The features of the optical pyrometry in the laser metal deposition process

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Abstract. Experimental results of online monitoring of the brightness temperature of the melt surface in the technology of direct laser deposition of the of AISI 304 steel at the off-axis technique are presented. The oscillograms of the temporal behavior of the maximum brightness temperature measured by the pyrometer, as well as the dependence of its average values on the scanning speed, laser power, and the distance from the substrate to the beam focus are presented.

1. Introduction
The creation of product in the technology of direct laser metal deposition (LMD) occurs through the sequential formation of separate tracks. Each track is created by the interaction of laser radiation with a gas-powder flow and a previously deposited material (or substrate) [1–3]. The spatial distributions of the powder flow and laser radiation are inhomogeneous: they have a convergent and then divergent profile, in addition, the powder flow has an annular structure [4–5].

The displacement of the waist positions of the laser beam and the powder flow relative to each other changes the region and the degree of heating of the particles by radiation. The distance to the substrate affects the efficiency of its melting by laser radiation, as well as the size of the settling area of the particles. The ratio of the energy inputs of the heating of the particles and the substrate by laser radiation also changes. As a result, these parameters and the structure of the radiation effect on the material determine the quality and efficiency of the LMD process. The monitoring of the parameters of the interaction of laser radiation with the powder flow and the substrate, the features of heat and mass transfer and the dynamics of the melt surface during the formation of the bead is relevant objective of non-destructive testing in LMD. This paper presents the results of evaluation the temporal behavior of the brightness temperature by pyrometry depending on the scanning speed and laser power, as well as the distance from the substrate to the laser focus position.

2. Experimental setup
Experimental setup, figure 1(a), includes a 400W ytterbium-doped fiber laser 1. The laser radiation passes through the laser head 2 and the coaxial flow of the gas-powder mixture (GPM) 3 and focused near the substrate 4. The bead 5 is formed as a result of the thermal effect of the laser radiation on the GPM and the substrate. The signals formed in block 6 have amplitudes proportional to the illumination of the ends of the optical fibers pressed into the sensor head 7. The ends are illuminated by light
coming from the heated area and a focused by lens 9. The optical filter 8 is installed between the sensor 7 and the lens 9.

**Figure 1.** The scheme of the experimental setup: 1 – laser, 2 – laser head, 3 – GPM flow; 4 – substrate, 5 – formed bead, 6 – block of photodiodes with preamplifier; 7 - sensor head; 8 – optical filter; 9 – pyrometer lens (a). The scheme of mutual disposition of the substrate, ring nozzle, GPM and laser beam (red lines) (b).

The scheme of interaction of laser radiation with the GPM and the substrate is shown on figure 1(b). The coaxial GPM flow is heated in the LMD process in the region of focused laser radiation. The $D_z$ is the distance from the bottom of the nozzle to the substrate. The $B_z$ is the distance from the substrate to the waist of the laser beam. The distance from the nozzle to the cross section of the minimum flow size of the GPS $C_z$ is 11 mm. The position of the focus of the laser beam changed independently of the $D_z$ by moving the collimating lens of the laser head 2 in the vertical direction. The quality and performance of the LMD process can vary significantly depending on the $B_z$, $C_z$ and $D_z$ parameters.

The multichannel pyrometer based on the set of two-color sensors described in [4] was used to control the temperature on the melt surface. The sampling rate of the data of the pyrometer was 5 kHz. Pyrometer have used SWIR spectrum in brightness mode. In previous works the pyrometer used the mode with the adjustment to “sharpness”: the sensor head is located in the plane of the image of the luminous surface of the object formed by the pyrometer lens [4, 6, 7]. In this work the sensor head is located behind this plane at a distance of $h \approx 2.5$ mm to measure the maximum brightness temperature of the molten area. That allows to avoid accidental interference with the shading of the powder particles of thermal radiation from the melt surface.

The powder of austenitic steel PR X18H9, the analogue of AISI 304 steel, with a carbon content of about 0.09% was used in the experiments. Granulometric composition of the powder is $(40...100)$ microns. The substrate of the size of $40 \times 10 \times 4$ mm$^3$ of steel 304 was used. The single 34 mm long track had applied to each substrate at the given values of the technological parameters $B_z$, $C_z$ and $D_z$, with the given scanning velocity $V$ and the laser power $P$. The velocity $V$ varied within $(350...500)$ mm/min in different series of experiments. The parameter $B_z$ took the values of 5 mm, 7 mm and 9 mm and the distance $D_z$ was 11 mm. The mass flow rate of powder $G_0$ was 15.6 g/min. The gas flow rate of the feeder was 15 nl/min, the pressure of the shielding gas was 0.6 MPa, the flow rate of the shielding gas was 10 nl/min.
3. Results and discussion
The temporal dependence of the maximum of the brightness temperature of the melt $T^*$ is shown on figure 2 at a velocity of 350 mm/min and a laser power of 240 W, $B_z=9$ mm. The $T^*$ varies randomly within certain limits with a frequency of about hundreds of hertz [6]. Regular temperature changes can be associated with the peculiarities defined in the balance of heating the metal by laser radiation and heat removal to the substrate [7].

Figure 2. The time dependence of the maximum brightness temperature of the melt $T^*$. The velocity $V=350$ mm/min. The laser power 240 W and parameters are: $B_z=9$ mm, $C_z=11$ mm, $D_z=11$ mm.

The dependences of the averaged values of the $T^*$ on the power $P$ for different values of $B_z$ and velocity $V$ are shown on figure 3(a). The standard deviation of the brightness temperature is shown in figure 3a and was near 1.5 % of the measured value. The dependences of the mass productivity $G$ on the power $P$ under the same other conditions are shown on figure 3(b) for $V=350$ mm/min.

Figure 3. The dependences of the averaged values of the $T^*$ on the power $P$. The values of the parameter $B_z$ and the velocity $V$: 1 – 5 mm and 350 mm/min; 2 – 7 mm and 350 mm/min; 3 – 9 mm and 350 mm/min; 4 – 5 mm and 500 mm/min; 5 – 7 mm and 500 mm/min; 6 – 9 mm and 500 mm/min (a) and the dependences of the mass productivity $G$ on the power $P$ under the same other conditions: $V=350$ mm/min and $B_z$: 1 – 9 mm; 2 – 7 mm; 3 – 5 mm (b).

The intensity of laser radiation on the substrate surface increases with decreasing in $B_z$, and melt temperature increases as shown on figure 3(a). However, the decreasing transverse size of the laser beam on the substrate in this case leads to a decrease in the mass productivity $G$, figure 3(b).
Samples of additive LMD technology were obtained using multi-bead mode. The obtained result is shown on figure 4a with the technological parameters: \( P = 400 \) W, \( B_z = 9 \) mm, \( C_z = 11 \) mm, \( D_z = 11 \) mm, powder mass flow rate is 8.4 g/min, scanning speed is 500 mm/min. The cross-section of the deposited metal is shown on figure 4(a). The sample was made by 5 layers with vertical step 0.7 mm and horizontal step 0.8 mm ensured the overlapping of adjacent tracks about 30%.

**Figure 4.** The time dependence of the maximum of the brightness temperature of the melt \( T^* \) (a) and the cross-section of the deposited metal, the scale is 300 microns (b).

4. **Conclusions**
The features of the use of optical diagnostics of the melt surface in the technology of laser metal deposition of AISI 304 stainless steel with an off-axis technique are shown. The results of pyrometric measurements of the maximum brightness temperature dynamics on the surface of the melt during the formation of the bead in the LMD technology are presented. The dependences of the averaged values of the melt temperature on the radiation power are obtained for different values of the scanning velocity and the distance from the substrate to the position of the laser focus.

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