Study on formation of aluminum alloy thin wall produced with WAAM method under various thermal conditions

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Abstract. The study reveals some formation aspects of a thin walls made by WAAM technology. The series of experiments about thin wall deposition in a various thermal condition was carried out. Temperature field finite element model was developed and solved under the giving conditions. Experimental results were treated after metallographic analysis, functional dependences of the width and height of the deposited layer by the temperature of the previous layer were constructed. In a range of 30-300°C sublayer temperature, layer height and width values show linear functional dependencies by sublayer temperature.

1. Introduction

WAAM (Wire Arc Additive Manufacturing) is a method of producing parts layer-by-layer by metal deposition using filler material in a form of welding wire. Both electric and compressed electric arc can be used as a heat source for this process. One of the key features in this technology is an ability to use standard welding equipment, such as MIG/MAG welding power source. In most of the cases WAAM is used to produce large parts from aluminum or titanium alloys.

WAAM has several advantages over the other metal 3D printing technologies. In comparison with selective laser sintering (SLM) method, this technology has much higher productivity rate and can significantly expands size of the parts to be printed\textsuperscript{[1]}. Compared to direct energy deposition (DED), WAAM allow using welding wire instead of metal powder as a deposit material, which led to easier material quality control and also benefited in material availability and cost\textsuperscript{[2],[3]}. Nowadays a lot of studies are devoted to WAAM implementation in various industries like shipbuilding or aerospace\textsuperscript{[4],[5],[6]}. The main focus most of researcher teams in this process are pulsed arc technologies, like cold metal transfer (CMT) method\textsuperscript{[7],[8],[9]}. CMT is a pulsed short-circuit welding technology developed by Fronius Inc. (Austria), which ensures deposition with controlled droplet transfer by a special welding parameters pattern using feedbacks, the droplet transfer occurs at 50-60 Hz frequency\textsuperscript{[10]}. In addition, CMT provides a significantly lower heat input in base metal compare to conventional MIG\textbackslash MAG welding methods and also has minimal spatter during the deposition\textsuperscript{[11],[12]}. Furthermore, CMT can significantly increase stability of WAAM process and ensure the deposited material mechanical properties to be close to annealed state\textsuperscript{[13],[14]}. However, during the deposition with constant process parameters (such as welding current, arc voltage, travel speed and wire feed speed) various layers formation can be observed, particularly in...
width and height values (fig. 1). The main cause of this phenomena is the thermal saturation of already completed previous layers. The new layer is depositing on previous preheated layer, which changes the spreading and formation condition of the material. This condition state can be described by the temperature of previous layer, i.e. sublayer temperature.

Finding influence degree of sublayer temperature on layers geometry is a very important step to ensure steady printed wall formation, especially for so-called thin walls. Thin walls (fig. 2 c) are such constructs that are made without welding torch oscillation (fig. 2 a) or multilayer deposition (fig. 2 b).

Therefore, the aim of this study is to determine the influence of temperature conditions on formation of a thin aluminum alloy wall and its shape parameters.

![Figure 1. Layer formation under different thermal conditions: a - hot sublayer; b - cold sublayer](image)

![Figure 2. Wall deposition patterns: a – wall with weaving; b – multilayer wall; c – thin wall; TS – travel speed of the heat source](image)

2. **Materials and methods**

In this study, the formation of a thin wall made by WAAM method using CMT technology was investigated depending on the temperature of the sublayer. Fronius TPSi 500 CMT welding machine was used as an energy source. Motoman MA2010 industrial robot represented the welding torch moving mechanism, ER5556A welding wire and argon shielding gas were user as consumables. The deposition was occurred from substrate plate of ER5356 aluminum alloy, 6x300x140 mm in dimensions.
During the experiment, the robot moved with constant speed along a linear path, rising through each layer for equal distance to maintain a constant electrode extension length. After each wall was finished, the reform was cooled to room temperature before proceeding to the next experiment.

Since the process of deposition is characterized by formation defects the starting and finishing areas, direction of the deposition pattern was alternating, as it is shown in Figure 3. Thus, these formation defects were compensated by each other during the deposition of the next layers.

![Travelling direction](Layer 4 → Layer 1)

**Figure 3.** Deposition pattern

To simulate different sublayer temperature effect during the experiment, the time between deposition passes (layers) was varied, thereby changing the sublayer temperature. Thus, with different times between layers, the previous layer cools to different temperature from one experimental sample to another, but within particular sample each layer cools the same time. In order to reduce the substrate influence on the heat transfer, the first two layers in each sample were deposite with the same process parameters regardless of the sample number and were not considered in further analysis. 7 samples in total with 30 layers each were performed on different welding parameters, presented in table 1 and table 2.

| Parameter                          | Value   |
|-----------------------------------|---------|
| Wall length                       | 140 mm  |
| Total layers amount               | 30      |
| Travel speed, layer #1            | 0.24 m/min |
| Heat input, layer #1              | 1.625 kW |
| Travel speed, layer #2            | 0.36 m/min |
| Heat input, layer #2              | 1.1 kW   |
| Travel speed, all other layers    | 0.6 m/min |
| Heat input, all other layers      | 0.67 kW  |

**Table 1.** Deposition parameters

| Sample # | Pause time between layers #3-30, sec |
|----------|-------------------------------------|
| 1        | 2                                   |
| 2        | 7                                   |
| 3        | 12                                  |
| 4        | 30                                  |
| 5        | 60                                  |
| 6        | 120                                 |
| 7        | 240                                 |

**Table 2.** Pause time between layers
After the experiment, the samples were cut out according to the scheme shown in Figure 4. Total of 28 cutouts were obtained to collect geometric parameters of the layers. Images were obtained from each cutout using optical microscopy, then were analyzed in the ImageJ image processing software. Height was calculated for each image by division of total height value (except first two) by the number of layers.

Based on the results of measuring shapes geometry, a finite element model was made in ANSYS software, simulating the temperature field during walls processing. In the calculation, the sublayer temperature in a point located directly below the heat source at a time corresponding to its passage through the center of the sample was taken into account. Normally distributed Gaussian source was used as a heat source model. Verification of the model was carried out using thermocouples with NI 9212 module (manufactured by National Instruments, USA, measurement accuracy of 0.71 °C) as a controller. Thermophysical properties of the material were set from the material library of ANSYS simulation software.

![Cutout scheme for geometrical parameters analysis](image1.png)

**Figure 4.** Cutout scheme for geometrical parameters analysis

![Sublayer temperature by pause between layers](image2.png)

**Figure 5.** Results of numeric modelling: sublayer temperature by pause between layers
According to the results of a numerical experiment, the dependence of the sublayer temperature for a point in the center of the sample by the time between the layers was obtained as shown in Figure 5.

3. Results and discussion

The results of layers geometric parameters measurements are shown in Table 3 and in Figures 6 and 7.

| Sample # | Pause between layers, sec | Sublayer temperature, °C | Mean height of a single layer, mm | Mean height measurements standard deviation, % | Mean width of a single layer, mm | Mean width measurements standard deviation, % |
|----------|---------------------------|--------------------------|-----------------------------------|-----------------------------------------------|----------------------------------|-----------------------------------------------|
| 1        | 2                         | 334                      | 1.51                              | 1.02                                          | 5.98                             | 2.85                                          |
| 2        | 7                         | 270                      | 1.60                              | 1.42                                          | 5.46                             | 0.55                                          |
| 3        | 12                        | 212                      | 1.65                              | 0.98                                          | 5.37                             | 1.79                                          |
| 4        | 30                        | 120                      | 1.78                              | 0.29                                          | 4.36                             | 12.43                                         |
| 5        | 60                        | 71                       | 1.83                              | 0.45                                          | 4.48                             | 2.38                                          |
| 6        | 120                       | 44                       | 1.86                              | 0.34                                          | 4.30                             | 0.81                                          |
| 7        | 240                       | 29                       | 1.89                              | 0.53                                          | 4.12                             | 6.781                                         |

**Figure 6.** Measurements results: layer height (a) and width (b) dependency by pause between layers

Based on the obtained data processing, linear dependencies in a form of $f(x) = ax + b$ were constructed using the least squares method. The coefficients are given in table 4.

|            | a     | b     |
|------------|-------|-------|
| Layer height | -0.0012 | 1.9229 |
| Layer Width  | 0.0059  | -3.9572 |
Thus, the dependences of the height and width of each layer are established depending on the temperature of the sublayer, which must be taken into account when developing technology for printing any large parts. Predictive modeling of the process can help forecast the real geometry of the part, but it will take considerable time and require significant calculating resources. Contactless tracking methods seem to be the most convenient way of monitoring natural sublayer temperature. Their implementation will allow real-time data analysis and, if there is a feedback process control system, real-time adjustment of the process parameters in such a way as to obtain the desired shape of the part. However, it is necessary to verify the obtained dependencies when changing the general parameters of the process during real-time control.

4. Conclusions
1. The sublayer temperature has a significant effect on the geometry of each layer during WAAM process.
2. It can be assumed that in the temperature range from 30 to 300 °C for certain deposition parameters, the dependence of the width and height by the temperature of the sublayer is linear.
3. The use of a real-time temperature monitoring system and organize feedbacks for main parameters of the deposition process might ensure stability of the thin wall geometry.

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