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The influence of scanning methods on the cracking failure of thin-wall metal parts fabricated by laser direct deposition shaping

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ABSTRACT

In order to improve the quality of thin-wall metal parts fabricated by laser direct deposition shaping method, using “element birth and death” technique, a three-dimensional multitrack and multilayer thin-wall model was developed. Different scanning methods, including long-edge parallel reciprocating scanning, short-edge parallel reciprocating scanning and inter-layer orthogonal parallel reciprocating scanning, were researched. The Von Mises equivalent stress, and its X-directional, Y-directional and Z-directional principal stresses were analyzed in detail. Under the same conditions used in the simulations, the deposition experiments were conducted, and the influence of different scanning methods on the cracking failure behavior of thin-wall metal parts was discussed.

1. Introduction

As a novel 3D printing technology, laser direct deposition shaping (LDDS) is an effective method to fabricate metal mechanical parts in “what you see is what you get” manner [1–7]. However, owing to the tremendous temperature gradient along height direction, highly concentrated energy inputting and large ratio of height to width, thin-wall metal parts, such as turbine blades, are more prone to cracking, even fracturing, under the action of the huge thermal stress during laser deposition process. Therefore, in order to restrain the initiation and propagation of cracks during LDDS process, it's necessary to reveal the influence of key parameters on the cracking failure of thin-wall metal parts, such as scanning methods.

In the past 20 years, much work has been done in exploring the thermal behavior during laser rapid production process [8–16], but most of it was concentrated on the laser metal sintering (LMS) technology. As for LMS and LDDS, there are essential differences between them, although they are both of the additive manufacturing methods. During the typical process of LDDS, the powder bed doesn't exist, and the substrate is fixed on the workdesk, which doesn't move at all. Therefore, the simulation methods of LMS and LDDS are also quite different. To date, researches on the thermal behavior of thin-wall metal parts fabricated by LDDS have rarely been reported [17–20], especially for different scanning methods.

Based on previous research [21–22], a three-dimensional multitrack and multilayer model was developed, using an “element birth and death” technique. Since scanning methods can significantly affect the temperature distribution between metal parts and their substrates, they were chosen as the main research object in this paper. The thermal behavior data under different scanning methods was obtained, including transient temperature and stress fields, temperature gradient vector graphs, the Von Mises equivalent stress, as well as its three principal stresses in X, Y and Z directions. The LDDS experiments were conducted

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Table 1
Chemical compositions of Ni60A powder.

	C	Al	Si	Cr	Fe	Ni
Ni60A (wt.%)	0.5	0.3	0.45	19	1.4	Bal

under the same conditions, the influence of different scanning methods on the cracking failure of thin-wall metal parts was also discussed.

2. Modeling of simulations

Through the ANSYS/LS-DYNA module, a three-dimensional multitrack and multilayer thin-wall model was developed. The classic governing and constitutive equations of heat transfer process in the material with isotropic thermal properties were used as those in Ref. [21]. For economy and practicality, Ni60A alloy powder was chosen as the deposited material, and Q235 (ASTM A283M Gr.D) plate was used as the substrate. All thermal–physical properties of both deposited material and substrate were temperature-dependent, and only heat conduction was considered in the simulations. The chemical compositions of Ni60A are listed in Table 1. The thermal–physical properties of Ni60A and Q235 were the same as in Ref. [21]. As shown in Fig. 3, the substrate was machined into 100 mm × 50 mm (long × width) with thickness of 10 mm. The thin-wall metal part was divided into four tracks and four layers, wherein the height of each layer and the width of each track were both equal to the laser spot diameter, i.e., 1 mm. The phase change phenomenon of nickel-based alloy powder during LDDS process was taken into account, using enthalpy method by an artificial increase in its liquid specific heat.

The long-edge parallel reciprocating scanning method (LPRS), short-edge parallel reciprocating scanning method (SPRS) and inter-layer orthogonal direction-changing parallel reciprocating scanning method (IODPRS) were all introduced (see Fig. 3). Obviously, IODPRS method was the combination of SPRS and LPRS. That is, in IODPRS method, LPRS method was used in odd layers, while SPRS method was applied in even layers. As shown in Fig. 2, after one layer was deposited, the laser beam would be moved from the end point (EP) of current layer to the starting point (SP), and lifted a distance by one layer's height along the Z-direction. And then, a new layer could be fabricated sequentially. The detail processing parameters included: laser power, 800 W, laser spot diameter, 1 mm, scanning velocity, 5 mm/s, simulation time, 160 s (i.e. 40 s per layer). All researches were conducted at room temperature (20 °C), with a relative humidity of 40%.

3. Results of simulations

3.1. Transient temperature variation during LDDS process

The temperature contours at different times using different scanning methods are shown in Fig. 4. It is evident that the temperature contours in Fig. 4(c) were the combination of the contours in Fig. 4(a) and (b). The temperature–time curves of different nodes at cross section *A–A* (see Fig. 2) using different scanning methods are demonstrated in Fig. 5. When LPRS was used, as shown in Fig. 5(a), node 1 was under "death" condition and kept at 20 °C before the 5th second, without any temperature variation. At the 5th second, when laser beam just moved to its upside, node 1 was activated and its temperature rose to 834 °C in an instant. It should be mentioned that, when node 2 was activated, for the short distance between node 1 and 2 (see Fig. 2), the temperature of node 1 would also be affected by the heat conducted from the molten pool region and its neighboring domain. With the ongoing of LDDS process, nodes 1, 2 and 3 were heated and cooled again and again, but their temperature variations were getting smaller. Distinctly, node 3 had a similar temperature–time curve as that of node 1, and the temperature–time variation regularities of nodes 4 and 6 were also similar to those of nodes 1 and 3, except for the different activated time.

Compared Fig. 5(b) with Fig. 5(a), when SPRS method was applied, node 1 and node 3 were activated almost at the same time for the short distance along the scanning path, and their highest temperatures were both lower than those in Fig. 5(a). As for the IODPRS method, the temperature curves shown in Fig. 5(c) were also the combination of Fig. 5(a) and (b), and its highest

Fig. 1. Cracked thin-wall metal parts fabricated by LDDS.