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A three dimensional transient model for heat transfer and fluid flow of weld pool during electron beam freeform fabrication of Ti-6-Al-4-V alloy

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ABSTRACT

A three-dimensional transient model is proposed to understand the heat transfer and fluid flow behaviors of weld pool during single track electron beam freeform fabrication (EBF^3) of Ti-6-Al-4-V alloy. Fluid flows driven by recoil pressure, surface tension and thermal capillary effect are coupling considered in the model. Free surface evolutions of weld pool are incorporated with Level Set method. An improved heat source model is also proposed to simulate the energy interactions between high energy electrons and deposits. Results indicate that there are vigorous fluid flows in the front part of weld pool and thermal-capillary force is the main driven force of fluid flow. Effect of droplet impacting could periodically influence the heat transfer and fluid flow of weld pool. High frequency elliptical scanning of electron beam could decrease the temperature gradient and the magnitude of fluid flow of weld pool. However, beam scanning does not essentially change the flow patterns. A good agreement is obtained between the simulations and experiments.

1. Introduction

Electron beam free form fabrication (EBF^3) is an emerging three dimensional printing technology for fabricating high performance metallic components, which is considered as a very promising process for on-orbit repairing the broken component of space vehicles [1,2]. In EBF^3 process, the metallic feed wires are heated and melted by the electron beam and changed as periodical molten droplets or continuous liquid bridge in a vacuum chamber. Layer by layer deposits are produced when the droplets or liquid bridge are transferred into the high temperature weld pool in the substrates or pre-deposited parts. After the deposits are cooled and solidified, a 3D metallic component can be produced. Fig. 1 shows the schematic of EBF^3 process. As comparing to other 3D printing technologies, EBF^3 process has many advantages such as high energy efficiency, very high speed deposition rates, clean forming environment and can be used to manufacture nearly all metallic materials [3].

In EBF^3 process, there may be complex heat transfer and fluid flow phenomena in weld pool due to the bombardment of high energy electrons. Phase transformations such as melting, solidification, evaporation and condensation may occur in weld pool at the same time. Potential fluid flow of weld pool could be driven by recoil pressure of metallic vapor, impacting force of the molten droplet or continuous liquid bridge, thermal-capillary force as well as surface tension of molten liquid [4]. The heat transfer and fluid flow behavior of weld pool is one of the key influencing factors of the temperature field and deformations of the deposits [5]. Also, these transport phenomena determine the solidification process and the final microstructure of the EBF^3 deposits. Moreover, they are closely associated with typical process defects such as porosity, cracks, lack of fusion and unfavorable rough surface morphology [6–8]. Therefore, the investigation of heat transfer and fluid flow of weld pool in EBF^3 process has both scientific and engineering significance for process understanding and development.

Fabrication of metallic parts by electron beam was pioneered by Dave et al. [9] at MIT in 1995. Later, this process was patented by Arcam Company and was usually named as Electron Beam Melting (EBM) [10] process or Electron Beam Selecting Melting (EBSM) process. The electron beam free form fabricating process, EBF^3, is another kind of electron beam based rapid prototyping technologies in which metal wires, but not metal powers, are deposited by high density electron beams. The EBF^3 process was proposed by Taminger et al. at NASA Langley Research Center [11]. Owning to its excellent potential capabilities, EBF^3 process has attracted

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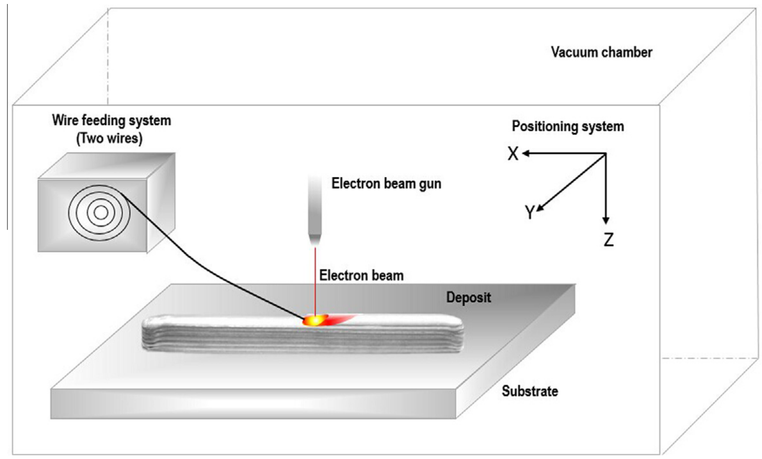

Fig. 1. Schematic of the EBF3 process.

Table 1
Chemical composition of Ti-6-Al-4-V titanium wires (mass fraction, %).

Al	V	Fe	C	N	H	O	Ti
5.5–6.75	3.5–4.5	⩽0.25	⩽0.05	⩽0.05	⩽0.012	⩽0.18	Balance

great research attentions in recent years. Microstructure and mechanical properties of vary EBF^3 deposits, as well as different heat treatment processes were extensively studied. Despite many research efforts have been made, the mechanisms of the weld pool in EBF^3 process is still not fully understood. To our best knowledge, no theoretical study is available for understanding the heat transfer and fluid flow behaviors of weld pool during EBF^3 process.

The heat transfer and fluid flow behaviors in some other similar 3D printing processes such as Laser Engineering Net Shape (LENS) process [12–16], Direct Metal Deposition (DMD) [17–21] and Selection Laser Melting (SLM) [22–24] process and so on [25] have been extensively studied over the past decades. However, due to the mechanism difference between laser matter interactions and electron matter interactions and the significant different beam spot size, the mechanisms understanding of laser based manufacturing process [26,27] may not be used to interpret the weld pool phenomena in EBF^3 process. Recently, heat transfer and fluid flow behaviors of electron beam welding (EBW) were studied by Rai et al. via direct numerical simulations [28]. However, there are distinct differences between EBF^3 process and EBW process. The analysis results of heat transfer and fluid flow mechanism of weld pool in EBW process cannot be directly applied to EBF^3 process.

In this paper, a 3D transient model is first developed to investigate the heat transfer and fluid flow phenomena of weld pool in single track EBF^3 of Titanium alloys. Heat transfer and fluid flow of weld pool during single track EBF^3 process are theoretically discussed and compared with experiments.

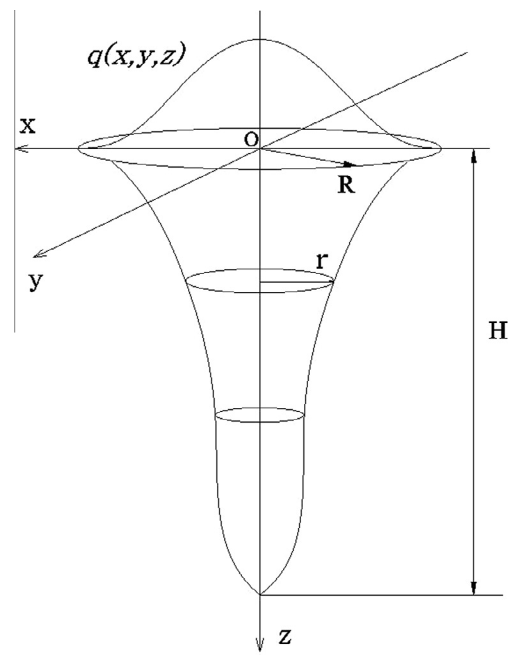

Fig. 2. Rotated Gaussian volumetric heat source.

2. Experimental

Single track Ti-6-Al-4-V Titanium alloy deposits were made on Ti-6-Al-4-V substrate by EBF^3 process in Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI), China. The substrate was 20 mm thick plate, and the metallic wire diameter was 2.0 mm. The chemical compositions of substrate and wires

Table 2
Experimental parameters.

Sequence No.	Acceleration voltage U (kV)	Beam current I_b (mA)	Focus current I_f (mA)	Wire feeding speed V_s (mm s^{-1})	Welding speed V_w (mm s^{-1})	Scanning mode
1	60	50	820	No	15	No
2	60	100	820	No	15	No
3	60	150	820	No	15	No
4	60	50	820	No	15	Elliptical
5	60	100	820	No	15	Elliptical
6	60	150	820	No	15	Elliptical
7	60	130	820	No	15	Elliptical
8	60	130	820	35	15	Elliptical