The control of the height and shape of the track in laser metal deposition by the QCW laser mode

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Abstract. The control of the track shape in laser metal deposition technology by the QCW laser mode has been studied. The different geometric characteristics of the tracks are shown to obtain at the same average laser power, depending on the selected laser power control mode. The difference in the temperature regimes of track formation is shown.

1. Introduction

The physical processes accompanying the laser metal deposition (LMD) technology are characterized by less stability compared to traditional manufacturing technologies. This variability leads to the appearance of heterogeneities in the construction and limits the use of LMD for the manufacture of critical structural elements, as well as in the aerospace and medical industries [1]. It is necessary to identify anomalies in the process dynamics in a timely and accurate manner to be able to carry out a corrective procedure for ensuring the required level of quality and stability of the LMD process. Thus, it is necessary to control the technological parameters of the LMD in real-time to change the parameters of the applied layer: the temperature and area of the melt region, the height of the applied layer, etc. [2–4]. The development of LMD process control systems is discussed in the review [5]. The powder feed rate is controlled, in particular, to change the height of the track [4]. However, the control system implemented in this work does not allow using the controller developed in existing LMD systems. It is shown in [6] to shift the position of the substrate relative to the nozzle the powder feed rate changes; on the other hand, it is proposed to change the position of the substrate to control the track height. In [7], it is shown how uncontrolled changes in the scanning speed lead to the formation of inhomogeneities in the height of the formed layer. In this paper, we study the influence of pulse-width modulation of laser power on the height and shape of the track in LMD technology.

2. Materials and method

The research facility developed at ILIT RAS was used (figure 1). The setup includes the ytterbium fiber laser (NTO "IRE-Polyus") with a power of 400 W. A robotic arm (Kuka KR10 900-2) moves the substrate relative to the laser head (Precitec YC52). The configuration and speed of the feed disc of the powder feeder (GTV PF 2.1 LC) determine the mass flow rate of the powder. The software part of the management system is implemented using the LabVIEW development environment.

The computing module is equipped with three RS-232 interfaces: one for loading control programs to the CNC controller, and two for switching the serial interface of the CNC communication with the
laser "in the gap". Communication with the L-CARD crate, which housed the ADC modules of the multi-channel pyrometer signals, was carried out via the USB interface. Thus, the developed control system intercepts the laser control commands, synchronizes with the radiation on/off commands, and takes into account the current set laser power when generating the corrected values.

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 implementing 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, the parallel architecture is used in the implementation of control algorithms.

The track in the LMD process was formed simultaneously with the registration of the optical response. The powder PR-X18N9 with the granulometric composition (40...100) microns was used, which was applied to substrates made of 08X18N10T steel. The powder consumption was 8.4 g/min at the scanning speed of 200 mm/min. During the scanning process, the average radiation power $P_a$ changed stepwise every 12 mm and was equal to 20%, 40%, 60%, 75%, 90% from the nominal laser power. Samples of the results of laser radiation exposure to the substrate are shown in figure 2. The track marked as (1) was made without the use of powder. For tracks (2) and (cw), powder was used. The impact power was changed in cases (1) and (2) with pulse-width modulation, so call QCW mode [8], - with the pulse repetition period $t_0=72$ ms. In the case of (cw), the power was set at the same levels in continuous mode.

The control system used to control the temperature on the melt surface is the multi-channel optical diagnostic (MCOD) system based on the set of two-color sensors, described earlier in [9]. The radiation of the local areas of the melt is illuminated by separate channels of photosensors. Each photosensor consist of two types of photodiodes mounted on the same optical axis and having sensitivity in different spectral ranges. The spectral sensitivity windows, taking into account the additional optical filters used, are in the ranges (1.7...2.2) microns for the first type of photodiode and (1.1...1.4) microns for the second type of photodiode. Two universal LTR11 ADC modules are used as part of the LTR-EU-8 (L-CARD) crate for digitizing photodiode currents. MCOD system measures the maximum temperature on the surface of the melt bath by the spectral ratio method with a time resolution of about 0.1 ms.

The temperature on the surface of the material at an average laser power $P_a$ of 80 W (20% of the rated power) in continuous mode slightly exceeded the melting point of the material. In the case of using the QCW mode, at the same average power, which corresponds to the fill factor $S$ (the ratio of the pulse duration to the repetition period in the QCW mode) of 20%, - at the irradiation stage, the
laser power was 400 W and the value $T^*$, the maximum temperature on the surface of the melt bath, exceeded the melting temperature by (400...500) K. QCW radiation is absent in the phase of crystallization.

**Figure 2.** The substrate with single tracks applied. 1. qcw mode of laser power in the absence of powder, period $t_0$ 72 ms; 2. qcw mode of laser power at the powder consumption of 8.4 g/min, period $t_0$ 72 ms; 3. cw – “continuous-wave” mode.

The value of $T^*$ thus at the same average power depends on the mode selection, in the case of (cw) with increasing laser power, $T^*$ gradually increases from a temperature just above the melting point to a maximum value of $T_m$ approximately 2600 K, at a laser power of 400 W. In mode (2), heating occurs during the period of laser action at the nominal laser power level $P_0$: $P_a = S^* P_0$. As $S$ increases in QCW mode, the time of temperature drop at the stage of no laser radiation generation (1-$S$) $t_0$ decreases, the $t_0$ increases while heating duration $S$, and thus the value $T^*$ increases to the same value $T_m$.

3. Results and discussion
Dependences of the melt bath of width $D$, height $H$, and the shape coefficient $R$ [ratio of height to width] of the track are shown on figure 3 on the maximum surface temperature $T^*$ at the speed of 200 mm/min and the powder consumption of 8.4 g/min. As follows from the results obtained, figure 3, it is possible to change the track height in the wide range by adjusting the average power id est by changing $S$ in QCW mode. The track width in both modes increases with increasing temperature. In the (cw) mode, the track height is weakly dependent on the laser power. As the result, it is possible to change the track shape factor from 0.4 to 1.6 depending on the selected mode and the average power level. In [3–5], data on the stabilization of the melt temperature by controlling the laser power are presented. It is shown in [6–7] that the ultimate goal of the control system is to stabilize the parameters of the formed layer, first of all, the track height, otherwise, on the next layer, the change in the distance from the layer surface to the nozzle leads to defects in the construction of the next layer. Using QCW mode allows you to control the track height by changing the $S$.

**Figure 3.** The dependence of the width $D$, height $H$ and the shape coefficient $R$ on $T^*$ at a speed of 200 mm per minute and at a powder consumption of 8.4 g/min.
The estimate of the cooling rate as the function of $S$ obtained by processing the time sequence of data from the pyrometric unit is shown in table 1. The cooling rate of the melt surface is higher with the increase in the duration of the pause between the radiation pulses in the QCW mode, and therefore with the increase in $S$. Thus, in QCW mode, the cooling rate can be adjusted by changing the duty cycle. The increase in the cooling rate to $10^5$ K/s and higher leads to additional effects in the formation of the microstructure in chromium-nickel steel [10].

| S, % | Cooling rate, K/s |
|------|-------------------|
| 1 20 | 0.12*10^6         |
| 2 40 | 0.08*10^6         |
| 3 60 | 0.014*10^6        |

4. Conclusions
Thus, the setup developed at ILIT RAS with the open control system architecture. It is used to study the effect of pulse-width modulation of laser power on the width and shape of the track in the LMD technology. The control system is placed "in the gap" between the existing CNC controller and the laser to allow the integration into existing systems, and the use of pulse-width modulation for adjusting the height of the track. PID control based on the signal of mismatch of the set temperature with the data of the multichannel pyrometer can be enabled separately or, if necessary, in conjunction with QCW mode of the laser power. The dependences of the width, height, and shape coefficient on the maximum temperature on the melt bath surface for two laser operating modes, cw and QCW, are obtained. It is shown to change the track shape coefficient from 0.4 to 1.6 depending on the selected mode and the average power level. In addition, it is possible to change the track height in a wide range by adjusting the power fill factor in QCW mode. The width of the track in both modes increases equally with increasing temperature. The track height is weakly dependent in cw mode on the laser power. The cooling rate in the PWM mode at the crystallization stage is estimated from the dynamics of temperature changes on the melt surface. It is shown to be possible in the QCW mode the regulation of the cooling rate at the crystallization front by changing the duty cycle. The obtained results are applicable in the LMD technology for controlling the geometric and microstructural parameters of the formed track.

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