The features of porosity formation in multilayer stainless-steel samples formed by laser deposition of metal

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Abstract. Experimental results of the identification of the intra-word and inter-layer porosity of multilayer objects formed during the laser deposition of austenitic stainless-steel powder at different values of technological parameters are presented. The dependences of the residual porosity, determined by processing the image from the cross-section sections of the samples, on the type of porosity and the scanning speed are given.

1. Introduction

The technology of laser metal deposition (LMD) has been significantly improved in recent years, both in terms of the resulting product quality and the coverage of a variety of metal (and other) materials. However, LMD has still a number of disadvantages, such as limited material uniformity, pores, non-melting, surface quality, and overall property stability. The situation is caused by the complexity of additive processes, the presence of many mutually influencing physical processes [1]. The gas pores and areas of incomplete remelting, reduced the strength of the material, is a common difficulty limited the use of LMD for the manufacture of critical structural elements, as well as in the aerospace and medical industries [2]. In this paper, the influence of technological parameters on the residual porosity of metal samples obtained by the LMD method was investigated.

2. Materials and method

The LMD experiments were carried out using the research unit (figure 1a) consisting of the powder feeder, the sealed unit, and the control rack. There are 400 W ytterbium fiber laser, Precitec Y-52 laser head and a robot arm that moves the substrate relative to the laser head inside the unit. The laser beam heats the particles of the gas-powder mixture (GPM) with a change in their phase state. The radiation is partially scattered on the particles, partially absorbed by them, and also heats and melts the substrate and previously deposited material. The track is formed as the particles are deposited on the surface of the substrate and the material solidifies. The scheme of interaction of laser radiation with GPS and the substrate is shown in (figure 1b). Dz is the distance from the lower surface of the nozzle to the substrate. Bz – the distance from the nozzle to the laser beam retainer (focus removal). The distance from the nozzle to the section of the minimum size of the GPM flow is 11 mm. The quality and performance of the LMD process can vary significantly depending on the Bz and Dz parameters [3].

The powder of austenitic steel PR-Kh18N9 (JSC "Polema") with a carbon content of about 0.09% was used in the experiments. Granulometric composition of the powder (40 ... 100) microns. The 20
mm long tracks were applied sequentially on the (34x34x4 mm3) substrates were made of 08Kh18N10T steel with a $d_y$ step at the same values of the technological parameters. The mass flow rate of the $G_0$ powder was 9.3 g/min, or 14.9 g/min. The two layers of 8 tracks were applied, then 3 more layers of 4 tracks were applied layer-by-layer in the same direction. The $d_y$ pitch varied within (0.6...0.9) mm, and the vertical offset pitch $d_z$ varied within (0.3...1.1) mm. The experiments used a maximum laser power of 400 watts. The pressure of the nitrogen at the feeder inlet was 0.3 MPa, the protective line with the pressure 0.6 MPa has the flow rate 10 nl/min.

Figure 1. Diagram of the experimental setup (a); Diagram of the relative position of the substrate, nozzle, particle flow, and laser beam (b).

The technological parameters of the LMD formation of multilayer objects are shown in table 1. The calculated beam size on the substrate surface and the vertical displacement step $d_z$, determined by the layer height, are also indicated. The samples were cut, ground, and etched after manufacturing. Chemical etching was carried out in a solution with the composition: 3 g of ferric chloride, 10 ml of hydrochloric acid, 90 ml of ethyl alcohol. The sections were examined on the Zygo NewView 7300 optical profilometer to determine the geometric characteristics and quality parameters (presence of defects, degree of adhesion to the substrate).

Table 1. Technological parameters of the LMD process.

| N  | $G_0$ [g/min] | $V$ [mm/min] | $D_z$ [mm] | $B_z$ [mm] | Beam size [mm] | $d_z$ [mm] |
|----|--------------|--------------|------------|------------|----------------|------------|
| 9  | 9.3          | 1000         | 11         | 2          | 1.34           | 0.3        |
| 10 | 9.3          | 500          | 14         | 2          | 1.78           | 0.7        |
| 11 | 9.3          | 500          | 11         | 6          | 0.75           | 0.6        |
| 15 | 9.3          | 500          | 11         | 2          | 1.34           | 0.7        |
| 16 | 9.3          | 500          | 11         | 1          | 1.49           | 0.7        |
| 17 | 14.9         | 500          | 12         | 3          | 1.19           | 1.1        |

3. Results and discussion
The typical photo of the sample cross-section section is shown on figure 2. The pore regions were localized in the obtained images and their integral area was calculated to determine the porosity. Image processing was performed using the open source software ImageJ [4]. The registered pores are indicated by colored lines in figure 2. It is important to note that, although the method used has not
been verified to determine the absolute value of porosity in the sample, it can, however, be used to estimate the relative change in porosity. Several types of pores distinguished from the obtained images. First, the samples contain pores of small size, about \(10^{-6}...10^{-5}\) m, of regular shape: spherical or elliptical. Such pores appear as a result of the capture of the gas phase from the surrounding atmosphere during the existence of the liquid bath, and they are irregularly distributed over the cross-sectional area. The trapped phase in the form of gas bubbles moves in the melt until it solidifies. At the same time, the convective movements of the melt promote the movement of gas bubbles in the melt, their coalescence into larger pores and, as a result, evacuation through the free surface. The porosity of this kind is referred to as intra-layer (intra-LP) [5].

In addition, with non-optimally selected process parameters, inter-layer porosity (inter-LP) occurs: regular voids appear on the samples between adjacent tracks. Also, in the samples there are irregularly shaped pores formed as a result of incomplete penetration of the material or rapid solidification of the bath, these pores can be intra-layered, that is, they also occur during the formation of a single track. But it is possible to form such pores during the formation of the next track, at the junction between adjacent tracks, in which case you should expect a regular pattern of their location.

The dependence of the average porosity in the sample on the intensity of the laser radiation \(I_s\) is shown on figure 3. The defects formed by mechanism of the presence of the residual gas phase in the melt were taken only into account for inter-LP. The analysis and the interpretation of the effect of laser radiation on the residual porosity is possible through its effect on the dynamics of the melt in this case. The inhomogeneous temperature distribution is formed on the surface of the liquid bath under the action of laser radiation. As the intensity increases, the temperature gradients increase, and the action of capillary effects, such as Marangoni convection, caused by temperature gradients on the free surface, sets the molten metal in motion. In addition, the size of the melt bath increases [6]. More residual gas has time to leave the melt before it crystallizes in this case.

The effect of convective removal is of a threshold nature according to the obtained data: the porosity decreases by almost an order of magnitude with an intensity higher than 16 kW/cm². The excessively rapid movement of the liquid potentially leads however to the capture of an additional volume of the gas phase from the environment: with a further increase in the intensity, intra-LP gradually increases, reaching a value of about 0.5% at a laser radiation intensity of about 90 kW/cm². Thus, the dependence of intra-LP on the laser radiation intensity is non-monotonic. The obtained data indicate that the minimum of defects is observed at the average intensity values in the used range, \((24...50)\) kW/cm², which can be considered as the optimal technological mode.

Let us introduce the complex parameter \(E_V\), defined as \(E_V = E_s/d_s\), where \(E_s\) is the specific radiation energy per unit surface, defined as: \(E_s = P/(d*V)\). Thus, the value of the specific energy per unit volume \(E_V\) is inversely proportional to the value \((V*d_s)\), which is proportional to the powder consumption with sufficient accuracy. Thus, the \(E_V\) parameter depends on the main technological parameters, increases
with increasing laser power, and is inversely proportional to the beam width and powder consumption. Figure 4 shows the dependence of the average porosity in the sample on $E_V$. High inter-LP values in the graph correspond to increased powder consumption or with significant beam defocusing (beam size above 1.4 mm).

**Figure 3.** The dependence of Intra LP on the laser radiation intensity.

**Figure 4.** Dependence of the inter-LP on the specific energy of the laser radiation $E_V$.

### 4. Conclusions

Thus, the porosity of the material formed in the LMD process is studied experimentally. The experiments were carried out using a powder of austenitic steel PR-Kh18N9 with a granulometric composition (40...100) microns on the developed research setup. The scanning speed, laser beam focus removal, distance between the nozzle and the substrate, mass flow rate of the powder, as well as the number of layers applied are varied in the LMD process. The porosity of the samples was studied by analyzing the images of the transverse sections of the samples. It is shown that the minimum of the intra-layer porosity corresponds to the intensity range of (24...50) kW/cm$^2$, the technological mode in order to avoid inter-layer porosity should be searched for when the value of the complex parameter of the specific energy per unit volume $E_V$ exceeds 25 J/mm$^3$.

### Acknowledgements

The work was supported by the Ministry of Science and Higher Education of the Russian Federation within the framework of the Task of the Federal State Budgetary Institution “Crystallography and Photonics” of the Russian Academy of Sciences in terms of the scientific problem, as well as with the grant support of the Russian Foundation for Basic Research in terms of the developed methodology, grant No. 18-29-03249, as well as grant No. 20-21-00158 in terms of conducting experiments and the experimental results obtained.

### References

[1] Demir A G and Previtali B 2017 *The Int. J. of Adv. Manuf. Technol.* 93(5-8) 2697
[2] Mahamood R M 2015 *Trans. on Eng. Technologies* (Springer. Dordrecht)
[3] Zavalov Y N, Dubrov A V, Makarova E S and Dubrov V D 2019 *J. Phys. Conf. Ser.* (IOP Publishing) 1396 12045
[4] Schindelin J, Arganda-Carreras I, Frise E, Kaynig V, Longair M, Pietzsch T and Cardona A 2012 *Nature methods* 9(7) 676
[5] Pinkerton A J 2010 In: *Advances in laser materials processing* (Woodhead Publ.) 461
[6] Zavalov Y N, Dubrov A V and Makarova E S 2020 *J. Phys. Conf. Ser.* (IOP Publishing) 1713 012048