Model of process parameters and sectional shape of samples in Single-layer Single-pass Sn63Pb37 Fused Coating Additive Manufacturing

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Abstract. Fused coating additive manufacturing is proposed to improve forming efficiency and material utilization. The forming property of single-layer single-pass is the basis of the process. The size of the sedimentary section is the smallest feature unit which includes the layer-height and pass-width. In this paper, the Design Expert 8.0.6 software is used to design the single-layer single-pass central composite experiment. In the reasonable parameters, the quadratic regression equations between the single-layer cross-sectional size and process parameters were established by performing the second regression experiments. The misalignment and significance of the quadratic regression equations were checked and the non-significant variables in the regression model equation were excluded. The quantitative influences of main forming parameters on the single-layer single-pass cross-sectional size were finally analysed in detail.

1. Introduction
Metal fused-coating additive manufacturing (MFCAM) is a new type of manufacturing process [1, 2]. MFCAM has been proposed as a commercial manufacturing technology which has the best prospect of commercialization for fabricating 3D metal functional parts. Making a comprehensive comparison with other metal additive manufacturing technologies, the advantages of low equipment cost of MFCAM are reflected. Additive manufacturing technology can realize the complex structure forming and greatly shorten the entire cycle of product development. AM is known as "manufacturing technology with the significance of industrial revolution" and has become a new strategic direction in the field of manufacturing technology [3-6].

Conclusions could be drawn that the MFCAM was derived from the further development of micro-droplet deposition forming. The essential difference had been found that the principle of continuous metal flow forming was adopted by the process of MFCAM rather than discontinuous metal flow. The molten metal was driven by gas pressure, hydrostatic pressure and surface tension, and flowed through the channel of the molten coating head, as shown detailed in Figure 1a.

Molten metal was transported from the channel of the fused-coating nozzle to the region between the horizontal moving substrate. High temperature melt encountered cold substrate or pre-solidified layers and began to cool and solidify at its interface. The solidified layers will be subjected to the same forming motion along with the substrate.
Onwubolu et al. had used the response surface methodology and dispersive search method to deal with the experimental data of laser cladding experiment, and finally got the mathematical model to predict the contact angle of the cladding layer [7]. Cheikh et al. had studied the linear relationship between the cross section shape and the forming process parameters, and results showed that the circular arc model could have a better prediction on cross section morphology of the cladding layer [8]. Xiong Jun, from Harbin Institute of Technology had studied the law between the forming process and the process parameters of single-layer single-pass under arc additive manufacturing process, and the model of process parameters and characteristic size was established [9]. Fu et al. had used Behnken design of response surface methodology (RSM) in the welding experiments [10].

The paper aims to study the forming relationship between macroscopic characteristics and the main process parameters of the MFCAM specimens. The software of Design Expert 8.04 was used to design a group experiments in the range of reasonable process parameters. Three factors were involved in the experiment: coating pressure, substrate of velocity and distance between nozzle and substrate.

2. Experimental condition

The range of reasonable process parameters were given based on large numbers of Sn63Pb37 (experimental materials) experiments, as shown in Figure 2a. All the experiments were carried out in the B region. The specific range of the research parameters need to be given in detail before experimental design. The good forming ranges parameters of coating pressure, substrate of velocity and distance between nozzle and substrate were given in Table 1 respectively. The method of control variable was adopted to study the main parameter, and the other process parameters remained unchanged during the whole experiment time. The metal fused-coating equipment practicality is shown in Figure 2b. The height and width of the sedimentary layer in the experiment were the important data which need to be elaborately measured.

Figure 2. Forming process curves and experimental platform: a forming process, b schematic diagram, b metal fused-coating equipment practicality picture.
Table 1. Parameters of metal fused-coating experiments.

| Process parameters | Coating Pressure $p$/Kpa | Velocity $v$/mm·s$^{-1}$ | Distance/mm (Nozzle-Substrate) $s$/mm |
|--------------------|--------------------------|--------------------------|---------------------------------------|
| Range              | 72–112                   | 8–12                     | 1–1.6                                 |

3. Experimental results

The coding space equation could be obtained by the processing of the experimental data. The specific experimental data was shown in the following table. Every specimen was made into standardized sample to get accurate sectional measurement as shown in Figure 3. Cross section perpendicular to the direction of forming was chosen to provide the significant data, measured results were shown in the Table 2.

Table 2. Process parameters of fused-coating experiments.

| Number | Regulate variables $Z_j$ | Process parameters | Width $w$/mm | Height $h$/mm |
|--------|--------------------------|--------------------|--------------|--------------|
|        | $Z_1$  | $Z_2$  | $Z_3$  | $p$ / Kpa | $v$ /mm·s$^{-1}$ | $s$ /mm |              |              |
| 1      | -1    | -1    | -1    | 40      | 8.8    | 1.12 | 3.68 | 1.26 |
| 2      | 1     | -1    | -1    | 52      | 8.8    | 1.12 | 4.10 | 1.38 |
| 3      | -1    | 1     | -1    | 40      | 11.2   | 1.12 | 2.96 | 1.21 |
| 4      | 1     | 1     | -1    | 52      | 11.2   | 1.12 | 3.55 | 1.29 |
| 5      | -1    | -1    | 1     | 40      | 8.8    | 1.48 | 2.76 | 1.70 |
| 6      | 1     | -1    | 1     | 52      | 8.8    | 1.48 | 3.54 | 1.76 |
| 7      | -1    | 1     | 1     | 40      | 11.2   | 1.48 | 2.38 | 1.56 |
| 8      | 1     | 1     | 1     | 52      | 11.2   | 1.48 | 2.81 | 1.65 |
| 9      | 1.682 | 0     | 0     | 36      | 10.0   | 1.30 | 2.98 | 1.34 |
| 10     | 1.682 | 0     | 0     | 56      | 10.0   | 1.30 | 3.60 | 1.59 |
| 11     | 0     | 1.682 | 0     | 46      | 8.0    | 1.30 | 3.72 | 1.62 |
| 12     | 0     | 1.682 | 0     | 46      | 12.0   | 1.30 | 2.96 | 1.30 |
| 13     | 0     | 0     | 1.682 | 46      | 10.0   | 1.00 | 3.78 | 1.21 |
| 14     | 0     | 0     | 1.682 | 46      | 10.0   | 1.60 | 2.58 | 1.81 |
| 15     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.62 | 1.38 |
| 16     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.50 | 1.36 |
| 17     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.52 | 1.42 |
| 18     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.56 | 1.41 |
| 19     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.41 | 1.45 |
| 20     | 0     | 0     | 0     | 46      | 10.0   | 1.30 | 3.42 | 1.42 |
4. Model equation

The spatial prediction model could also be obtained when the experimental data was imported into software. The quadratic polynomial was chosen to calculate the regression equation. The complete two polynomial of the regression equation was obtained in coding space as follows Formula 1, 2.

\[
\begin{align*}
  w &= 3.51 + 0.24Z_1 - 0.27Z_2 - 0.35Z_3 - 0.022Z_{12} + 0.025Z_{13} + 0.020Z_{23} - 0.082Z_{11} - 0.065Z_{22} - 0.12Z_{33} \\
  h &= 1.41 + 0.056Z_1 - 0.068Z_2 + 0.18Z_3 - 0.00239Z_{12} - 0.014Z_{23} + 0.019Z_{11} + 0.018Z_{22} + 0.035Z_{33} - 0.006194Z_{13}
\end{align*}
\]  

Table 3. Coefficient elimination table of regression equation.

| Process Parameters | Canonical Variable |
|--------------------|--------------------|
| Width-\(F\)        | Width-\(p\)        |
| Height-\(F\)       | Height-\(p\)       |
| \(q\)              | \(Z_1\)            | 68.18 | <0.0001 | 25.95 | 0.0005 |
| \(v\)              | \(Z_2\)            | 85.81 | <0.0001 | 37.54 | 0.0001 |
| \(s\)              | \(Z_3\)            | 148.67 | <0.0001 | 281.87 | <0.0001 |
| \(qv\)             | \(Z_{12}\)         | 0.44   | 0.5649 | 0.0075 | 0.9329 |
| \(qs\)             | \(Z_{13}\)         | 0.35   | 0.5234 | 0.19   | 0.6750 |
| \(vs\)             | \(Z_{23}\)         | 0.28   | 0.6083 | 0.99   | 0.3644 |
| \(q^2\)            | \(Z_{11}\)         | 8.56   | 0.0152 | 3.13   | 0.1073 |
| \(v^2\)            | \(Z_{22}\)         | 5.33   | 0.0436 | 2.59   | 0.1389 |
| \(s^2\)            | \(Z_{33}\)         | 18.72  | 0.0015 | 10.59  | 0.008  |

Width-\(F\): Variance ratio of pass width; Height-\(F\): Variance ratio of layer height. Width-\(p\): \(p\) value of pass width; Height-\(p\): \(p\) value of layer height.

In order to verify the scientific credibility of the obtained model, the regression equation should be checked in some detail by reasonable statistics. The obtained equations need three checks: the significance test of regression equation, the fitting degree test of regression equation and the verification of the regression coefficient. Firstly, the model had been checked by the \(F\) value, and the equation was remarkable. Secondly, the fitting degree should be checked at the same method. The results showed that the mismatch of the width regression equation was not significant. We could make a conclusion that the equations could meet the requirements of the check in significance, and the influences of process parameters on sample shape were respectively 97.02\% and 97.38\%, which show the regression equation has a good fitting degree. Given that the regression equation was significant.
and valid in the expected condition, however, it is uncertain that every variable factor in the equations was significant. Therefore, the regression coefficients in the regression equation should be checked necessarily. The data marked with a deleted line had been removed.

The regression equations would be more concise by eliminating the coefficients of the regression equation in the model as follow formulas 3, 4. After many calibrations, the final model could be used to establish the relationship between process parameters and macroscopic topographic features of samples.

\[ w = -9.49481 + 0.12722p + 0.69177v + 7.94715s - 0.045797v^2 - 3.81322s^2 - 0.000582211p^2 \]  
\[ h = 1.90901 + 0.0047439p - 0.056762v - 1.56582s + 1.00104s^2 \]  

5. Conclusion and discussion

5.1. Discussion

The curves of regression prediction models on single-layer single-pass were observed, and the predicted values (width and height) were arranged on both sides of diagonal lines randomly in Figure 4a, b. One of the parameters changes is maintained, the other parameters were fixed at the coding zero level. In the MATLAB environment, a mathematical model was used to obtain the impacts of single process parameters (coating pressure, substrate of velocity and distance between nozzle and substrate) on the morphology characteristics in Figure 5a, b, c, respectively.

**Figure 4.** Comparisons of actual and predicted values: a actual – predicted width, b actual – predicted height.
Figure 5. The influences of single process parameters: a velocity-width & height, b distance-width & height, c coating pressure-width & height.

5.2. Conclusion
The studied findings could provide a fundamental basis for further research on the prediction of forming morphology. The obtained experimental laws could offer some technological reserves for parameter optimization and active control of forming morphology. According to the analysis of experimental results, the following conclusions could be concluded:
1. The response surface method design has been adopted in the experiment design and the process parameters - morphology feature models had been established successfully.
2. Full analysis of the established models were given, and the quantitative research on the law of MFCAM process parameters on the shape were also taken.

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