The influence of technological parameters on the bead geometry in the manufacture of parts by laser metal deposition

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Abstract. The dependences of geometric characteristics of single tracks obtained by laser deposition of austenitic steel powder on the shift of the laser beam focus and the distance from the nozzle to the substrate at different values of mass flow and scanning speed are investigated. It is shown that the characteristic value of the track height decreases from 900 to 700 microns with a decrease in the beam size by half at a powder flow rate of 8.4 g/min and a speed of 350 mm/min, decreases from 1100 to 900 microns at a flow rate of 15.6 g/min, and increases by 30-50% with an increase in flow rate by 2.3 times. The ratio of height to width (shape factor) decreases with the growth of the scanning speed from about 0.7 to 0.4 at a flow rate of 15.6 g/min and to 0.25 at a flow rate of 8.5 g/min. Process performance scaling parameters are defined. The results obtained make it possible to optimize the technological parameters of the laser metal deposition process.

1. Introduction

In the additive technology of laser metal deposition (LMD), the product is manufactured by sequential layer-by-layer deposition of individual tracks as a result of the action of the laser beam on the powder flow near the previous layer or substrate [1]. Meanwhile, the spatial distributions of the powder flow and laser radiation are heterogeneous. A shift in the waist positions of the laser beam and the powder flow relative to each other changes the region and the degree of heating of particles by radiation, and the distance to the substrate affects the efficiency of its melting by laser radiation and the size of particles deposition region. Consequently, these parameters and the structure of the laser radiation interaction with material determine the productivity and efficiency of the LMD process [2, 3]. As a result, during layer-by-layer synthesis of a product, it is necessary to control both technological parameters, for example, laser beam power, scanning speed, as well as process characteristics: temperature and size of the melt region, height of the deposited layer [4–8]. In this work, we studied the dependences of the geometric characteristics of single tracks on the distance from the nozzle to the substrate and the shift of the laser beam focus at different values of mass flow rate and scanning speed.

2. Experimental results

The experimental setup was described in [9]. In the setup, LK-400-V fiber laser of 400 W power and Precitec YC52 laser head with a coaxial nozzle were used together with the Kuka KR10 900-2 manipulator. GTV PF 2.1 powder feeder was used for feeding of austenitic steel PR-Cr18Ni9 powder.
with a particle size distribution (40…100) microns. Powder flow rate $G_0$ ranged from 8.4 g/min to 19.6 g/min. Scanning speed $V$ was set within (350...1100) mm/min. The distance from the lower plane of the nozzle to the plane of the maximum concentration of the gas-powder mixture $C_z$ was 10 mm.

Let us introduce the notation of the distance from the lower plane of the nozzle to the position of the laser focus (shift of the beam focus) $B_z$, and to the position of the substrate $-D_z$.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Dependences of the height of the track $H$ and the ratio of the height to width $K$ on the shift of the focus $B_z$ for various values of $V$ and $G_0$. Designations for speed $V$: 1 - 350 mm/min; 2 - 500 mm/min; 3 - 800 mm/min; 4 - 1100 mm/min.

Experiments were conducted on the formation of single tracks on an AISI 304 steel substrate. The experiments were repeated at different $B_z$ values: 1, 2, 4, and 6 mm. In total, about 200 samples were obtained at various values of the technological parameters. Figure 1 shows the results of measuring the geometric characteristics of the obtained tracks: height $H$ and the ratio of the height of the track to its width (shape factor) $K$, depending on the focus shift for different values of $V$ and $G_0$.

As follows from the obtained results, the dependence of the track height on the shift of the beam focus is observed only at a speed of 350 mm/min. With a powder flow rate of 8.4 g/min, the height decreases from about 900 to 700 $\mu$m with an increase in focus shift from 1 to 6 mm (and a corresponding decrease in the beam size by almost half), and with a flow rate of 15.6 g/min - from
1100 to 900 μm. With increasing speed, there is no significant dependence of the track height on the focus shift. With an increase in flow rate by 2.3 times, the characteristic value of the height increased by 30-50%. The shape coefficient of the track $K$ decreases with increasing scanning speed from about 0.7 to 0.4 at a flow rate of 15.6 g/min and to 0.25 at a flow rate of 8.5 g/min.

In order to scale the performance of LMD, the initial experimental data were parameterized in the space of generalized technological parameters. Attempts to parameterize the LMD model were undertaken in [3–5]. We based on the model described in [10]. In this model, describing the temperature distribution on the substrate surface under the influence of a Gaussian beam of laser radiation, it is shown that, taking into account the thermal losses, the dynamics of the system is characterized by a scaling parameter depending on $\omega$ and $V$. It was shown earlier in [11] that for the model described in [10], the quadrature formulas and the trigonometric function can be replaced by approximate power-law dependencies of the arguments with the constraint $0.3 < \frac{\omega V}{\chi} < 8$, where $\omega$ is the beam size and $\chi$ is the thermal diffusivity of the material. The characteristic radius of the beam $\omega$ on the substrate can be determined depending on the values of $B_z$ and $D_z$ [1], as:

$$\omega(B_z, D_z)^2 = \omega_0^2 + (BPP/\omega_0)^2(D_z - B_z)^2,$$

where $\omega_0$ is the characteristic radius of the beam in the waist, $BPP$ is the quality parameter of the laser beam. In our case: $\omega_0=50$ μm and $BPP=3.71$ mm·mrad, and in the experiments described by us, the condition $0.3 < \frac{\omega V}{\chi} < 8$ is satisfied over the entire range of technological parameters.

Figure 2(a) shows the dependence of the experimental values of the track width $B(\alpha)$ and the sum of the track height and penetration depth $H_1(\beta)$ for different values of powder flow rate $G_0$: A - 8.4 g/min; B - 12.5 g/min; C - 15.6 g/min; D - 19.1 g/min.

Figure 2(a) shows the dependence of the experimental values of the track width $B$ on the generalized technological parameter $\alpha \sim V \cdot \omega^{-0.4}$ for $G_0 = \text{const}$. The introduction of the parameter $\alpha$ makes it possible to approximate the data of the track width obtained for different values of $V$, $B_z$, and $D_z$ with one power-law dependence of $\alpha$:

$$B \sim \alpha^{-0.433}. \quad (2)$$

From the obtained set of dependences of the track width for various mass flow rates $G_0$, one can determine the contribution of the latter:
\[ B \sim \alpha^{-0.433} G_0^{0.33} \]. \hspace{1cm} (3)

Figure 2(b) shows the dependence of the experimental values of \( H_1 \) (the sum of the track height and penetration depth) on the parameter \( \beta \sim V \cdot \omega^{0.46} \), \( \frac{\text{mm}}{\text{s}} \). Similarly, carrying out the parameterization of the experimental dependences \( H_1 \), we obtain:

\[ H_1 \sim \beta^{-0.9} G_0^{0.4} \]. \hspace{1cm} (4)

Given that the performance of the LMD \( G \sim BH_1 V \), as well as taking into account the obtained dependences (3)-(4), we can write:

\[ G \sim \omega^{-0.25} V^{-0.333} G_0^{0.733} \]. \hspace{1cm} (5)

We introduce the parameter \( E_S \) - energy averaged over the area of the beam per unit surface:

\[ E_S = \frac{2 \varepsilon P}{\pi \omega V} \], \hspace{1cm} (6)

where \( \varepsilon \) is the thermal efficiency of the laser radiation. From (5)-(6) we obtain the expression:

\[ G \sim E_S^{0.333} \omega^{0.083} G_0^{0.733} \]. \hspace{1cm} (7)

Note that expression (7) was experimentally verified by us only for the \( \varepsilon \) value of the material and the wavelength used, and also under the condition of \( P = 400 \text{ W} \). As follows from (7), the performance of the LMD technology in the range of technological parameters studied is proportional to \( E_S \) raised to the 0.333 powers and \( G_0 \) raised to the 0.733. In [4], the exponent 0.75 was established for \( G_0 \). Moreover, the performance is almost independent of the size of the beam if, with its change, \( \omega \cdot V = \text{const} \) is kept.

3. Conclusions

It is shown that the characteristic value of the track height decreases from 900 to 700 \( \mu \text{m} \) with a decrease in the beam size by half at a powder flow rate of 8.4 g/min and a speed of 350 mm/min, from 1100 to 900 \( \mu \text{m} \) at a powder flow rate of 15.6 g/min, and increases by 30-50% with an increase in flow rate by 2.3 times. The ratio of height to width (shape factor) decreases with increasing scanning speed from about 0.7 to 0.4 at a flow rate of 15.6 g/min and to 0.25 at a flow rate of 8.5 g/min. Process performance scaling parameters are defined. The results obtained make it possible to optimize the technological parameters of the laser metal deposition process.

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