Research on remelting phenomena and metal joining of fused-coating additive manufacturing

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Abstract. Metal fused-coating is a novel additive manufacturing technology used to building complex components. In order to determine good metallurgical bonding between layers, a two-dimensional model was established to predict the temperature needed to promote the metallurgical bonding of multi-layer specimens. The temperature of the cladding process was tracked and measured by the thermal imaging system. The influence of heat transfer on the forming characteristics of the fusion track was studied systematically. In addition, the maximum remelting depth of the liquid-solid interface was evaluated and the interlaminar bonding state was further confirmed by the formation of three-dimensional samples and optical microscopy images. This work may help to develop metal fused-coating to the produce effective process control and performance prediction.

1. Introduction
In the past two decades, additive manufacturing (AM) has drawn the public’s attention for its unique advantages. Compared with the traditional manufacturing technology, additive manufacturing has the advantages of low cost, high speed, high reliability and high precision [1, 2]. The mainstream methods of metal additive manufacturing technology include: laser engineered net shaping (LENS), electron beam melting (EBM) [3], selective laser melting (SLM), metal droplet deposition and wire and arc - AM. Laser and electron beam forming have better dimensional accuracy [4–6]. However, high energy density sources result in expensive equipment, while also limiting the size of the forming [7]. Metal droplet deposition process has been extensively used in the three-dimensional manufacturing of printed circuit components [8]. However, it is difficult to control the droplets positional accuracy and temperature. Wire arc additive manufacturing (WAAM) equipment’s has low cost and high deposition rate, but at the expense of dimensional accuracy and surface quality [9, 10].

Due to the high cost, low efficiency and inconsistent product performance of traditional metal additive manufacturing, a new metal 3D printing technology - Metal Fused-coating Additive Manufacturing (MFCAM) was proposed. The significant advantage of MFCAM is the reduction of equipment and material costs. In addition, this technology gives the opportunity to produce parts with complex geometries using freedom style raw materials such as wire, rod and bar-like. Currently, Fang et al. using numerical simulation method studied the primary thermo-physical phenomenon occurring in the fused-coating process [11]. Wang et al. studied the effect of layer thickness on macroscopic morphology multilayer single-track, however, did not consider the effect of temperature on it. [12]. Some problems need to be solved urgently, such as the interlayer bonding state, microstructure, cold
lap. These problems seriously affect the forming quality and precision of parts [13]. Therefore, investigate the heat transfer and flow of the molten metal on the substrate can better understand and control the process parameters [14].

This paper aims to elucidate the fundamental mechanisms of the relationship between the morphology and the temperature of single-track Sn–Pb alloy parts during the fused-coating process. The samples were prepared through successive depositing the metal to explore forming characteristics and related parameters. The surface morphology evolution of molten metal during the forming process has been examined. The geometric characteristics of the stable track was obtained during the forming process through using optimum processing parameters. Consequently, a sample with good surface morphology, i.e. a high quality was obtained.

2. Experimental

2.1. Experimental system

Figure 1a shows the schematic diagram of MFCAM. The equipment of MFCAM includes a pressure control system, an inert environment system, a process monitor system, forming platform and machine control system. Use a pressure control system to generate the demanded pressure to extrude the molten metal from the nozzle. It consists of a pressure control device, a proportional 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 process monitor system is composed of a CCD camera and an image acquisition card was used to observe the deposition and spreading process. The 3D platform consists of a deposition substrate, a substrate heating device, a temperature control device and a 3D motion control device PMAC. According to the part data information, the 3D platform coordinated by the industrial computer control to complete the manufacture of complex components. Figure 1b shows the principle of MFCAM process and Figure 1c shows experimental platform. A special fused-coating nozzle was designed to fabricate dense metal parts. A 3D manufacturing software was used for controlling processing parameters to build the parts from molten material layer by layer.

![Schematic diagram](image1.png)

(a)

![Principle of MFCAM process](image2.png)

(b)

![Experimental platform](image3.png)

(c)

**Figure 1.** Metal fused-coating additive manufacturing: (a) Schematic diagram, (b) Principle of MFCAM process, (c) Experimental platform.

2.2. Experimental method

Since single-track morphological evolution plays an important role in determining process parameters during fused-coating processing, its evolution needs to be monitored during solidification. In order to obtain a successive molten track with good morphology from Sn-Pb alloys, a deposition velocity of 18 mm/s was used in the fused-coating process according to previous studies. At the same time, the temperature of the molten metal should be maintained at 270 °C, the copper-clad substrate should be...
preheated to 50 °C, in order to reduce thermal stress and thermal deformation. The detailed processing parameters and thermo-physical properties of material are listed in Table 1. Stable pressure is applied through the high-frequency proportional valve to spray the molten metal at a constant velocity.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Fused-coating nozzle temperature | 270 °C                 |
| Substrate temperature            | 50 °C                  |
| Argon mass flowmeter             | 50 mm³/ₘ             |
| Deposition velocity              | 18 mm/s                |
| Initial distance                 | 1.6 mm                 |
| Layer thickness                  | 1.2 mm                 |
| Coating nozzle                   | 0.3 mm                 |
| Glove box                        | Ar (99.999%) (20 ppm)  |
| Size of copper-clad substrate    | 300 mm × 200 mm × 10 mm|
| Density                          | 8.4 g/m³               |
| Surface tension                  | 0.49 N/m               |
| Specific heat                    | 176 J/Kg·K             |
| Thermal conductivity             | 50 W/m·K               |
| Dynamic viscosity                | 1.3×10⁻³ N·s/m²        |

3. Experimental results and discussion

3.1. Single track deposition
Temperature control is very important, however, not much previous work has been reported on the MFCAM. In addition, forming process requires real-time monitoring to ensure the authenticity and accuracy of the temperature. The thermal imaging system is used to fully measure the surface temperature of the workpiece to understand the manufacturing characteristics of the forming.

Figure 2. Single-track forming experiment: (a) single-track forming process in thermal imaging system, (b) single-track deposition experimental, (c) surface morphology of the single-track, (d) cross-section view of the single-track.
In this section, the morphology evolution of fused-coating was discussed. Figure 2a, b shows the morphology and temperature evolution of single-track during MFCAM process. In the fused-coating nozzle uniform melt flows out of the channel under pressure. Complex surface evolution encompasses various interdependent influence factors in fused-coating process. Single-track and substrate will fuse together in a very short period of time. In this stage, the melt flow is very complex, they would influence the quality and performance of the formed parts at the initial stage of fused-coating process. Subsequently, a “local thermodynamic equilibrium” was achieved and the surface was stabilized.

Figure 2c, d shows the morphology of the single-track. It can be seen from the figure that a solidified track with a good surface finish was obtained by dragging the molten metal spreading onto the substrate and the melt has been completely spread after 0.5 mm.

3.2. Multi-layer deposition

In order to study the behavior of the interface remelting in the deposition process, a one-dimensional two-phase Stefan model was established. The remelting principle as shown in figure 3a, the dotted line in figure 3b is the boundary between layers. When the melt contact with the solidified layer is about 0.01 s, the liquid-solid boundary moves to the lowest point of the deposited part (solid phase), then moved to the liquid phase until the melt solidifies completely. At the moment, the maximum remelting depth is 0.096 mm by calculating, that is 7% of the layer thickness \( \delta \), as shown in figure 3c.

Figure 4 shows the surface morphology and internal microstructure of the multi-layer deposition. The thickness was set as 1.2 mm. As shown in figure 4a, the first layer forming on the substrate, the other layers forming on the previous tracks. The heat carried by the new layer transfers to the conjoint layer, and some remelting layers are formed at the contact area. The melt pool will be spread and adjacent surface will experience a deformation during the spontaneous fusion within an extremely short time. The liquid-solid interface undergoes complex morphology evolution, such as merging, fluctuating and spreading of two layers melts. The liquid-solid interface spontaneously fuse together between layers, resulting in a good metallurgical bond. The fusion line between the layers was retained throughout the deposition process until the process was complete as shown in Figure 4b.

As the thermal capillary flow tends to be stable, this technology enables the melt to pile up layer by layer along the height direction into a complex three-dimensional metal parts. In the process of metal deposition, the extent of melting has great influence on the bonding quality and cross section morphology between layers. Forming accuracy and quality can be reflected in the morphological characteristics and metallurgical defects. To obtain better quantitative results, the multilayer microstructures and solidification morphology of formed parts was observed by metallographic microscope. As shown in Figure 4c, no obvious porosities occur and metallurgical bonding was observed. It is shown that the simulation results can be used to predict the bonding quality between different temperatures. The maximum remelting depth is 0.084 mm by experiment. The error between experimental and simulation results is within 14.3%, the established model is in a good agreement with experimental results.
Figure 4. Surface morphology and internal microstructure in the multilayer deposition: (a) multilayer forming process in thermal imaging system, (b) surface morphology of the experimental samples, (c) comparison of numerical and experimental results for the solidification morphology.

3.3. Fabrication of the three-dimensional specimen
Using the parameters in Table 1, a 68-layer specimen was formed shown in figure 5a, the specimen weigh is 304 g with 22 minutes, and the forming efficiency is 829 g/h. The optical microscope image and the confocal laser scanning microscopy were used to observe the surface morphology as shown in figure 5b, c. It can be seen that there is no obvious defect in the surface quality of the formed part.

Figure 5. Three-dimensional part by metal fused-coating (a) three-dimensional specimen, (b) optical microscope image, (c) confocal laser scanning microscope image
4. Conclusions
Metal fusion-coating additive manufacturing technology for a variety of materials provides a new way to flexibly fabricate complex-shaped metal parts with good surface finishes. From the experimental results we can draw the following conclusions:

- The MFCAM process was investigated, and the experimental system was developed. This system can sequentially deposit molten metal forming three-dimensional parts.
- Combined with the thermal imaging system, the temperature needed for the metallurgical bonding of multi-layer samples was confirmed, and the interlayer bonding state of the three-dimensional samples was verified by optical microscope images.
- Calculating the liquid-solid remelt depth contributes to the preparation of metal fused-coating to produce good morphology parts.

References
[1] Bourell D, Leu M, Rosen D. Roadmap for additive manufacturing identifying the future of freeform processing. (2009) University of Texas at Austin, Austin TX. Pp.9-11.
[2] Levy, G. N., Schindel, R., & Kruth, J. P. (2003). Rapid manufacturing and rapid tooling with layer manufacturing (lm) technologies, state of the art and future perspectives. Precise Manufacturing & Automation, 32(2), 589-609.
[3] Dirk Herzog, Vanessa Seyda, Eric Wycisk, & Claus Emmelmann. (2016). Additive manufacturing of metals. Acta Materialia, 117, 371-392.
[4] Edson Costa Santos, Masanari Shiomi, Kozo Osakada, & Tahar Laoui. (2006). Rapid manufacturing of metal components by laser forming. International Journal of Machine Tools and Manufacture, 46(12–13), 1459-1468.
[5] Wanjara, P., Brochu, M., & Jahazi, M. (2007). Electron beam freeforming of stainless steel using solid wire feed. Materials & Design, 28(8), 2278-2286.
[6] Wanjara, P., Brochu, M., & Jahazi, M. (2007). Electron beam freeforming of stainless steel using solid wire feed. Materials & Design, 28(8), 2278-2286.
[7] Baufeld, B., Biest, O. V. D., & Gault, R. (2010). Additive manufacturing of ti–6al–4v components by shaped metal deposition: microstructure and mechanical properties. Materials & Design, 31(1), S106-S111.
[8] Cossali, G. E., Marenzi, M., & Santini, M. (2008). Thermally induced secondary drop atomisation by single drop impact onto heated surfaces. International Journal of Heat & Fluid Flow, 29(1), 167-177.
[9] Mughal, M., Fawad, H., & Mufti, R. (2006). Three-dimensional finite-element modelling of deformation in weld-based rapid prototyping. ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science 1989-1996 (vols 203-210),220(220), 875-885.
[10] Silva, R. J., Barbosa, G. F., & Carvalho, J. (2015). Additive manufacturing of metal parts by welding. Ifac Papersonline, 48(3), 2318-2322.
[11] Silva, R. J., Barbosa, G. F., & Carvalho, J. (2015). Additive manufacturing of metal parts by welding. Ifac Papersonline, 48(3), 2318-2322.
[12] Wang, X., Du, J., Wei, Z., Fang, X., Zhao, G., & Bai, H., et al. (2016). Morphology analysis of a multilayer single pass via novel metal thin-wall coating forming. Metals, 6(12), 313.
[13] Du, J., & Wei, Z. (2015). Numerical analysis of pileup process in metal microdroplet deposition manufacture. International Journal of Thermal Sciences, 96(4), 35-44.
[14] Song, Z., Xing, W., Gu, M., Ma, Y., & He, Y. (2013). Numerical simulation of interface bonding strength of coating and substrate. Shanghai Coatings.

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