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Overhang structure and accuracy in laser engineered net shaping of Fe-Cr steel

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ABSTRACT

Laser engineered net shaping (LENS), developed from laser cladding and rapid prototyping, has different promising applications such as aerospace, automotive, marine, tool manufacturing, etc. Due to the features of LENS process, the capability of overhang structure deposition was limited and some geometrical structures cannot be perfectly built. Investigating overhang building mechanisms and angle accuracy are crucial. In this study, the effects of scanning patterns (reciprocating and unidirectional deposition way) and vertical increment (z-increment) on overhang structures in LENS have been investigated. It was found that the overhang deposited in a reciprocating way exhibited higher geometry accuracy than that deposited in a unidirectional way. By optimizing z-increment, the discrepancy between the designed and experimental inclined angles of overhangs greatly decreased. The effects of processing parameters, including laser power, scanning speed, and powder feed rate, on the optimal z-increment were also investigated.

1. Introduction

In recent years, laser additive manufacturing (LAM) process has received a great amount of attention in the different industries of aerospace, automotive, marine, tool manufacturing, etc. due to the advantages of high energy efficiency, high geometry freedom, and high production flexibility, etc. [1,2]. LAM, mainly including powder bed fusion mode and direct laser deposition mode, is an incremental layer-by-layer manufacturing process that creates the final shape by adding materials [3]. Compared with powder bed fusion LAM, such as selective laser sintering/ selective laser melting, direct laser deposition, such as laser engineered net shaping (LENS), presents more advantages, including capabilities of metallic coating, high-value component repair, and functionally graded materials fabrication [4,5]. In LENS process, a substrate is melted by a laser beam to create a small molten pool that catches and melts metal powders. These powders can be delivered by a flowing inert gas (such as Argon) stream through the coaxial nozzles. With the melting of the powders and solidification of the molten pool, the track/layer is deposited according to the trajectory of designed structures. Afterward, the deposition head ascends one layer thickness to a new position for the next layer deposition. Then a similar process will be repeated many times until the three-dimensional metal parts are consequently fabricated in a track-by-track and layer-by-layer mode [6–10]. Due to the lack of supporting structure, the capability of overhang structure deposition in LENS is limited. The overhang structure fabrication is hard to achieved in LENS, as the actual fabricated overhang angle is usually different from the designed one [11]. Thus, it is of great significance to investigate the LENS-fabricated overhang structures in an accurate dimensions and good quality.

It was reported that the overhang structure deposition was mainly affected by scanning pattern and vertical increment (z-increment) [12]. The scanning pattern would affect the temperature distribution within the deposited parts, thus resulting in a various residual stress distribution and part deformation. Therefore, the scanning pattern played a significant role in the deposition of overhang structure. Ensz et al. studied the optimal border outlines and fill patterns for LENS and founded that the deposition is affected by the scanning path [13]. He et al. focused on the influences rule scanning pattern on the solid parts fabricated by LENS process and analyzed the relationship between the inclined angle

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of molten pool on the edge of solid part and the scanning pattern [14]. Wang et al. investigated the offset value, forming height and inclined angle in the LENS-fabricated inward and outward thin-walled parts. The inward thin-walled part presented larger forming height and larger inclined angle than the outward one under an equal offset condition [15].

In LENS process, the z-increment not only determines the build rate but also directly influences the characteristics of the molten pool, such as the mass transfer, heat transfer and cooling rate, and thus further affects the performance of the final part [16]. The relationship between the z-increment and deposition height is a crucial factor to fulfill the high-quality deposition. In an ideal situation, the z-increment should be kept consistent with the deposition height to guarantee the same processing condition in each layer [15,17]. However, owing to the uncontrollable residual heat and deposition process, the deposition conditions (such as the powder utilization efficiency) were not constant for each deposition layer. Therefore, the z-increment in single wall deposition process should be fixed at a value which is smaller than the height of the first deposited layer, as shown in Fig. 1(a) where Δz is z-increment, h is the height of the clad and w is the laser clad width. Some studies have made efforts to investigate the effects of z-increment in LENS process. Ma et al. studied the influences of z-increment on relative density, metallurgical bonding mechanisms, microstructure and mechanical properties of 1Cr18Ni9Ti stainless steel parts by LENS. Zhang et al. and Guan et al. investigated the effects of z-increment on the density and tensile properties of the fabricated samples by LENS [18,19]. Shim et al. proposed a new procedure for determining the z-increment setting for use in the slicing off a part based on the single-layer height for a given depositing condition in LENS [20]. Zhu et al. investigated the effect rules of z-increment on surface quality by fabricating the thin-walled parts under three different powder defocusing distance and three different laser defocusing distance. They obtained the smooth surface of parts in LENS and developed a simple model of track height [21].

Fig. 1 (b) shows the schematic diagram of overhang structure deposition, in which the designed inclined angle of overhang (θ) equals to $arctan\ (\Delta y/\Delta z)$, where, Δy is y-offset. The angle θ is closely related to the z-increment and y-offset. With the increase of y-offset (Δy), the z-increment (Δz) decreases and the inclined angle (θ) increases. The z-increment affects defocusing distance, laser energy density, the capability of powder capture of molten pool, the deposition height, and the overhang accuracy as well [20].

Therefore, the overhang structure and accuracy in LENS process are needed to be investigated. In this work, thin-wall was fabricated in order to investigate the overhang structure. The effects of scanning pattern and z-increment on the thin-walled overhang deposition were investigated.

2. Materials, experimental set-up and production procedures

The spherical stainless-steel powder (17-4PH, Carpenter Powder Products Inc., Bridgeville, PA, USA) was utilized for thin-walled overhang deposition and the range of particle size was 40–105 µm. Table 1 shows the chemical composition of 17-4PH stainless steel powder. The substrate material utilized in the experiments was low carbon steel with dimensions of $130 \times 20 \times 8$ mm^3.

The experiments were carried out on a LENS system (450XL, Optomec Inc., Albuquerque, NM, USA). As shown in Fig. 2, the LENS system mainly included a standard IPG fiber laser which could supply 400 W maximum laser power, a coaxial deposition head for powder and argon gas delivery, a 3-axies motion numeric control system, and a powder feeder system in which the powder was delivered by argon gas with the purity of 99.99%. The oxygen level was lower than 500 ppm in the chamber.

In order to investigate the overhang structure and accuracy in LENS, a series of experiments were conducted to fabricate thin-wall overhangs under different conditions. The processing parameters were chosen based on single wall deposition, including laser power of 350 W, scanning speed of 6.50 mm/s, powder feed rate of 0.089 g/s and z-increment of 0.25 mm. The single wall can be perfectly built using these processing parameters. The experimental inclined angles of overhangs were obtained by measuring the image of overhang cross-section with the help of AutoCAD software.

3. Results and discussions

3.1. Effects of scanning pattern

The effects of scanning pattern on geometry accuracy of overhang were investigated by depositing two kinds of thin-walled overhangs with different scanning pattern, including reciprocating and unidirectional deposition way. Fig. 3(a) and (b) show the front and side views of deposited thin-walled overhang. It can be seen from Fig. 3(a) that the overhang deposited by reciprocating way exhibited high geometrical integrity with even and symmetrical surface. On the other side, the overhang deposited by unidirectional way exhibited uneven surface and large cavities on the left side (end side of path), as shown in Fig. 3(b). These phenomena were explained in Fig. 3(c) and (d). Due to the fluidity of molten pool and support of the former deposited layer, the molten pool at the end of deposition path was inclined. Then, the height of the newly deposited layer at the end of deposition path (Region A) decreased because of the decrease of powder utilization and energy density induced by defocusing. In reciprocating deposition

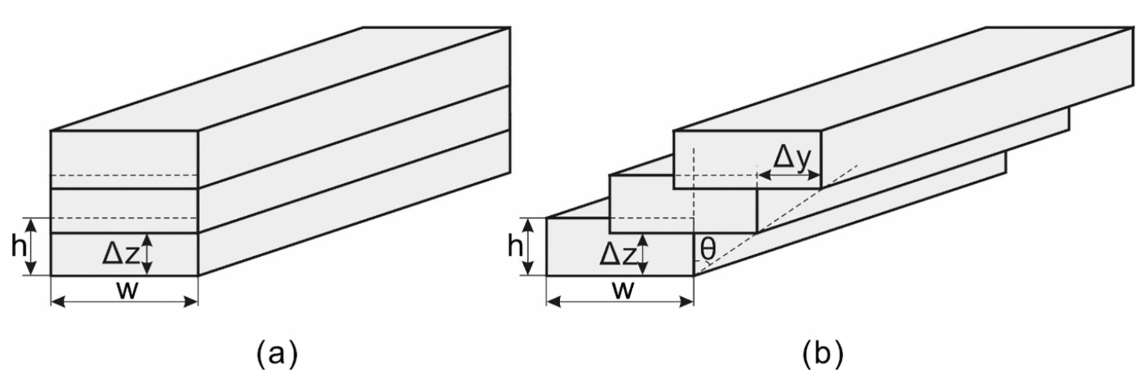

Fig. 1. Schematic of the cross-section of deposited (a) single wall and (b) overhang structure.