Application features of the multi-wave optical diagnostics complex in the technology of laser metal deposition

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Abstract. The features of the application of the multi-wave complex (MCOD) for optical diagnostics of physical processes under the action of laser radiation on the melt surface in the technology of laser deposition of metals (LMD) are considered. The registration of thermal radiation in different ranges of the optical spectrum is used in the MCOD to evaluate the geometric characteristics of the melt pool and determine the maximum temperature of the melt pool \( T_{\text{max}} \). The dependences of the track height and the width of the melt pool on \( T_{\text{max}} \) are obtained for different values of the scanning speed. It is shown that in the speed range from 5 to 8 mm/s, the track height practically does not change while maintaining \( T_{\text{max}} \).

1. Introduction

Laser metal deposition (LMD) technology allows to create complex-shaped parts by adaptive manufacturing (AM) methods in one technological stage without the use of additional equipment. However, the processes accompanying AP are characterized by less stability compared to traditional production technologies due to the peculiarities of the effect of laser radiation on the material and the small size of the heating region [1]. In this regard, the stabilization of the physical processes of forming products of complex shape in the additive technology of LMD using on-line monitoring methods is the important and actual task [2–3]. The surface oxidation as shown in [4] does not allow reliable measurement of surface temperature under atmospheric conditions.

Uncontrolled change in the emissivity coefficient on the melt surface leads to the methodological measurement error. It is need to measure the geometry of the melt pool (MP) to determine the evolutionary change in the shape of the track, one of the key parameters of the detail reproducibility in the additive technology of layer-by-layer synthesis [5]. In particular, the correlation was found in [6] between the dynamics of the physical parameters of the MP and the geometry of the formed track. The attention is also drawn to the need to use several spectral ranges of thermal radiation of MP to improve the accuracy of temperature measurement. The such solution was considered in [7] in relation to the technology of selective laser melting. The high-speed single-wave pyrometer, the IR camera, and the high-speed CCD camera with pulsed laser illumination were used to diagnose the processes on the MP surface.

In this paper, the features of the device and the use of the multi-wave complex of optical diagnostics (MCOD) of processes on the melt surface under the influence of laser radiation in the LMD technology are considered.
2. Materials and method

The research facility was previously developed at ILIT RAS for manufacturing complex-shaped products using LMD technology [8]. The setup has the laser with the power of 400 W and the wavelength of 1.07 microns. The laser head (Precitec YC52) is fixed in the vertical position, and the substrate is attached to the 6-axis robot manipulator. The setup was modified for optical diagnostics of the physical processes during the track formation under the influence of laser radiation on the surface of the metal melt in the laser metal deposition technology (LMD). The MCOD is integrated coaxially into the optical scheme of the laser head.

The optical scheme of the MOD installation is shown in figure 1 (a). The plane-parallel optical plate (OP) 1 is used to divert thermal radiation from the affected area to the recording systems: high-speed video camera and the sensor of the pyrometric unit. OP 2 is installed to compensate the displacement of the optical axis of the laser head introduced by the first plate. The optical filter 3 does not allow the laser radiation reflected from the MP to enter the recording system. OP4 transmits thermal radiation to the pyrometer. OP 5 divides the thermal radiation into two branches. Figure 1 (b) shows a general view of the MCOD, the laser head 6 and the radiation divert unit 7, installed between the collimator and focal lenses. The focal length of the collimate lens and the focus lens of the laser head is the same and is 200 mm.

![Figure 1. Installation diagram with MCOD designations (a): 1, 2 and 5 – rotary optical plates; 3, 4 – optical filter. General view of the MCOD (b): 6 – laser head, 7 – radiation removal unit, 8 – nozzle, 9 – substrate, 10 – rotary mirror, 11 – video camera, 12 – pyrometer sensor. Consecutive, (n, n+1), frames of the image of the melt surface (c); scale 800 microns.]
The laser radiation passes through the central part of the coaxial nozzle 8 and acts on the surface of the melt of the track formed on the substrate 9. The thermal radiation of the melt passes in the opposite direction through the focus lens and, partially reflected from the first plate 10, propagates in the horizontal direction, leaving the block 2 and forming the MP image on the matrix of the video camera 11. The pyrometer lens in the second branch focuses the thermal radiation on the receiving part of the pyrometer sensor 12, schematically shown in figure 1 (a). In order to determine the geometric characteristics of the MP in the MCOD, a high-speed camera Mikrotron 3110 was used. The total magnification of the system was 1.4. Images of the MP surface with a spatial resolution of about 10 microns, a frame rate of up to 3000 Hz, and a frame size of 560 x 280 pixels were obtained.

The control system has access to all aspects of the technological process directly during its execution due to the open architecture of the setup. This allows to implement not only the preliminary planning of the production strategy of the object, but also the modification of the strategy "on the go", if such a need is detected as a result of automatic analysis of operational data from the sensors of the installation. Real-time operation imposes increased requirements on the speed and reliability of the control system. To speed up processing, a parallel architecture is used in the implementation of control algorithms.

The use of video diagnostics of the process of exposure to thermal radiation on the MP surface allows you to register the horizontal projection of the surface of the formed track, including MP. The successive (n, n+1) frames of the melt surface image are shown in figure 1 (a). The following geometric characteristics of MP are distinguished in real time: the area and the perimeter of the MP region; the lengths of the minor and major axes of the equivalent ellipse. The developed image processing method makes it possible to detect and exclude from consideration the melt region at the leading edge, with the high, due to the lack of convection with a small thickness of the molten region, – intensity of thermal radiation. The interfering factors of video diagnostics of the geometric characteristics and temperature of MP include the luminescent glow of oxides, fluxes or slag on the surface of the melt bath, metal vapors, as well as the reflection of laser radiation from the surface of MP [4, 5, 9].

The range of measured temperatures is quite narrow in the case of measuring the temperature by video camera with the CMOS matrix as shown in [10] and determined by the dynamic range of the sensitivity of the matrix. The exposure of the video camera was set to displayed the melt at the boundary with the solid material and, accordingly, with the luminosity of the melting temperature $T_m$ (about 1500 K) on the video frame in low-grey level. Thus, the image of areas with the temperature above 1900 K will be highlighted. Therefore, the additional optical system is required to measure the maximum temperature $T_{\text{max}}$ on the surface. The MCOD include the multi-channel pyrometer for this purpose.

Taking into account the above, the requirements for the optical system MCOD were formulated: optical signal recording devices must be protected from the penetration of laser radiation, including reflected from the object of observation: in total, the transmission coefficient in the optical system MCOD, including the reflection coefficient of the front face of the OP 1 and the transmission coefficient of the filter 3, should not exceed the value of 0.01% (optical density OD 4.0) in the wavelength range of optical radiation (1000...1090) nm compared to the transmission coefficient at a wavelength of 550 nm. The necessary transmission and reflection requirements of optical filters were met by using the technology of applying a multilayer interference coating in vacuum [11].

To control the temperature on the melt surface, the MCOD uses a multichannel pyrometric system, which differs from the one described earlier in [12] by the type of two-color photosensors. The use of six pairs of diodes, with a different sensitivity spectrum in the infrared region of the spectrum in each pair of diodes, allows us to obtain the values of the brightness temperature in 6 subdomains of the melt region, including local areas of oxidation of the melt surface, using the spectral ratio method. The field of view of each channel of the pyrometer used, taking into account the magnification of the optical system, is about 120 microns.
3. Results and discussion

The MCOD was used to diagnose the process of maintaining the quasi-stationary melt bath under the action of laser radiation, feeding the gas-powder mixture, and scanning the substrate to form the track. The obtained dependences on the $T_{max}$ of the height of the obtained track $H_0$ at different scanning speeds in the range of $V$: (5...12.5) mm/s are shown on figure 2 (a) at different power $P$: (180...400) W and at the constant mass flow rate of the powder $G_0$ 8.4 g/min.

![Figure 2](image)

**Figure 2.** The dependence of the height of the resulting track $H_0$ on $T_{max}$ (a); the dependence of the width of the melt bath $D_0$ on $T_{max}$ (b).

The height $H_0$ was measured on the finished sample. As follows from the obtained results, the track height increases from 0.4 to 0.6 mm with the increase in $T_{max}$ from 1700 K to 2300 K. At the same time, the height of the melt pool practically does not change at the same value of $T_{max}$ with the change in the scanning speed in the range (5...8) mm/s, but this temperature is set at different speeds with appropriate power adjustment. Thus, as follows from the data in figure 2 (a), in the range of scanning speeds from 5 to 8 mm/s, it is possible to stabilize the track height with the arbitrary change in the scanning speed, for example, with the sharp turn of the contour, by changing the laser power while maintaining the measured temperature of the melt bath at the constant level. Thus, the use of MCOD would increase the stability of the track height stabilization system by controlling the laser power while maintaining the pyrometer reading at a given level. Thus, the use of MCOD will increase the stability of the track height stabilization system by controlling the laser power while maintaining the pyrometer reading at a given level. The track height decreases with the increase in the scanning speed of more than 8 mm/s at the constant $T_{max}$ (figure 2, a). In the range from 10 to 15 m/s, the constant value is $H_0 \cdot V$, which weakly depends on the melt temperature in the studied temperature range and the form factor $F$, the ratio of the width of the track to its height, increases with increasing scanning speed $V$ (figure 2, b). In this case, the stability of the track height is related to the stability of the scan speed.

4. Conclusions

The results of using the multi-wave optical diagnostic system to study the physical processes of track formation under the influence of laser radiation in the LMD technology was presented. The MCOD includes the video diagnostic system and the multi-channel spectral ratio pyrometer, as well as the primary data processing system, and uses optical elements with a multilayer interference coating. MCOD was used to online monitoring of the geometric characteristics of the bath and the maximum temperature of the melt in the conditions of interfering factors: the appearance of oxides, fluxes or slag on the surface of the melt bath, as well as the effects of luminescence of metal vapors. Structurally, the MCOD is made according to the coaxial scheme and can be used as part of commercially available laser heads. The dependences of the width of the melt bath and the height of the formed track on the maximum temperature in the melt zone at different values of the scanning speed and laser radiation
power are obtained. The stabilization of the track height under conditions of speed instability, for example, at turns of the scanning contour is shown in the range of scanning speeds from 5 to 8 mm/s to maintain of the pyrometer reading at the given level by adjusting the laser power. The use of MCOD in the system of stabilization of the parameters of the formed track during the LMD process would increase the reliability of the control and expand the area of stable operation of the control system with feedback in the range of changes in technological parameters.

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