Parameterization of the characteristics of the melt pool using the video diagnostics of the laser metal deposition process

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Abstract. The dependences of the geometric characteristics of the melt bath on the scanning velocity and radiation power during laser metal deposition (LMD) are shown. The data were obtained experimentally at different values of the intensity $I_s$ up to 60 kW/cm² in the range of changes in the specific energy per unit surface area $E_s$ (20...60) j/mm² using the high-speed video camera installed in coaxial scheme. A powder (40...100) microns of PR-Kh18N9 austenitic steel with a mass flow rate of 8.4 g/min was used. It is found that the length of the melt pool $L$ increases with the growth of $I_s$ and practically does not depend on the scanning velocity in the range (5...10) mm/s. The melt volume is estimated taking into account the measured track height. At the same velocity, the volume of the melt increases with the value of the $I_s$ exceeding the threshold. The value of threshold increases with increasing velocity. The volume of the melt increases with the specific energy $E_s$. The relationship between the geometric characteristics of the melt bath and the shape of the track formed in the LMD process is shown.

1. Introduction

In additive laser metal deposition (LMD) technology for multi-layer material deposition, it is important to know the geometric characteristics of a single track in order to calculate the step between adjacent tracks or the distance between layers. The track is formed during the crystallization of the melt at the interphase boundary of the bath formed by the thermal action of laser radiation during scanning of the substrate or the previous deposited layer. In this regard, the article presents the dependences of the geometric characteristics of the melt bath on the scanning velocity and radiation power in the LMD process. The dependences of the size of the melt bath on the power $P$ and velocity $V$ are presented in [1], but in this work, when the mass flow rate of the $G_0$ powder is less than 3 g/min (tool steel 32CrMoV 12-28), the size of the melt pool (MP) it was determined by the size of the laser spot and the length of the MP approximately coincided with the width. In [2], the length and width dependences on $P$ and $V$ of the 431L steel powder with $G_0$ of about 12 g/min are presented. However, the paper does not provide the geometric characteristics of the formed tracks. Earlier in [3], such data were presented in a wide range of changes in $P$, $V$, and $G_0$. In [4], the dependences of the depth of penetration of the substrate under these conditions are also presented, which is important for estimating the associated necessary heat costs in addition to the energy costs for forming the track. In particular, it is shown that the mass productivity increases as $E_s^{1/3}$ when the mass flow rate of the powder is constant, where $E_s$ is the specific energy per unit
surface of the irradiated substrate [3]. The depth of penetration of the substrate is largely determined by the intensity of the \(I_s\) radiation of the substrate [4]. This paper presents data on the parameters of the melt bath and the geometric characteristics of the track formed in the LMD process.

2. Experimental setup

The experiments were carried out on the additive technology unit developed at ILIT RAS (figure 1). Experimental samples of single tracks with the length of 40 mm each were made using LMD technology. The fiber ytterbium laser LK-400-V (NTO “IRE-Polyus”) was used. The laser radiation passes through the coaxial stream of the gas-powder mixture and focused in Precitec YC52 laser head near the substrate.

![Figure 1. The photo of the LMD experimental setup: a) General view, b) inside view.](image)

The KR10 900-2 manipulator (KUKA Roboter GmbH) provides laser scanning of the substrate. Powder PR-Kh18N9 with the granulometric composition (40...100) microns was deposited on the substrates made of St 3 steel with the mass flow rate of 8.4 g/min. Each track was formed in the quasi-stationary mode with constant values of the scanning velocity \(V\), laser power \(P\), distance from the nozzle to the substrate, and the position of the beam focus relative to the substrate. Velocity ranges (5...12.5) mm/s and power (180...410) W. To diagnose processes on the melt surface of the formed track, data was recorded with the high-speed video camera Mikrotron 3010, installed according on the coaxial scheme.

![Figure 2. The sequence of frames (n, n+1... n+3) of the melt bath, scale 800 microns.](image)

The use of video diagnostics of thermal radiation allows you to register the horizontal projection of the MP surface. An overview of diagnostic methods is given in [5]. The magnification of the optical scheme was x1.33 when using the telescopic nozzle with the scattering lens x2.2. Thus, the spatial resolution of the system was about 10 microns with the time resolution of 300 µs. Consecutive frames of the MP image are shown in figure 2 at \(P = 210\) W and \(V = 8\) mm/s, the frame repeat rate is 650 Hz.
MP is separated, figure 2, from the solid phase of the track by a clearly visible boundary, the position of which is slightly shifted in time relative to the laser heating region. The area of increased glow of the melt is observed in the anterior region of the MP in the direction of movement. The melt has the increased temperature relative to the main part of the MP, which leads to the increased glow. Overheating is due to the fact that there is no convection in this region of the thin layer of the melt, and heat removal is determined by thermal conductivity. In the main volume of MP, the depth is significantly higher, and the convection that occurs in the melt reduces the surface temperature.

3. Experimental results
The obtained dependences of the length $L$ and width $D$ of the melt bath on the intensity $I_s$ of the substrate radiation are shown in figure 3 for different velocity values. The average value of the radiation intensity of the substrate $I_s$ was calculated taking into account the Gaussian distribution in the far zone of the defocused laser beam as:

$$I_s = \frac{P}{\pi \omega^2},$$

where $\omega = 0.63$ mm – characteristic size of the beam radius. The maximum intensity value on the beam axis is twice the average value of $I_s$ and reaches a value of 60 kW/cm$^2$. The length of the melt region $L$ increases with the growth of $I_s$ and practically does not depend on the scanning velocity in the range (5...10) mm/s. When the scanning velocity is increased to 12.5 mm/s, $L$ is noticeably reduced. The width of MP increases with increasing $I_s$. The Width decreases with increasing velocity in the range (8...12.5) mm/s.

Measurements of the height $H_0$ were made for each track formed under the conditions described above. Dependencies of $H_0$ are shown on $I_s$ in figure 4(a). The track height in the velocity range of (5...8) mm/s increases firstly with increasing laser intensity in proportion to $I_s$ from 18 kW/cm$^2$ to 25 kW/cm$^2$, and then increases slightly with increasing $I_s$ to 33 kW/cm$^2$. The track height is almost unchanged in the velocity range above 8 mm/s for $I_s$ from 18 kW/cm$^2$ to 25 kW/cm$^2$, and then increases distinctly.

4. Results of the processing of experimental data and discussion
To scale the LMD process, it is important to know the influence of various factors on the shape and height of the track. Figure 5(a) shows the height data $H_0$, figure 4(a), as a function of $E_S$ for different values of the velocity $V$. As follows from the data obtained, figure 5, the track height is determined primarily by the $E_S$ parameter. In the case of a constant $E_S$ value, the $H_0$ value increases with $P$ in the studied power range in the limit (20...30) %. The dependence of the form factor $F = H_0/H_0$ on the velocity $V$ is shown in figure 5(b) for $I_s$ values over 25 kW/cm$^2$. For these $I_s$ values, the Form factor
depends more on the velocity $V$ over a wide range of $E_S$ changes. It is found that up to $V=8$ mm/min, $F$ changes slightly, and with further growth of the velocity, $F$ increases linearly.

![Figure 4](image1)

**Figure 4.** Dependencies of $H_0$ (a) and $D_0$ (b) on $P$ for different velocity $V$, [mm/s].

The result of measuring the height and form factor of tracks obtained by the CVD method using powder, steel 09CrNi2MoCu, for $I_S$ values up to 60 kW/cm$^2$ in the range of $E_S$ (25, 100) J/mm$^2$ are presented in [6]. The same result was obtained as for us: the form factor practically does not change when the $I_S$ is varied over 30 kW/cm$^2$. The form factor increases linearly with $F$ within $(2...3)$ in the studied velocity range of $(20...50)$ mm/s.

![Figure 5](image2)

**Figure 5.** The dependence of height $H_0$ on $ES$ for different velocity $V$ [mm/s] (a); the dependence of form factor on the velocity $V$ (b).

Thus, if $I_S$ increases at a constant velocity, that is, $E_S$ increases accordingly, and, consequently, the volume of MP will increase, but primarily due to the length of the melt bath, figure 4(a). The height and width of the track will increase slightly while maintaining the shape of the track. As previously mentioned, the mass productivity, determined primarily by the mass flow rate of the powder, increases approximately as $E_S^{1/3}$. If the scanning velocity increases with an increase in $I_S$ over 25 kW/cm$^2$ ($E_S = \text{const}$), the volume of the melt will not change its value, Fig.4(b), but the length of the MP will
increase, figure 3(a), at the same time the height and, accordingly, the form factor of the track will decrease with increasing velocity (figure 5).

5. Conclusion
At the LMD setup, designed at ILIT RAS, the geometrical characteristics of the melt bath were measured at different values of the technological parameters: scanning velocity and radiation power. Experimentally data was obtained with mounted on the coaxial scheme high-speed cameras. Obtained dependences of the width $D$ and length $L_{MP}$ were presented. The height of the received tracks with different values of intensity $I_s$ up to 60 kW/cm$^2$ in the range of $E_s$ from 20 to 60 J/mm$^2$ are shown. The powder (40...100) microns of austenitic steel PR-Kh18N9 with a mass flow rate of 8.4 g/min was used. The length of the melt region $L$ increases with the growth of $I_s$ and practically does not depend on the scanning velocity in the range (5...10) mm/s. The melt volume is estimated taking into account the measured track height. At the same velocity, the volume of the melt increases with the value of the $I_s$ exceeding the threshold, the value of which increases with increasing velocity. The volume of the melt increases with the specific energy $E_s$.

The relationship between the geometric characteristics of the melt bath and the shape of the track formed in the LMD process is shown. The dependence of the form factor on $V$ in the range of variation (5...12.5) mm/min was obtained. When the speed changes (5...8) mm/ min, $F$ will change slightly, with further velocity growth, $F$ increases linearly to 3.

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