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Theoretical Calculation and Experimental Verification of Z increment in Laser Metal Direct Manufacturing

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***Abstract*—In order to improve the quality of laser metal direct manufacturing parts, the Z increment mathematical model was established, and the optimal Z increment was solved theoretically. The results show that Z increment is the function of single-track single-layer forming height, and has nothing to do with forming width. In order to verify the theoretical model, the contrast experiment was carried out. The results demonstrate the correctness of the theoretical model, and it is found that when the Z increment and forming height meet the corresponding function, the forming results are the most ideal. This study provides a practical reference for laser metal direct forming process optimization.**

***Keywords*—Laser metal direct manufacturing, Z increment, Experimental verification**

I. Introduction

Laser Metal Direct Manufacturing (LMDM) technology is a combination of rapid prototyping technology and laser cladding technology. It is a kind of advanced manufacturing technology which can convert the CAD model into complex metal parts directly without tools and dies [1]. The technology can directly produce 3D full density metal parts with complex shape and good mechanical properties. It has a series of advantages such as fast manufacturing speed, good flexibility, short production cycle, low cost and so on. It has a wide application prospect in aerospace, automobile and ship, weapons and equipment, biomedical and other fields [2, 3].

In the process of laser metal direct manufacturing, the interaction of laser, metal powder and substrate is a complex physical process. The process parameters in the forming process play a decisive role in forming quality [4]. Z increment is one of the most important parameters in laser metal direct manufacturing technology. Its size will directly affect the macro level and the quality of precision. The theoretical model of Z increment is established and verified by experiments in this paper.

II. Theory and Method

Single-track multi-layer stacking forming is based on single-track single-layer forming. It is obtained from the continuous accumulation of Z, which is the basis of thin-walled parts laser direct deposition manufacturing. Single-track multi-layer stacking forming diagram is shown in Fig. 1. The coaxial powder feeding head is driven by robot along the Y to the linear motion. After the movement to the endpoint, the powder feeding head exercises a certain distance along the Z, and then returns along the Y. So repeated, the required height of the single-track multi-layer thin walled parts is got finally.

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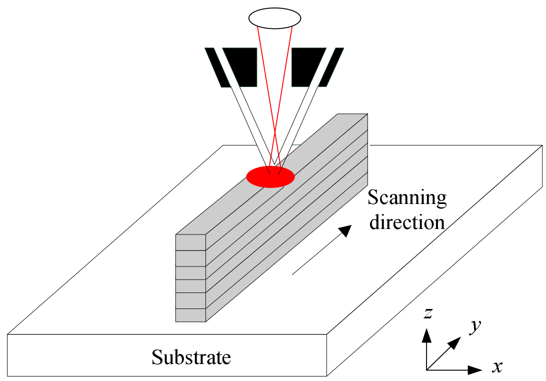


Fig. 1. The diagram of single-track multi-layer formation.

According to the principle of single-track multi-layer stacking forming, it is not difficult to see that the process is not only affected by the laser power, scanning speed and powder feeding rate, but also by the Z increment. The distance between the powder collecting point of the coaxial powder feeding nozzle and the molten pool (defined as the powder defocusing amount) is different with different Z increment. So is the distance between the focus of the focusing lens and the molten pool (defined as the laser defocusing amount). The powder defocusing amount determines the size of the powder flow density in the molten pool. The laser defocusing amount determines the distribution of laser energy in the molten pool. The two have direct effect on the molten pool size, and have influence on the forming height and width. Therefore, it is of great significance to set up appropriate Z increment for the single-track multi-layer stacking forming in metal laser direct deposition.

The Z increment is calculated by the establishment of the process model according to [4].

In order to facilitate the analysis and calculation, it is assumed that the cross section of each forming trajectory is parabolic, and the curvature of each trajectory remains unchanged. In addition, each trajectory powder usage is the same. The model is shown in Fig. 2.

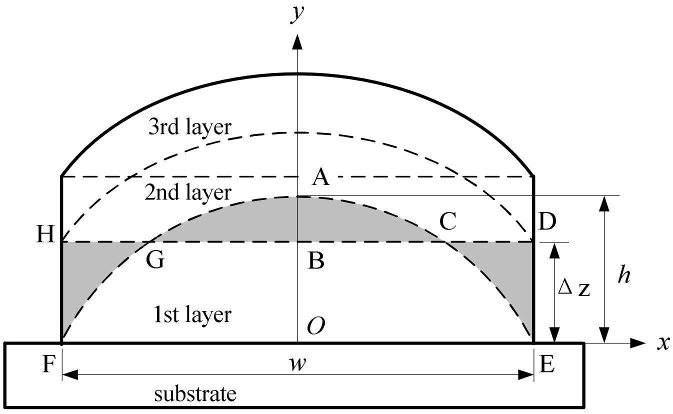


Fig. 2. The model of Δz in single-track multi-layer formation.

The first layer is formed on the substrate and the second layers are formed on the formed layers in single-track multi-layer formation. According to the above, each layer of trajectory section is a parabola. In order to ensure the surface level of the subsequent accumulation layer, each layer accumulation before, the forming trajectory overlap (curved triangle in the GAC region in Fig. 2 of this layer and the layer before should be melt and complemented to both sides of the melting region (curved triangle FGH and CDE area in Fig. 2.

A following equation is obtained by the analysis above

$$S_{GAC} = S_{FGH} + S_{CDE} \tag{1}$$

According to the asymmetry

$$S_{ABC} = S_{CDE} \tag{2}$$

In the coordinate system shown in Fig. 2, the parabolic equation of the first layer trajectory section can be evaluated.

$$f_1(x) = -\frac{4h}{w^2}x^2 + h \tag{3}$$

The linear HD equation is;

$$f_2(x) = \Delta z \tag{4}$$

Assuming that the coordinates of the intersection point C of $f_1(x)$ and $f_2(x)$ is (a, b), the area is solved by the integral method

$$S_{ABC} = \int_0^a [f_1(x) - f_2(x)]dx \tag{5}$$

$$S_{CDE} = \int_a^{\frac{w}{2}} [f_2(x) - f_1(x)]dx \tag{6}$$

$$\begin{aligned} S_{ABC} - S_{CDE} &= \int_0^a [f_1(x) - f_2(x)]dx - \int_a^{\frac{w}{2}} [f_2(x) - f_1(x)]dx \\ &= \int_0^a [f_1(x) - f_2(x)]dx + \int_a^{\frac{w}{2}} [f_1(x) - f_2(x)]dx = \int_0^{\frac{w}{2}} [f_1(x) - f_2(x)]dx \\ &= \int_a^{\frac{w}{2}} \left[-\frac{4h}{w^2}x^2 + h - \Delta z \right] dx = \frac{w}{6}(2h - 3\Delta z) = 0 \end{aligned} \tag{7}$$

Solving the (7) yields

$$\Delta z = \frac{2}{3}h \tag{8}$$

III. EXPERIMENTS

The experiments were carried out with the DLF setup. The setup system includes a fiber laser with a 2000 w maximum output power, a robot with six-axis, a powder feeder system and other auxiliary equipment. The substrate material used in the experiments was Inconel 625 alloy, polishing the substrate before the experiment to remove the surface oxide scale layer and increase its surface finish, and then wash it with acetone [5]. The powder material used was also Inconel 625 alloy, the composition of the powder is shown in Table I. The Inconel 625 alloy powder was placed at 120 centigrade vacuum environment for drying treatment.

TABLE I. POWDER COMPOSITION OF INCONEL 625.

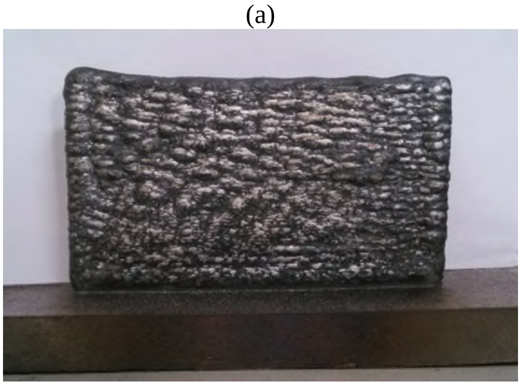
Cr	Mo	Nb	Fe	Si	C	Al
21.3	8.58	3.73	0.11	0.09	0.053	0.18
Ti	Mn	S	P	Co	Ni	
0.16	0.04	0.001	0.04	0.025	Bal.	

TABLE II. THE MAJOR PROCESS PARAMETERS IN MULTI-TRACK SINGLE-LAYER FORMATION EXPERIMENT.

Laser power P/W	Scanning speed v/ mm·s^{-1}	Powder feed rate f/g·min^{-1}	Laser spot diameter D/mm	Standoff distance L/mm	Carrier gas flow rate q/ml·h^{-1}	Shielding gas flow rate Q/ml·min^{-1}
2000	4	20	3	16	450	300

It can be seen in (8) that Z increment is the function of single-track single-layer forming height, and has nothing to do with forming width. In order to verify the correctness of the Z increment theoretical model, the $\Delta z = h$ and $\Delta z = \frac{2}{3}h$ is used for validation test respectively. The parameters used in the experiments are as shown in Table II. In order to determine single-layer forming height, the single-track single-layer forming test is carried out first in accordance with the same parameters. The $h = 2.25mm$ is measured. The $\Delta z = h = 2.25mm$ and $\Delta z = \frac{2}{3}h = 1.5mm$ is sot for validation test respectively. The test samples are shown in Fig. 3. It can be seen that the forming quality is poorer when the Δz is $2.25mm$. The samples appear larger waves, and the surface smoothness is not very ideal. The surface uneven situation is more and more serious with the increase of the layer number of forming. The forming test have to be terminated eventually. However, when the Δz is $1.5mm$, the samples surface is relatively smooth, and can form stably and continuously. Therefore, the above model is correct and feasible.

(a)



(b)

Fig. 3. The impact of Δz on formation quality in single-track multi-layer (a) $\Delta z = 2.25mm$ (b) $\Delta z = 1.5mm$.

IV. SUMMARY

Z increment is the function of single-track single-layer forming height, and has nothing to do with forming width. The results of contrast experiment demonstrate the correctness of the Z increment theoretical model. It provides a practical reference for laser metal direct forming process optimization.

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