Welding parameters effect and optimization on bead geometry during arc additive manufacturing

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Abstract. This paper discusses the effect of parameters in MIG based wire and arc additive manufacturing (WAAM) using stainless-steel wire and Q235 as substrate. The response surface methodology (RSM) and ANOVA were used to determine the effects of current, voltage, and welding velocity on the responses of bead height and width. It was found that voltage had the largest effect on the bead width, followed by welding velocity and current. But on the bead height, welding velocity is the most significant parameter, followed by current and voltage. The genetic algorithm (GA) was utilized to optimize the parameters to obtain the maximum ratio of weld bead width to height for multi-layer single-pass arc additive deposition.

1. Introduction
The gas metal arc welding (GMAW)-based arc additive manufacturing is a promising technique that uses the arc as the heat source to accumulate layer by layer through the droplet transfer mode \cite{1,2}. Compared to selective laser melting (SLM), the shaping precision and complexity of WAAM are much lower. However, because of its advantages in improving design flexibility, higher deposition rates, and less cost of materials \cite{3}, WAAM is considered a preferable method as a deposition approach to fabricate thin-walled parts \cite{4}. As a basic unit of WAAM, the geometric size of weld bead can directly affect the quality of multi-layer arc additive deposition, which can be controlled by a number of welding parameters. Therefore, it is essential to set up the proper welding process parameters.

During the manufacturing process, the excessive thermal cycling can be observed as being repeatedly heated in the same place, which is the basic cause of complex thermal stress \cite{5}. In order to reduce the effect of thermal stress on bead formation, it is necessary to add appropriate cooling at the end of each layer deposited \cite{6}. Even so, multi-layer deposition work can take many times longer to find the optimal process parameters than conventional surfacing. So, it is a key challenge to determine the optimal
process parameters of single weld bead before multi-layer stacking. Ding and Li built a numerical model of weld bead and the principle of superposition to fabricate a multi-bead with a better geometry accuracy in WAAM, it is beneficial to multi-layer stacking when the ration of bead width and height is relatively large [7,8]. By comparing the RSM and GA in GMAW parameters optimization, Correia proposed that the problem with the RSM technique in irregular regions is that its power in finding the optimum relies greatly in building good models, with linear regression, for the responses; the optimization by GA technique requires a good setting of its own parameters, such as population size, number of generations [9].

The above researches show that the efficiency of multi-layer WAAM deposition can be improved by optimizing the process parameters of single-layer weld bead. This paper aims to explore the effects of input parameters (current, voltage, and welding velocity) on weld beam formation, to find a set of process parameters suitable for multi-layer single-pass deposition based on GMAW additive manufacturing. Through RSM experiments, quadratic regression equations between weld bead geometry and input parameters were obtained, which could be used in the objective function of GA to find the process parameters of the maximum ratio of bead width to height. Multi-layer single-pass arc additive manufacturing was carried out by the optimum parameters and nice bead formation was obtained.

2. Materials and methods
Experiments were conducted on automation MAG machine attached with a six-axis controlled work station shown in Figure 1, the deposition torch was held stationary in a fixed angle of 45. The length of feed wire (FW) is 10 mm and the wire to distance (WTD) is 3 mm. The substrate materials were used Q235 carbon structural steel with the dimensions of 200 mm × 100 mm × 10 mm. A manufacturing wire with a 1.0 mm diameter was ER308. A shielding gas (98% volume fraction of argon and 2% volume fraction of CO2) with a constant flow rate of 30 L/min was utilized to protect the molten pool.

RSM is an effective empirical approach using polynomials as local approximations to the true input/output relationship. Input parameters (current, voltage, and welding velocity) are proved to be the most significant influence factors on weld bead formation. Parameter ranges were determined by single factor experiment. Then the levels of the parameters chosen as current 130 to 190 A, voltage 18 to 24 V and welding velocity 8 to 14 mm/s. A central composite design with three factors and two responses (bead width and height) was used to carry out the experiments. The response function in terms of process variables can be expressed by

\[ W_{o}H = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \]  

(1)
Parameters’ optimization procedure by genetic algorithm is shown in Figure 2. GA is a set of computer procedures of search and optimization based on the concept of the mechanics of natural selection and genetics, which operates over a set of individuals represented by a binary string comprised between 0 and 1. By means of mathematics and computer simulation, the algorithm converts the solving process into the process of crossover and mutation of chromosome genes similar to biological evolution. In order to obtain the maximum ratio of the bead width to height, the objective function of the GA can be expressed by

\[ \text{aimFunc}(I,U,V) = \frac{W(I,U,V)}{H(I,U,V)} \]  

(2)

Where the \( W(I,U,V) \) and \( H(I,U,V) \) can be obtained by RSM expressed by Eq. (1). And the fitness function can be expressed as

\[ \text{Fitness}_i = 2 - SP + 2(SP - 1) \left( \frac{i-1}{N_{\text{ind}} - 1} \right) \]  

(3)

The individual value range in the GA is the same as that in the above RSM. The number of individuals in the initial population is 30, and the maximum genetic algebra is 50. The selection method of random sampling is adopted to carry out two-point cross recombination by using binary coding method, and the cross-recombination probability is 0.9. The probability of mutation is related to the length of chromosomes, which is set as 1/52 in this paper.

![Figure 2 Parameters optimization procedure by genetic algorithm.](image)
Table 1  Experiment parameters and response values of RSM

| No. | Current (I/A) | Voltage (U/V) | Welding velocity (V/mm-s) | Width (mm) | Height (mm) |
|-----|---------------|---------------|----------------------------|------------|-------------|
| 1   | 130.0         | 18.00         | 8.00                       | 5.026      | 2.664       |
| 2   | 190.0         | 18.00         | 8.00                       | 6.226      | 3.218       |
| 3   | 130.0         | 24.00         | 8.00                       | 6.542      | 2.642       |
| 4   | 190.0         | 24.00         | 8.00                       | 7.6        | 3.168       |
| 5   | 130.0         | 18.00         | 14.00                      | 3.556      | 2.112       |
| 6   | 190.0         | 18.00         | 14.00                      | 4.486      | 1.88        |
| 7   | 130.0         | 24.00         | 14.00                      | 4.464      | 2.606       |
| 8   | 190.0         | 24.00         | 14.00                      | 6.28       | 2.368       |
| 9   | 109.6         | 21.00         | 11.00                      | 4.002      | 2.032       |
| 10  | 210.4         | 21.00         | 11.00                      | 6.354      | 2.812       |
| 11  | 160.0         | 15.96         | 11.00                      | 4.616      | 2.708       |
| 12  | 160.0         | 26.04         | 11.00                      | 7.696      | 2.054       |
| 13  | 160.0         | 21.00         | 5.96                       | 7.046      | 3.326       |
| 14  | 160.0         | 21.00         | 16.04                      | 5.22       | 1.92        |
| 15  | 160.0         | 21.00         | 11.00                      | 5.44       | 2.638       |
| 16  | 160.0         | 21.00         | 11.00                      | 5.312      | 2.604       |
| 17  | 160.0         | 21.00         | 11.00                      | 5.03       | 2.64        |
| 18  | 160.0         | 21.00         | 11.00                      | 5.334      | 2.528       |
| 19  | 160.0         | 21.00         | 11.00                      | 5.668      | 2.576       |
| 20  | 160.0         | 21.00         | 11.00                      | 5.664      | 2.568       |

3. RESULTS AND DISCUSSION

3.1. ANOVA analysis
RSM experiment parameters and their response values are shown in Table 1. According the Eq. (1), the Quadratic regression equation about the bead width and height can be obtained as follow:

\[ W = 10.9187 + 0.045982 \times I - 0.78775 \times U - 0.74875 \times V - 1.6647 \times 10^{-4} I^2 \]  

\[ H = -0.3055 + 0.0422 \times I + 0.0783 \times U - 0.1725 \times V + 0.0146 \times U \times V - 4.0182 \times 10^{-5} \times I^2 \]  

By the method of ANOVA analysis, the process parameters effect on weld bead width is shown in Figure 3. Figure 3 (a) shows that voltage is the most significant factor affecting the width of weld bead. As the voltage increase, the arc power increases the arc length and the distribution radius increases, so the melting depth decreases slightly and the melting width increases, leading to an increase in bead width. But the welding velocity has the opposite effect on the bead height. Current has the least effect on the bead width among these factors. Figure 3 (b) shows that the welding velocity has the largest effect on the weld bead height followed by current and voltage.
3.2. Parameter optimization

Figure 4 shows the parameters optimization result by GA, after about 20 iterations, a stable ratio can be obtained. The maximum ratio of width to height is 2.642, and the welding parameters in this ratio are current 138 A, voltage 22 V, welding velocity 8 mm/s.

Multi-layer single-pass WAAM experiments were carried out under the above conditions. When the weld bead surface temperature was 35°C, the next layer of deposition operation was carried out with the trajectory of Z-shaped. 10 layers were deposited in this work. The deposition width and accumulated height of each layer were measured by vernier calipers. The results are shown in Figure 5, the actual ratio of width to height of the first layer is 2.82, which is a perfect value to multi-layer single-pass arc additive deposition manufacturing. The bead width value begins to remain stable after six layers. The odd layers are affected by the pull force and even layer by the thrust force due to the angle of the torch. The bead height value is larger in odd layers, but smaller in even layers.
Figure 4 Parameter optimization results by GA.

(a) Bead width of each layer in multi-layer single-pass deposition

(b) Bead height of each layer in multi-layer single-pass deposition

Figure 5 Bead size of each layer in multi-layer single-pass deposition
4. CONCLUSIONS
In this study, RSM was used to design WAAM experiments to expose the influence of input parameters on the width and height of the weld bead. Then GA was used to optimize the test parameters to carry out multi-layer single-pass deposition manufacturing. The conclusions can be drawn as following:

(1) RSM can effectively reduce the number of experiments, and the weight of the influence of current, voltage and welding velocity on the bead width and height can be obtained:
   Bead width: voltage > welding velocity > current;
   Bead height: welding velocity > current > voltage.

(2) The process parameters were further optimized by GA, and the process parameters were obtained under the condition of the maximum ratio of width and height which was helpful for the multi-layer deposition.

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