The correlation of the parameters of the melt pool with the form of the track in the technology of laser metal deposition

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Abstract. The temporal dependence of parameters of the melt pool (MP) during the formation of the track in the process of laser metal deposition (LMD) was obtained. The video monitoring in the LMD process was used by the coaxial scheme with the frame rate of up to 3 kHz and the spatial resolution of down to 10 μm. The technique was developed to process video data, to analyse images of the illuminated area in LMD process and to determine the MP key characteristics. The method of the MP – contouring detects areas of solid material with high intensity due to differences in the emissivity of the material in images and to exclude them from consideration. 3D approximation of the tracks was made using the interferometric profilometer. The correlation analysis of the relationship between the geometric characteristics of the track and the characteristics of the MP was carried out. The maxima of the correlation of the height of the track profile and the MP width is detected on the scale of (0.1...1) mm. The additional conditions should be investigated to establish the reliable correlation between the deviations observed in the experiment.

1. Introduction

For parts manufactured using the additive method, the number of defects (porosity, residual stresses, anisotropy of properties, etc.) are characteristic, as well as a general variability of properties. This is largely due to the lower stability of the accompanying processes as compared to traditional production technologies. The effect of laser radiation on the flow of the gas-powder mixture and the surface of the synthesized object in laser metal deposition (LMD) technology is accompanied by rapid changes in the volume of the melt pool (MP), the shape and temperature of the surface. The relationship between temporal changes in the geometry formed in the process of the LMD track, with the change in the process parameters is considered in works [1–2]. In [3] machine learning approach based on artificial neural networks is developed to find the correlation between the laser metal deposition process parameters and the output geometrical parameters of the deposited metal trace produced by laser direct metal deposition on 5-mm-thick 2024 aluminum alloy plates. The MP monitoring tool for selective laser melting (SLM) is developed, [4], and the correlation of SLM – melt pool events with the tensile properties of Ti-6Al-4V of the printed cylinders is detected. Correlation method is widely used in process analysis in additive manufacturing. In [5] the algorithm correlates time-dependent measurement data in LMD setup with the spatial position of the stream, derives a volumetric distribution plot and predicts the catchment efficiency of the process considering any misalignment. The correlations of melt pool geometry and process parameters
during laser metal deposition by coaxial process monitoring are considered in [6]. This paper presents the results of studying the influence of the MP parameters on the geometric characteristics of the track in the technology of laser deposition of metal (LMD).

2. Experimental setup
The laser head (Precitec YC52) was modified on the LMD setup developed at ILIT RAS (figure 1) in order to direct the part of the thermal radiation perpendicular to the passing through the lenses direction: the plane-parallel optical plate and the optical axis offset compensation plate are located between the focusing lens and the collimator of the laser head in an additional housing at an angle of 45° to the optical axis. For spectral selection of laser radiation reflected from the melt surface, as well as for translucence of plate surfaces at the laser wavelength, multilayer interference coatings of plates are used. In addition, the set of optical filters is used to limit the sensitivity of the video matrix of the Mikrotron 3010 high-speed video camera to the visible spectrum range and thus to observe processes on the melt surface of the formed track under conditions of reflected laser radiation, luminescent glow of metal oxides or salts on the surface of the melt bath, as well as ionized metal vapors. The rate of video sequence is up to 3 kHz with the frame of 640×640 and the spatial resolution of down to 10 μm. The overview of diagnostic methods including coaxial scheme is given in [7].

![Figure 1](image.png)

**Figure 1.** The modified LMD laser head: a) General view, b) the block of optical plates with the interference coating.

The flow of PR-X18N9 powder with the mass flow rate of 8.4 g/min and the granulometric composition of (40...100) microns was concentrated through the conical nozzle on substrate of mild steel with the thickness of 4 mm. The 400 W fiber ytterbium laser (LK-400-V) was used. The laser radiation passed through the coaxial flow of the gas-powder mixture and focused near the substrate. Each track was formed at constant values of the scanning speed \( V \), laser power \( P \), distance from the nozzle to the substrate, and the position of the beam focus. Speed ranges (5...12.5) mm/s and power is varied inside (180...400) W. Experiments on the formation of tracks were carried out with the online monitoring of the MP using the high-speed video camera installed.

3. Experimental results
The surface relief of the obtained samples was measured using the profilometer of the scanning white light interferometer (Zygo NewView 7300). The X-and Y-axis resolution was 4.4 microns, and the Z-axis resolution was 0.1 nm. The algorithm has been developed to distinguish the spatial dependencies of the geometric characteristics of the tracks – the set of the heights and widths (in different horizontal sections) from the field of points obtained using the profilometer. Examples of the resulting 3D track profiles are shown in figure 2. The characteristic feature of measurement devices operating on the principle of scanning interferometry is the limitation of the permissible surface slope [8], as the result of which some of the data in the obtained fields is missing. The permissible slope \( \theta \) of the surface is
determined by the value of the numerical aperture (NA) of the lens: $\theta \leq \sin^{-1} NA$. The 20X lens with the value $NA = 0.4$ was used and the corresponding limit (aperture) angle $\theta_{0.4} = 23.6^\circ$.

![Figure 2](image)

**Figure 2.** 3D approximation of the track, a) $P = 320$ W, $V = 5$ mm/s; b) $P = 400$ W, $V = 8$ mm/s; c) $P = 240$ W, $V = 8$ mm/s.

4. Processing of experimental results and discussion

The technique was developed to process video data, to analyze images of the illuminated by laser area in LMD process and to determine the MP key characteristics. The operation of selecting the connectivity component is performed to exclude erroneous areas after binarization. The following "key MP characteristics" are highlighted in real time: minimum and maximum brightness; average and standard deviation of brightness; integral brightness over the MP area (sum of pixels); area and perimeter of the MP area; the lengths of the minor and major axes of the equivalent ellipse (figure 3).

Developed method detects areas of solid material with high intensity due to differences in the emissivity of the material in images and to exclude them from consideration.

![Figure 3](image)

**Figure 3.** The front panel of interface of the MP – contouring and the MP – analysis program.

The technique can be used in real time to process streaming video with the output of the set of key MP characteristics from the coaxial video monitoring system. The control system with feedback can design based on the dynamics of MP characteristics. The dependence of the MP width on time and the profile of the resulting track is shown in figure 4 for $P = 400$ W, $V = 8$ mm/s. The correlation analysis was used to study the relationship between MP characteristics and geometric properties of tracks (figure 4). The time dependence of the MP characteristics obtained from the video data was transferred to depend on the spatial coordinate. There is the correlation of maxima detected on the scale of
(0.1...1) mm when measuring the height of the track profile and the MP width. However, track width maximums can also be reached in the absence of changes in track height.

![Graph](image_url)

**Figure 4.** The time dependence of the MP width, pixels (top). The profile of the track (bottom).

5. Conclusion

In order to study the relationship between the geometric characteristics of the track and the melt pool characteristics, the video monitoring in the coaxial scheme was used in the LMD process. The 3D approximation of the track shape was measured using the interferometric profilometer. The obtained data, time fluctuations in the parameters of the melt bath, and spatial changes in the shape of the track were compared, taking into account the constant scanning speed. The preliminary data obtained from the correlation analysis showed that additional conditions should be investigated to establish the reliable relationship between the deviations observed in the experiment.

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