw technological conclusions on the side of performance and comparison among different overlapping profiles, conclude that:

- It is possible to represent weld bead profiles with accuracy, less than 2% error, using second degree functions;
- The overlapping method considering the valley area and overlap area is functional and represents the real cases;
- Lack of fusion is increased as a function of the center distance growth. It was evaluated that decreasing the center distance for values less than 10% of the nominal calculated distance mitigated this defect (lack of fusion) without significantly geometrical variation.
- The center distante among overlap beads can be from 60% to 73% of the weld bead base width, corroborating with the related studies evaluated in this paper. However, the present study evaluated that the great center distance is about 60% of the weld bead width, which decreases defects like lack of fusion.

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