Influence of technological parameters on the geometry of single-track laser clad nickel based alloy on grey cast iron substrate

D S Gusev¹,², *, A B Lyukhter¹, **
¹ Vladimir State University named after Alexander and Nikolay Stoletovs, Vladimir, Russia
² LLC "Engineering Center at VlSU", Vladimir, Russia

E-mail: *gusev@laser33.ru; **3699137@mail.ru

Abstract. On the example of glass forming equipment, the surfaces of which must have high wear resistance during repeated contacts with molten glass, a study was made of laser cladding of nickel based alloys on a substrate of gray cast iron. In study the shapes of individual tracks are investigated with varying laser radiation power, processing speed and powder feed rate. The influence of technological parameters on the width and height of the clad is shown. A similarity is found between the two principles of measuring the dilution through linear dimensions and the areas of track in cross section. A high correlation between dilution and laser radiation power over a wide range of speeds has been established, which has made it possible to develop a scheme of control laser cladding process with achieving a low level of dilution in order to minimize the heat effect zone (HAZ).

1. Introduction
In the manufacture of shaped glass products in large batches (millions of pieces), glass container manufacturers are faced with a problem associated with the permanent failure of the critical components of equipment. In the process of using the glass forming equipment, the details of glass molds operating under conditions of cyclic alternating thermomechanical loads and produced, in most cases, from cast iron, are subject to the greatest defectiveness. A significant influence on the stability of glass forming equipment is the desire of container manufacturers to reduce the mass of produced glass products (reducing the wall thickness), increase the rate of release of packaging, while improving the quality of melted glass [1, 2].

One of the most promising technologies to improve the service life of glass forming tooling is to restore the working surfaces of wear-resistant, corrosion resistant and other coatings obtainable laser cladding a nickel-based powders. [3, 4]

The wide application of laser cladding is limited to the use of automated process control systems that do not have in their arsenal of algorithms for adjusting operation windows with changing geometric parameters of the deposited layer. This is caused by an insignificant share of research in the field of dependencies and regularities of the formation of the clad on the technological parameters of the processing time.

The aim of this work is to identify patterns of geometric characteristics of the tracks on the technological processing parameters for the creation of an automated process control system of laser cladding.
In studies [5–8] on the assessment of the influence of technological parameters, the main characteristics of the clad were the height, width and shape of the clad, the depth of penetration, and the percentage of defects. Parameters of control were the laser radiation power, processing speed and powder feed rate.

2. Experimental
The experiments were carried out on an installation consisting of: a 6-axis Kuka HR 60LH robot, a Sulzer Metco Twin 10C powder feeder, ytterbium fiber laser YLS-6 (max. average power 6 kW), COAX powder nozzle.

The chemical composition used in the experiments of cast iron and surfacing powder Eutroloy 16233 (particle size 40–120 μm, initial hardness 31–36 HRC) was determined using a Bruker Q-8 Magellan spectrometer and is presented in tables 1 and 2.

| Table 1. Chemical composition of the experimental cast iron. |
|-------------------------------------------------------------|
| Element (wt %)                                               |
| Fe              C   Si   Cr   Mn   Ni   Cu   Na   Al   P    S   Mo |
| Bal            3.09 1.35 0.54 0.5  0.25 0.09 0.08 0.07 0.05 0.04 0.03 |

| Table 2. Chemical composition of the surfacing powder Eutroloy 16233. |
|-------------------------------------------------------------|
| Element (wt %)                                               |
| Ni   Cr   Si   Fe   B   C |
| 85   7    <3.1 <3    1.3 0.3 |

Deposition process was performed using a continuous laser radiation in inert gas (argon). The height of the deposited layer was significantly lower than the thickness of the substrate to ensure sufficient heat removal from the treatment zone.

Review papers [5–8] allowed to choose the following processing parameters: laser power $P$ of 700 to 2800 W, the processing speed $S$ from 9 to 18 mm/s, powder flow rate $F$ of 12 to 25 g/min.

The clad height $H$ [mm] is defined as the height of laser track over surrounding substrate, the clad width $W$ [mm] is a distance between side points where the laser track touches and $b$ is the clad depth representing the thickness of substrate melted during the cladding and added to the clad region. The clad area $A_c$ [mm$^2$] is the cross-section of the clad area above the surrounded substrate surface and the molten area $A_m$ [mm$^2$] is the cross-section molten area under the surrounded substrate surface. The area of defects were measured in the clad and melted areas and was determined as $(A_{def}(A_c+A_m))·100%$.

The measurements were carried out with the help of JMicroVision software on cross sections. Photographing of the microstructure was performed on an inverted microscope with magnification x25 on the Nikon Epiphot TME200.

Regression analysis and processing of experimental results are implemented in STATISTICS software [9].

3. Results and discussion
To evaluate the effect of laser radiation power $P$, processing speed $S$ and powder flow $F$ on geometric parameters, 32 clad tracks were manufactured. The results of measuring are shown in table 3.

With constant powder flow ($F = 12$ g/min), the height and width of the deposited layer were plotted against laser radiation power and processing speed (figures 1 ... 4).
Table 3. Results of measuring the geometric dimensions of the clad.

| track | $P, W$ | $S, \text{mm/s}$ | $F, \text{g/min}$ | $W, \mu m$ | $H, \mu m$ | $b, \mu m$ | $A_{1}, \text{mm}^2$ | $A_{\text{m}}, \text{mm}^2$ | $A_{\text{def}}, \text{mm}^2$ |
|-------|--------|------------------|------------------|-----------|---------|-------|-----------------|-----------------|-----------------|
| 1     | 2100   | 9                | 15               | 3.052     | 0.479   | 0.549 | 1.117          | 1.089           | 0.00            |
| 2     | 2100   | 12               | 15               | 2.902     | 0.531   | 0.687 | 1.188          | 1.131           | 3.62            |
| 3     | 2100   | 15               | 15               | 3.392     | 0.651   | 0.496 | 1.540          | 1.068           | 1.15            |
| 4     | 2100   | 18               | 15               | 3.691     | 0.737   | 0.721 | 1.895          | 1.641           | 0.00            |
| 5     | 1750   | 9                | 12               | 3.260     | 0.745   | 0.543 | 1.585          | 1.197           | 2.37            |
| 6     | 1750   | 12               | 12               | 2.937     | 0.525   | 0.626 | 1.002          | 1.144           | 0.28            |
| 7     | 1750   | 15               | 12               | 2.801     | 0.475   | 0.415 | 0.909          | 0.658           | 6.70            |
| 8     | 1750   | 18               | 12               | 2.741     | 0.449   | 0.478 | 0.849          | 0.813           | 0.00            |
| 9     | 1400   | 18               | 12               | 2.283     | 0.449   | 0.342 | 0.603          | 0.505           | 1.44            |
| 10    | 1400   | 15               | 12               | 2.640     | 0.457   | 0.367 | 0.779          | 0.531           | 1.07            |
| 11    | 1400   | 12               | 12               | 2.725     | 0.614   | 0.291 | 1.165          | 0.481           | 2.43            |
| 12    | 1400   | 9                | 12               | 2.983     | 0.684   | 0.342 | 1.364          | 0.609           | 0.00            |
| 13    | 700    | 9                | 12               | 1.946     | 0.572   | 0.164 | 0.700          | 0.350           | 0.00            |
| 14    | 700    | 12               | 12               | 1.797     | 0.515   | 0.131 | 0.600          | 0.290           | 0.00            |
| 15    | 700    | 15               | 12               | 1.725     | 0.401   | 0.176 | 0.516          | 0.233           | 0.00            |
| 16    | 700    | 18               | 12               | 1.598     | 0.296   | 0.172 | 0.340          | 0.171           | 0.78            |
| 17    | 2800   | 18               | 12               | 3.064     | 0.380   | 0.737 | 0.813          | 1.636           | 1.59            |
| 18    | 2800   | 15               | 12               | 3.235     | 0.449   | 0.766 | 0.958          | 1.644           | 8.72            |
| 19    | 2800   | 12               | 12               | 3.829     | 0.471   | 0.784 | 1.120          | 2.038           | 6.33            |
| 20    | 2800   | 9                | 12               | 3.895     | 0.546   | 0.905 | 1.423          | 2.444           | 3.26            |
| 21    | 2800   | 9                | 20               | 4.445     | 1.034   | 0.669 | 3.200          | 2.084           | 3.97            |
| 22    | 2800   | 12               | 20               | 4.143     | 0.823   | 0.589 | 2.453          | 1.594           | 3.58            |
| 23    | 2800   | 15               | 20               | 3.927     | 0.722   | 0.599 | 1.982          | 1.487           | 2.71            |
| 24    | 2800   | 18               | 20               | 3.614     | 0.631   | 0.584 | 1.657          | 1.307           | 0.98            |
| 25    | 2100   | 18               | 12               | 3.018     | 0.369   | 0.708 | 0.819          | 1.473           | 1.92            |
| 26    | 2100   | 15               | 12               | 3.087     | 0.451   | 0.540 | 0.832          | 1.083           | 3.71            |
| 27    | 2100   | 12               | 12               | 3.621     | 0.728   | 0.511 | 1.594          | 1.346           | 1.56            |
| 28    | 2100   | 9                | 12               | 3.869     | 0.902   | 0.573 | 2.298          | 1.162           | 3.93            |
| 29    | 2800   | 9                | 25               | 4.764     | 1.119   | 0.415 | 4.030          | 0.940           | 0.70            |
| 30    | 2800   | 12               | 25               | 4.331     | 0.997   | 0.476 | 3.210          | 0.979           | 1.46            |
| 31    | 2800   | 15               | 25               | 4.081     | 0.802   | 0.521 | 2.377          | 1.157           | 0.71            |
| 32    | 2800   | 18               | 25               | 3.827     | 0.650   | 0.466 | 1.795          | 1.232           | 1.45            |
Figure 1. The dependence of the clad width on the processing speed at different laser radiation powers:
\[ W_{700} = 2.2687 - 0.0372 \cdot S \quad (R = -0.99) \]
\[ W_{1400} = 3.6410 - 0.0728 \cdot S \quad (R = -0.97) \]
\[ W_{1750} = 3.6966 - 0.0564 \cdot S \quad (R = -0.94) \]
\[ W_{2100} = 4.7879 - 0.1029 \cdot S \quad (R = -0.96) \]
\[ W_{2800} = 4.8949 - 0.1029 \cdot S \quad (R = -0.95). \]

Figure 2. The dependence of the clad height on the processing speed at different laser radiation powers:
\[ H_{700} = 0.8699 - 0.0314 \cdot S \quad (R = -0.99) \]
\[ H_{1400} = 0.9389 - 0.0287 \cdot S \quad (R = -0.95) \]
\[ H_{1750} = 0.9706 - 0.0313 \cdot S \quad (R = -0.89) \]
\[ H_{2100} = 1.4567 - 0.0625 \cdot S \quad (R = -0.98) \]
\[ H_{2800} = 0.6955 - 0.0173 \cdot S \quad (R = -0.98). \]

Figure 3. The dependence of the clad width on the laser radiation power at different laser radiation powers:
\[ W_9 = 1.5073 + 0.00096 \cdot P \quad (R = 0.94) \]
\[ W_{12} = 1.2338 + 0.00100 \cdot P \quad (R = 0.97) \]
\[ W_{15} = 1.4534 + 0.00071 \cdot P \quad (R = 0.94) \]
\[ W_{18} = 1.2576 + 0.00073 \cdot P \quad (R = 0.94). \]

Figure 4. The dependence of the clad height on the laser radiation power at different laser radiation powers.

As the processing speed increases (Figures 1 and 2), the width \( W \) and the height \( H \) of the clad decrease according to a linear relationship: the correlation coefficient \( R \) for \( W \) is from -0.94 to -0.99, and for \( H \) – from -0.89 to -0.99. But at a laser radiation power \( P = 2800 \) W there is a drop in height, especially noticeable at lower processing speeds (9 and 12 mm/s). It is caused by excess heat, which is expressed in a significant depth of penetration (from 0.737 to 0.905 mm) and lack of powder: the base metal is melted to great depths and feed powder fills the melt pool instead of forming effective deposited layer.

Increasing the power of the laser radiation causes linear increase (\( R \) from 0.94 to 0.97) of the track width (figure 3), and the maximum track height for each speed is at a power level of 1400–2100 W with a peak at 2100 W (figure 4).
Figure 5 represents the laser track cross-section map for \( P \) and \( S \) variations at a constant consumption of the powder feed (12 g/min).

\[
| F = \text{const} = 12 \text{ g/min} | \quad \text{Power, W} |
|-------------------------------|-----------------|
| 9  | 700  | 1400 | 1750 | 2100 | 2800 |
| 12 |      |      |      |      |      |
| 15 |      |      |      |      |      |
| 18 |      |      |      |      |      |

**Figure 5.** Laser tracks cross-section map for side cladding of Ni-based alloy on gray cast iron substrate with different scanning speed and laser power.

To evaluate the effect of powder flow on geometric parameters of clads prepared at different scanning speeds (9–18 mm/s) with a different powder flow (12–25 g/min) at constant power \( P = 2800 \text{ W} \) for maximum deposition rate process. The cross-sections map of these clads are shown in figure 6.

\[
| P = \text{const} = 2800 \text{ W} | \quad \text{Feed powder, g/min} |
|-------------------------------|-----------------|
| 9  | 12  | 20  | 25  |
| 12 | 15  | 18  |

**Figure 6.** Laser tracks cross-section map for side cladding of Ni-based alloy on gray cast iron substrate with different scanning speed and feed powder.

Increasing the powder feed allows to increase the width (figure 7a) and the height (figure 7b) of the clad layer, thereby forming tracks with a lower dilution (figure 7c), obtaining up to 5 mm² of effective area of clad in a single track in a cross section (figure 7d).

In this case, the effect of the scanning speed on the geometric parameters of clads is preserved: with its growth, the width, height of the track, dilution and effective area of clad decrease as well as at constant feed powder.
Figure 7. Dependence of the geometrical parameters of the clad on the processing speed and feed powder:
(a) – width track $W = 4.1543-0.0984 \cdot S + 0.0581 \cdot F$;
(b) – height track $H = 0.5875-0.0381 \cdot S + 0.034 \cdot F$;
(c) – dilution $b/(H+b) = 0.2453-0.0103 \cdot S + 0.0221 \cdot F$;
(d) – effective area of clad $A_c = 1.6521-0.1626 \cdot S + 0.1383 \cdot F$.

The obtained dependences (figures 1–4. 7a. 7b) made it possible to confirm the existing regularities of the influence of technological parameters on the width and height of clad. but not enough to create a control system for the laser cladding process. To solve this problem, the effect of the technological parameters of laser cladding on the dilution, which is one of the indicators of the quality of the deposited layer, was analyzed.

Dilution $b/(H+b)$, reflecting the ratio of the thickness of substrate that was melted during the cladding process $h$ to the total melt height $H+b$.

This calculation is similar to the area ratio $A_m/(A_c + A_m)$ of the melted base metal $A_m$ to the sum of the areas of the clad layer and the melted base metal $(A_c + A_m)$. Since these ratios are almost identical for all tracks (figure 8). This can be explained by the use source of a laser radiation with a Gaussian energy distribution and the use of a coaxial feed powder which results in a uniform melt pool relative to the laser beam axis (the laser beam in all experiments was directed along the normal to the substrate). The low dilution indicates a small penetration depth of the substrate. a decrease in the HAZ and the probability of defects in the clad. so it is more preferable.
Dilution $b/(H+b)$ has a high level of correlation with the laser radiation power at different processing speeds. dependence is shown in figure 9.

Figure 9. Dependence of the dilution $b/(b+H)$ on the laser power $P$ at different speeds:

1 – 9 mm/s; $b/(b+H) = 0.08354 + 0.00018 \cdot P$ ($R = 0.95$);
2 – 12 mm/s; $b/(b+H) = 0.08191 + 0.00019 \cdot P$ ($R = 0.90$);
3 – 15 mm/s; $b/(b+H) = 0.20946 + 0.00015 \cdot P$ ($R = 0.99$);
4 – 18 mm/s; $b/(b+H) = 0.25108 + 0.00016 \cdot P$ ($R = 0.93$).
It can be seen from the figure 9 that for coaxial laser cladding the tendency to obtain a low dilution is possible only at low values of the laser power, while the laser power can act as a control parameter for the dilution quality, since it has a linear dependence in a wide range of changes in scanning speeds. Based on the found regularities the following control scheme laser cladding process. shown in figure 10.

![Figure 10. Control scheme of laser cladding process.](image)

The principle of this system is monitor the width clad with a laser scanner in real time; the control system calculates the dilution and compares it with the value set by the operator. introducing a correction for the laser power through the established regularities (figure 9). Repeated measurement of the width clad is carried out after obtaining correction in the system or after the set time (for cases when the dilution is within the permissible range).

Another indicator of the quality of the deposited layer are the coating defects, in particular cracks, pores and sinks. Defects detected in cross sections of experimental samples occurred at the boundaries of the remelted base metal and the HAZ. The presence of pores in this location due to the solubility of gases in the molten metal, as well as chemical reactions that occur during its cooling.

Changes cause the generation of gas clusters at the interface. If a closed volume of gas doesn’t have time to float to the surface, then closed pores are formed. Thus, the presence of gas and liquid in the powder mixture leads to increased pore formation in the clad metal if during the coating process the gas didn’t escape [10].

Defects in the samples ranges from 0–9% while, for 20 processing modes, this value doesn’t exceed 2%. defects were not detected on 7 samples. Obtaining defect-free coatings is one of the most important tasks. connected with the increase of the strength characteristics of the part and solves additional difficulties in the fight against corrosion of cast iron. This is because the nickel coating with respect to the cast iron is cathodic. while cathodic coatings can serve as a reliable protection against corrosion only in the absence of pores, cracks and other defects in them. In case of damage to the coating or the presence of pores, a corrosion element appears in which the cast iron serves as an anode and dissolves, and the coating material is a cathode, on which the process of hydrogen reduction or ionization of oxygen [11].

High performance correlation between the process parameters (including complex) and defect area (or percentage defect of total area) were not detected. Thus, it is necessary to continue searching for alternative approaches, which can have a direct impact on the formation of defect-free clad tracks. An example is preheating, carried out by various methods and considered in [12], including, by means of laser radiation.
4. Conclusions
   1. Investigated 32 single track with a variation in laser radiation power \( P \) from 700 W to 2800 W, processing speed \( S \) from 9 mm/s to 18 mm/s, powder feed rate \( F \) from 12 g/min to 25 g/min.
   2. Confirmed existing patterns of influence of process parameters on the geometry of clad. The greatest influence on the width of the clad is the laser power. The effective height of clad is the feed powder, when the excess energy is reached. and the effective height of the clad is falls.
   3. The desire to obtain clad layers with a low dilution limits the use of high laser power.
   4. A similarity is found between the two principles of measuring the dilution through linear dimensions and the areas of the track in the cross section.
   5. The laser radiation power can serve as a control parameter for the dilution. An algorithm for controlling the laser cladding process is proposed.

Acknowledgments
The authors thank D.Yu. Tatarkin for the experiments in the territory of NTO IRE-Polus in Fryazino. The work was carried out with the financial support of the Foundation for Assistance to Small Innovative Enterprises under the program "UMNIK".

References
[1] Chistyakov D G 2014 The development of manufacturing technologies mould of iron castings with increased operational resource: Diss. of masterdegree in mechanical engineering: 05.16.04 (Nizhny Novgorod) 245
[2] Leushin I O and Chistyakov D G 2014 Defect in the details of cast iron mould and measures against premature of their failure Vestnik UGATU (Ufa: UGATU) 18 27
[3] Birykov V P. Petrova I M and Gadolina I V 2013 Laser cladding influence on characteristics of fatigue resistance Mechanical engineering and engineering education 2 54
[4] Ocelık V. Oliveira U. Boer M and Hosson J Th M 2007 Thick Co-based coating on cast iron by side laser cladding: Analysis of processing conditions and coating properties Surface & Coatings Technology 201 5875
[5] A V Dolgovechniy. Demidova L A and Morozov E A 2012 Technologies of alloy steel buildup-up welding on the basis from carbon steel Proceedings of the Samara Scientific Center of the Russian Academy of Sciences (Samara: Samara Scientific Center of the Russian Academy of Sciences) 14 550
[6] Grigor'yanc A G. Misyurov A I and Tret'yakov R S 2011 Analysis of the influence of the coaxial laser cladding parameters on the formation of clad Tekhnologiya Mashinostroeniya (Moscow: Technology of Mechanical Engineering) 11 19
[7] Oliveira U. Ocelık V and Hosson J Th M 2005 Analysis of coaxial laser cladding processing conditions Surface & Coatings Technology 197 127
[8] Egunov A I. Artemenko Yu A and Rodionova I N 2012 Formation of pores in composite alloy WC+NiCrMoFe during laser cladding Zagotovitel'neproizvodstva v mashinostroenii 4 8
[9] Borovikov V 2008 Neural networks. STATISTICA Neural Networks. Methodology and technology of modern data analysis. 2-nd edition (Moscow.GoryachayaLiniya – Telecom) 392
[10] Grigor'yanc A G. Misyurov A I. Shiganov I N.Tret'yakov R S and Stavertii A Ya 2012 Porosity investigation of the cobalt- and nickel-based laser coatings Vestnik MGTU im. N.E. Baumana (Moscow: MGTU im. N.E. Baumana) 6 165
[11] Maltseva G N 2000 Corrosion and protection of the equipment against corrosion ed Vinogradov S N (Penza: Penza State University)p 211
[12] Yi P. Xu P. Fan C. Li C and Shi Y 2015The effect of dynamic local self-preheating in laser cladding on grey cast iron StrojniškiVestnik - Journal of Mechanical Engineering 61 43

9