



Review

Review on thermal analysis in laser-based additive manufacturing

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ABSTRACT

Laser-based Additive Manufacturing (LAM) has been widely used in different industries. However, the quality and repeatability of the components and parts produced by LAM have hindered the spread of this technique. The better understanding of the LAM underlying mechanism can provide insight into acquiring high-quality products. Among researches on underlying physics, there are efforts to study the thermal behavior, as one important part of the complex mechanisms, and its influence on the product quality. This review is presented to comprehensively analyze different approaches to study the thermal behavior. The relationship between thermal behavior and product quality is identified and some recommendations for future research are discussed.

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1. Introduction

Laser-based Additive Manufacturing (LAM) is gaining rapid progress in recent years and widely adopted in different industries such as tool-making [1], aviation and aerospace [2] and biomedical [3]. As the laser beam irradiates the surface of the substrate, the metal substrate fuses and liquid melt pool forms. A product is produced by joining mental material layer by layer from a 3-D model. Compared to the conventional Metallurgy and Subtractive Manufacturing, LAM has a number of advantages:

- (1) The high energy density and small heat affected zone lead to a high cooling rate in the melt pool. This contributes to finer grain size and better mechanical properties of products [4].
- (2) Due to high temperature in the melt pool, it is feasible to process difficult-to-machine or refractory material [5].
- (3) By changing the chemical composition of the input metal material, LAM can be used to process functionally graded components [6].
- (4) Since the material is deposited layer by layer, the components with complex structure, which is usually difficult to produce by traditional processing methods, can be produced by LAM [5].

Laser-based Powder Bed Fusion (PBF) and laser-based Direct Energy Deposition (DED) are two categories in LAM. Laser-based PBF uses the laser as a heat source to selectively fuse powder which is preplaced layer by layer. Among various PBF systems, Selective Laser Sintering (SLS), first created at the University of Texas [7], is a technology that fuses the substrate and binds powder together to make a solid product. Compared to SLS, Selective Laser Melting (SLM) uses a comparatively high-power laser to fully fuse the powders and a fully dense product can be produced [8]. Laser-based DED process uses a laser to fuse metal powders, which are injected into the melt pool by a feeder. In different literature and systems, laser-based DED is also called Laser Metal Deposition (LMD) [9], Laser Engineered Net Shaping (LENS) [4] and Laser Cladding (LC). Laser Cladding is successfully used in repairing machine part and improving corrosion, erosion and wear resistance [10].

However, the quality of the product cannot fully meet the requirement of the industrial application and hamper further development of LAM. The quality issues such as dimensional and form errors, unexpected mechanical property and internal defects are still challenging due to a serial of reasons: There is need to optimize the process parameters for the product quality to meet the requirements, but the underlying physics process is not completely clear at present. This physics process involves heat and mass transfer, convection of liquid metal and non-equilibrium solidification due to high heating and cooling rate and temperature gradient. Insufficient understanding of the formation mechanisms of defects results in higher defect ratios with respect to conventional production systems [11]. The material experience a serial of the phase transition processes, that is solid-liquid-solid and the solid phase transformation process [12]. The microstructure evolution influences the final mechanical properties of the product [13]. Thermal expansion and cooling of material cause thermal stress, which, leads to distortion and cracking of product. The issue of prevention and control of thermal stress is especially necessary for producing large parts [14]. In the underlying physics, thermal behavior, as a

key factor governing the transformation of microstructure, evolution of stress and pattern of fluid convection, has a significant influence on acquiring high-quality products.

To solve quality issues, many high-level literature reviews about online monitoring and control have been provided in recent years [15,16]. Schoinchoritis et al. [17] summarized the numerical models in powder bed additive manufacturing and concluded that the temperature field was what most studies target at. These published works give an overview of the monitoring and control methods or numerical models, but there is few published review summarizing the investigation of thermal behavior and relationship between temperature distribution and the product quality. In this paper, we focus on the thermal behavior of LAM and consider it as the process signature that links the process parameters and the product quality. This review is organized as follows. In Sections 2 and 3, the temperature monitoring methods and mathematical models of thermal analysis are discussed respectively. The parameters-thermal behavior-quality relationships are illustrated in Section 4. At last, the conclusion of this review is reached and some future research opportunities are proposed.

2. In-situ temperature monitoring sensors available in LAM

The accuracy and reliability of the temperature process signature should meet the requirement of providing insight into the quality of the product. However, the severe monitoring condition imposes restrictions on the possible temperature sensors. Although the LAM product demands dozens of hours to be completed, the process is extremely fast at the scale of the laser process zone [18]. The size of melt pool is rather small compared to that of the product. Due to these restrictions, high speed of data acquisition and high resolution are needed for sensors to capture signatures of the melt pool. Researchers have explored new forms of temperature measurement technique and appropriate methods applied in LAM process, including the contact measurement and contactless measurement.

2.1. Contact measurement

Thermocouples are sensors that carry out contact measurement of temperature by fixing the one end of the sensor on the metal. Thermocouples consist of two metal wires of various materials with one end connected to form a closed circuit, in which potential difference is detected and converted into temperature. Although there are a number of advantages such as low cost, high accuracy and convenient calibration, thermocouples have limited use in LAM because of some weaknesses. First, the temperature distribution is disturbed by the initial temperature of the thermocouples for the direct contact between the sensors and the part. Second, the thermocouples are fixed on the part by welding. As a result, they are liable to interfere with the laser spot and fail to trace the movement of the melt pool with the moving laser head.

The major usage of thermocouples is in-situ monitoring of substrate temperature. Griffith et al. [19] first monitored the temperature by implanting a type C thermocouples into one-line width wide shell boxes during fabrication. Ya et al. [20] inserted four thermocouples into the substrate at different depths below the top surface of the substrate along the cladding direction and the other four perpendiculars to the cladding direction. Zhang et al.

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