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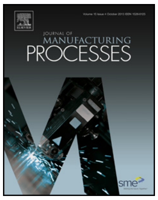

An investigation on effects of process parameters in fused-coating based metal additive manufacturing

Xuewei Fang[a,*], Jun Du[b], Zhengying Wei[a,b], Pengfei He[a,b], Hao Bai[a], Xin Wang[a], Bingheng Lu[a,b]

[a] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University (XJTU), Xi'an, 710049, China
[b] Collaborative Innovation Center of High-End Manufacturing Equipment, Xi'an Jiaotong University (XJTU), Xi'an, 710049, China

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ABSTRACT

Fused-coating based additive manufacturing (FCAM) is a novel metal solid freeform fabrication technology that builds metal parts by selectively deposition the material layer by layer from the CAD model. It gives an alternative to build metal components with low costs, high efficiency, clean and cheap materials compared with other AM processes. An experimental system including a molten metal generator, a fused-coating nozzle, a three-axis motion platform, an inert atmosphere protection and temperature measurement unit and the controlling hardware and software has been established. This paper presents the basic principle and some experimental results of the FCAM process as well as its potential applications. The effects of different processing parameters on the forming layer width and thickness were investigated. The process parameters include: the molten metal flow rate, the substrate moving speed, the gas pressure, the gap between nozzle and substrate, the nozzle temperature, the substrate temperature, the property of material and the scanning strategy. The optimal parameters were chosen to fabricate thin-wall work pieces based on the parameters analysis and experiment. This paper presents the basic principle and some experimental results of the FCAM process as well as its potential applications. Preliminary experiments prove that metal components can be built with high efficiency and good metallurgical bonding.

1. Introduction

Additive manufacturing (AM) was developed in the late 1980s which has expanded dramatically and gained increasing popularity since it does not need moulds and complex tools to form arbitrary shapes directly from CAD models [1]. This process also called solid freeform fabrication or layer-based manufacturing and nowadays it is popularly called 3D printing [2]. This technology has caused the paradigm shift from conventional manufacturing process through building three dimensional objects by slicing the CAD model into two-dimensional layers and joining each layer to the previous one.

Nowadays, low cost AM equipment for plastic is very common and many machines are available. However, Metals are quite different from plastics in viscosity, melting temperature and surface tension which make them hard to continuous feeding. Metal parts are manufactured for design rather than being designed for manufacture when using AM. Some of the current metal AM technologies include Laser Engineered Net Shaping (LENS), Selective laser melting (SLM), Laser Cladding (LD), Electron beam melting (EBM), and wire and arc additive manufacturing (WAAM) that are the typical methods for metal [3–7]. Combining with AM, arbitrarily complex geometries, such as honeycomb structures, lattice structures and components with complex internal features, can be produced directly from 3D CAD model. Unfortunately, with all what AM has offered, the quality and repeatability of metal parts still impede their wide application, such as the aerospace and healthcare sectors.

Currently, research has been widely explored on fabricating metal components in campus, industry and academia. For metals, the major researches are focused on powder bed and powder feed methods since powder bed/feed method has good geometric accuracy [8,9]. LENS can fabricate near-net shape, fully dense metallic parts, such as titanium alloy, stainless steel and superalloy, with reasonably complex geometrical features directly from a CAD solid model in the early times. Compared with wire-feed AM, powder feed rate of LENS is quite low, usually under 10 g/min, because the energy is just focused on one point that limits the application in fabricating very large metal parts, such as more than 2 m parts.

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[*] Corresponding author.
E-mail address: fangxuewei0920@gmail.com (X. Fang).

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AM in wire and arc-welding has been established that uses electric arc as energy to build components. Research has been studied in WAAM about surface quality, residual stress, microstructure combining [10]. However, the relative complex equipment, high cost and residual stress, low mechanical properties are the main problems of the WAAM which prevent its wide application [11]. The fused deposition modeling(FDM) technology extrude and deposit a continuous filament of a thermoplastic polymer, wax, or metal through a heated liquefier and a small diameter nozzle onto the building substrate [12]. The advantage of FDM is the lack of expensive lasers or an electron beam in sintering and electron beam melting process. Besides, using FDM process that less expensive materials and systems are available compared with sintering and melting technologies. However, the FDM process is limited to low-temperature and strength alloys [13]. Jorge Mireles [14] using a modified FDM 3000 system to deposition of Sn60Bi40 and Bi58Sn42 alloys. It is just an original attampt to achieve metal depostion. However, the control of microstructure and mechanical properties have not been studied.

Liquid Metal Jeting technology is solid freeform fabrication process that based on the ink-jet method. This method dispenses and controls molten droplets to the specific location using digital stored computer-aided data in a highly reproducible manner [15]. There are two manners that used for droplet generation, namely, drop-on-demand (DoD) and continuous inkjet (CIJ) [16]. In DOD technique, droplets are solely delivered when they are demanded to be printed. The molten metal droplets of desirable material are ejected through pressure pulse which is melted in a crucible. The CIJ mode can produce high frequency droplets with a piezoelectric ceramic actuator. However, it is difficult to control the fall position and temperature of the droplets compared with the DoD [17]. The studies of liquid metal droplet deposition were originated at MIT [18] and University of California at Irvine in the later 1990s [19]. After that, the forming mechanism and control theories about metal droplets manufacturing were also studied. The liquid metal jetting manufacturing is a sophisticated fluid and heat transfer process, which includes the melting, impacting, spreading, remelting, cooling and solidification of the material [20,21]. In this way, it is hard to obtain good metallurgical bonding between metal droplets and retain forming shape of components after solidification [22]. Micro-void and cold lap are the unavoidable defects of metal droplets deposition process in building 3D components.

Aiming at achieving time, cost and energy saving, a novel fused-coating based metal AM is proposed which is meant at expanding the application of AM technology. The FCAM process builds metal parts by selective deposition the material layer by layer. During manufacturing, molten metal material is heated by resistance heating or electronmagnetic inducting. Then molten metal is transported from the fused-coating nozzle to the substrate and thermal capillary zone is formed between the nozzle end and the moving substrate. Molten metal spreads into a specific shape under the influence of pressure, gravity, metal viscosity and surface tension. In FCAM process, pneumatic pressure is played as driving force coupled with the effect of exhauster under the control of frequency converter and pluse width of solenoid valve. The frequency converter and solenoid valve are used to control the formation and termination of molten metal. The special fused-coating nozzle with a certain cone angle is designed to assist fabrication of dense metal parts. FCAM has many potential advantages, first and foremost, dense parts can be built that micro-void and cold lap are avoided. It has the potential in fabricating metal materials, such as Sn-Pb alloy, alumnium alloy, copper alloy and even steel. In addition, this method needs less expensive material and equipment and is energy saving compared with other AM method.

Compared with other metal AM process, the fused-coating based metal AM has its own characteristics. Hence, it is necessary to give a fundamental investigation about the fabrication process. The molten metal flow rate is a key factor during the FCAM process and it can affect the heat transfer and the molten metal deposition. The other process parameters include the moving speed of substrate, the crucible pressure, the substrate temperature, the nozzle temperature, the distance between the nozzle and the substrate and so on. Only through appropriate integration of these process parameters can high quality metal parts be fabricated. Therefore, in this paper, the study about the influence of process parameters on the layer width and thickness were performed. Based on the experiment results, the optimized parameters were found and used to build metal parts. This is the initial study about the FCAM process and the metal parts fabricated by FCAM have good shape although the surface roughness has not been measured. This paper introduces the current progress in our team's research and not a complete studied of the FCAM process.

2. Experimental procedures

The schematic diagram of the experimental apparatus used to investigation the newly established FCAM method in fabricating metal parts is shown in Fig. 1. The experimental system includes a molten metal generator, a fused-coating nozzle, a three-axis motion control unit, an inert atmosphere protection and temperature measurement unit and the controlling hardware and software.

Sn63Pb37 alloy was chosen as raw material and was melted in the molten metal generator. The generator was comprised of a graphite crucible and an induction coil which can provide enough power to melt metal. A heated fused-coating nozzle was located at the bottom of the crucible with a threaded connection. The nozzle has a detachable tip that connected the main body by a threaded connection. The nozzle can assemble easily which just needs to replace the nozzle tip. A 700 W band heater was covered around the nozzle and a thermocouple was inserted to the nozzle wall to monitor the temperature accurately. In this study, the fused-coating nozzle tip inner diameter with 0.4 mm was used. The STL format CAD model is created using modeling software (Solidworks) and then model is sliced into specific layer thickness by slicing software and the scan paths and control instructions are generated. At last, the control unit controls the motion of substrate and molten metal jet formation and builds metal parts layer by layer.

During forming, the top of the furnace was connected with nitrogen gas through a cross-junction (Swagelok, SS-400-4) which has four ports. The outlet pressure was controlled under 200KPa using a series of valves. A solenoid valve (Burkert, 2871) was installed in the line path to maintain the pressure of the crucible. The response time of the solenoid is within 10 ms. The third port of the cross-junction was connected with a precision pressure transducer to measure the dynamic pressure in the crucible. The last port of the cross-junction is connected with an exhauster which can generate negative pressure within 150KPa in the crucible. By adjusting the frequency of the frequency converter, the pulse width of the solenoid valve that stable molten jet can be produced and controlled. The Sn63Pb37 alloy, an eutectic composition is used and the material properties are shown in Table 1. A glove box (DELLIX, China) was used to protect the molten metal form oxidization. The oxygen content was maintained under 50 ppm. The nozzle was fixed while the preheated substrate can move along the X-Y-Z axis. Three servo motors were adopted(accuracy is ±5um) to control the motion and the traveling distance of the X, Y and Z axis was 250, 250 and 400 mm, respectively. A copper-clad substrate with 200×300 mm, was fixed on the heating board which can be heated up to 300 °Cunder the control of a temperature controller (Yu Dian, 518P)and K-type thermocouple.