Morphology Analysis and Process Research on Novel Metal Fused-coating Additive Manufacturing

Wang Xin, Wei Zheng ying, Du Jun, Ren Chuan qi, Zhang Shan, Zhang Zhitong, Bai Hao

State Key Laboratory of Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an 710049, China

Corresponding author: wx624753588@gmail.com

Abstract. Existing metal additive manufacturing equipment has high capital costs and slow throughput printing. In this paper, a new metal fused-coating additive manufacturing (MFCAM) was proposed. Experiments of single-track formation were conducted using MFCAM to validate the feasibility. The low melting alloy was selected as the forming material. Then, the effect of process parameters such as the flow rate, deposition velocity and initial distance on the forming morphology. There is a strong coupling effect between the single track forming morphology. Through the analysis of influencing factors to improve the forming quality of specimens. The experimental results show that the twice as forming efficiency as the metal droplet deposition. Additionally, the forming morphology and quality were analyzed by confocal laser scanning microscope and X-ray. The results show that the metal fused-coating process can achieve good surface morphology and without internal tissue defect.

1. Introduction

High performance metal components are made of alloy powder or metal wire as raw material, through high power laser or electron beam to layer by layer rapid melting [1]. However, this equipment and raw materials are usually very expensive, and not conducive to the promotion of application[2-3]. Fabrication of metal fused-coating additives manufacturing (MFCAM) is a new method for fabricating three-dimensional metal functional components [4].

To overcome the shortages of traditional AM, metal fused-coating metal additive manufacturing (MCMAM) has been proposed as a commercial manufacturing technology. Compared with traditional metal AM technologies, MCMAM has shown several advantages. At first, it provides a higher material utilization than selective laser melting (SLM) with a high deposition rate. Second, it produces less dust pollution than powder-based equipment when the powder material was recycled. Third, it has a lower equipment cost than SLM and electron beam machining (EBM) [5].

Xiong et al. investigated the forming characteristics of a multilayer single pass with the application of GMAW-based additive manufacturing [6]. Jorge et al. developed a fused deposition modeling (FDM) system for metals that can deposit electronic structures directly [7]. Yao et al. adopted a metal droplet deposition manufacturing process to reduce product development time as well as the cost of manufacturing [8]. However, deposition accuracy was difficult to control. In addition, the novel metal additive manufacturing process proposed in this paper was analyzed using a numerical simulation method. Nevertheless, the influences of process parameters on the forming morphology have never been mentioned [9].
Therefore, this paper is aimed at revealing the key factors that affect the morphology of MFCAM, such as flow rate, deposition velocity and the initial distance. The statistical analysis of the forming morphology has obtained abundant information. "Experimental details" section describes the experimental details, followed by "Results and discussion" section, which present the effect of process parameters on forming appearance. The last section ends the paper with some central conclusions.

2. Experimental procedure

2.1. Experimental System

In order to increase productivity and reduce cost, a novel metal fused-coating technology called MFCAM was proposed. A special fused-coating nozzle was designed to assist in fabricating dense metal parts. The way to build metal parts can be defined as continuous deposition. Molten metal is transported from the fused-coating nozzle to the substrate and thermal capillary zone is formed between the nozzle end and the directional moving substrate. Controlled by our 3D manufacturing software (software copyright: 2016SR070404), melt solidifies and forms layer by layer. The technology integrated the parts of the design, forming and processing, which reduces energy consumption and has the sophisticated processing application potentials. Therefore, they are well suited for aerospace, automotive, national defense transportation and other fields, etc.

Fig. 1 provided a conceptual view of the overall process. The equipment of MFCAM includes a pressure control system, an inert environment control system and a machine control system with a movable platform. The pressure control system was used to produce molten metal on demand. It consisted of a pressure control device, a solenoid valve, a crucible, a heating furnace, a thermocouple, a temperature control device and argon gas source. The inert environment control system consists of the glove box and gas circulation device, which are used to protect molten metal from oxidation. The 3D platform system has a PMAC (programmable multi-axis controller), which is consists of a deposition substrate, a substrate heating device, 3D movement platform, a motion control device and a temperature control device. The form parts according to data information through controlling the motion of the 3D platform, and the whole process were coordinately controlled to complete the fabrication of prototype parts by industrial computer. Crucible and nozzle inner wall wipe with hydrochloric acid, Sn63-Pb37 alloy in argon environment refining again after being washed with alcohol. Finally, the raw materials into the crucible within the 220 mesh stainless steel mesh for metal smelting.

FIGURE 1. Schematic of the metal fused-coating additive manufacturing.
2.2. Arrangement of the Experiments

In the course of the experiment, the temperature of the molten metal is too low to be squeezed out of the nozzle, and the temperature is too high, which leads to the phenomenon of the collapse. Therefore, the choice of crucible temperature and substrate temperature is very important. This paper is based on the simulation results of the research group combined with the actual conditions preferred temperature value. The nozzle pressure corresponds to the flow rate, and its selection is based on the fluid Bernoulli equation, taking into account the loss along the way, local loss and hydrostatic pressure. The data on pressure-flow are obtained after analytical calculations. In order to study the influence of flow rate, deposition velocity and the initial distance. According to previous experience we will be set the crucible temperature was 270 °C, the initial distance between the nozzle and the substrate is set to 1.6 mm, the substrate temperature was set as 90 °C, argon mass flowmeter pressure was set as 150 KPa.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Coating Head Temperature         | 270 °C                 |
| Argon Mass Flow Rate             | 10~80 mm$^3$/s         |
| Deposition Velocity              | 9~27 mm/s              |
| Initial Distance                 | 1.6 mm                 |
| Coating Nozzle                   | 0.3 mm                 |
| Pressure                         | 100 KPa                |
| Glove Box                        | Ar (99.999%) (20 ppm)  |
| Size of Copper-clad Substrate    | 300*200*10 mm          |
| Single-track Deposited Length    | 130 mm                 |

3. Results and discussion

Metal fused-coating process evaluation standard includes surface morphology and internal tissue, and the geometry size has directly affected the quality of the single-track. The single-track height has an important influence on the bonding strength between layers. The single-track width has an important influence on the lap ratio. As a basic unit, the forming process of a single-track specimen should be primarily investigated. There are many process parameters in the MCMAM forming process, including the deposition velocity, the flow rate, the distance from the nozzle to the workpiece, the heating temperature, the nozzle size, and the heat dissipation conditions, having great impacts on the final forming quality of specimens. The present paper focuses on the deposition velocity, the flow rate, and the initial distance; thus, other factors are kept constant.

3.1. Influence of Deposit Velocity on Forming Appearance in Surface Morphology

The deposition velocity is a very important process parameter. According to the preliminary experimental data, the coating head temperature is set at 270 °C, nozzle diameter 0.3 mm, flow rate of 50 mm$^3$/s, the initial distance between nozzle and substrate is 1.6 mm, the deposition velocity were 9 mm/s, 12 mm/s, 15 mm/s, 18 mm/s, 21 mm/s, 24 mm/s, 27 mm/s were deposited, as shown in Fig. 2(a) – (g), there are seven different shapes of the surface morphology with single factor experiment on deposition velocity.

From Fig. 2 a, b we can see that the surface quality is not satisfactory, which indicates that the flow rate is too large and the deposition velocity is small. The single-track width increased significantly, and the end of shape had piled up. From Fig. 2 f, g we can see that the deposition velocity too fast to produce fewer overlaps by surface tension. And this phenomenon has led to necking into droplets, the necking in place will lead to declining mechanical properties. From Fig. 2 c, d, e we can see that the deposition velocity and flow rate matching are good with 15 mm/s ~ 21 mm/s. The process parameter matching test can be carried out in this range.
In order to study the process parameters more directly, we have made the curve of width and height with different deposition velocity. The depositing dimension includes the height and the width of the single-track part. In this work, the width and the height after layer finished were measured and recorded by the vernier caliper after deposition of each layer. The average value was calculated according to the measurements as shown in Fig.3. The width and height decrease gradually with the increase of deposition velocity. However, the effect of deposition velocity on the width is more significant, and the trend is slowing down. In order to quickly find the test parameters, we choose medium deposition velocity 18 mm/s medium for subsequent experiments.

3.2. Influence of Flow Rate on Forming Appearance in Surface Morphology
The effects of different flow rates on the width and height as shown in Fig. 4. The deposition velocity is 18 mm/s and the initial distance is 1.6 mm. From the graph, we can see that the width and height increases with the increase of flow rate, but the impact of flow rates on the width is more significant. When the flow is 50 mm³/s, the inflection point appears, and the influence of gravity and surface tension reaches a balance value.

3.3. Influence of Initial Distance on Forming Appearance in Surface Morphology

The distance from the nozzle to the substrate is defined as the initial distance; the effect of different initial distances on the height is shown in Fig. 5. The deposition velocity is 18 mm/s, and the flow rate is about 30 mm³/s, 50 mm³/s, 70 mm³/s. From the graph, we can see that the height increase with the increase of the initial distance. The surface tension of the metal liquid reaches a relatively stable state at the initial distance. When the flow rate is different, the initial distance of the steady state is different. The larger the flow rate, the greater the initial distance to the steady state. The flow rate is 50 mm³/s, the height change trend is relatively stable.

The effect of different initial distances on the width is shown in Fig. 6. From the graph, we can see that the width decrease with the increase of the initial distance, and finally tends to be stable, and when the flow rate is 50 mm³/s, the width change trend is relatively stable. The change tendency of width is opposite to that of height.
3.4. Surface Morphology Analysis
As a basic unit, the forming process of a single-track specimen should be primarily investigated. In single forming the high-temperature melt being extruded from the nozzle once contacts with the pool, as the melt flow is very complex and the melt shape fluctuates frequently, they would influence the quality and performance of the formed parts at the initial stage of fused-coating process. Therefore, it is necessary in order to explore the single-track forming process.

In this section, A micro-focus X-ray multi-functional three-dimensional imaging detection system with 1.5 um dimensional accuracy to observe the internal microstructure, as shown in Fig. 7 (a), it can be seen in single-track internal microstructure uniform and no cracks, and has good spread ability, similar to the shape of oval section. A Confocal Laser Scanning Microscope (CLSM) with 0.12 um dimensional accuracy to observe the surface morphology, as shown in Fig. 7 (b), It can be seen that it has a good surface morphology, roughness average of about Ra3.2, with a good subsequent processing potential.

4. Conclusions
In this study, based on the accumulation of experimental data, optimal process parameters of MFCAM were analyzed to achieve good appearance and internal morphology. The main results can be summarized as follows:

- The MFCAM technology is considered an economical and effective forming process. Forming efficiency of the MCMAM up to 50 mm³/s (viz. 1490g/h) is doubled, compared to the metal droplet deposition.
• There is a strong coupling effect between the single track forming morphology, the deposition velocity, the flow rate and the flow initial distance. The experimental results show that the optimal process parameter for the initial distance is 1.6 mm, the flow rate is 50 mm³/s and the velocity is 18 mm/s.

• Single-track specimen’s surface morphology was observed by confocal laser scanning microscopy and internal microstructure was observed by X-ray diffraction. Results show that the metal fused-coating process can achieve good surface morphology and without internal tissue defect. The research foundation is established for the next print of the whole parts.

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