The effect of laser cladding modes on the geometrical parameters and adhesion strength of the deposited layer on a steel substrate 08Kh18N10T of corrosion-resistant powder 08Kh17N8S6G

A N Gotz¹, D S Gusev¹*, V F Guskov¹, A V Zavitkov¹, A B Lukhter¹, V G Prokoshev¹ and I V Rumyantcev¹

¹ Vladimir State University named after Alexander and Nikolay Stolотовs, 87 Gorky St., Vladimir, 600000, Russian Federation

*e-mail: gusev@laser33.ru

Abstract. The results of testing samples of steel 08Kh18N10T with deposited tracks and layers of corrosion-resistant powder 08Kh17N8S6G at various laser cladding modes for the development of coating technology for working surfaces of shut-off valves on nuclear and thermal power plants. Laser cladding the steel substrate was carried out on a robotic cladding complex with an ytterbium fiber laser and coaxial powder feed. Laser output, processing speed, mass flow rate and track overlap were variable parameters for evaluating the quality of laser cladding. Macrogeometry was performed on transverse sections, adhesion tests were carried out on special samples using a testing machine. The absence of pores, cracks, undercut by visual inspection and cross section samples, the adhesion strength of the layer to the substrate, penetration depth and clad height are used as quality of coating. Identified cladding parameters having an effect on increasing the clad height, the penetration depth, as a result, the adhesion strength are revealed. Laser cladding modes are selected that provide a deposited layer with a height of more than 1 mm and good adhesive properties.

1. Introduction

Laser cladding technology uses a laser to melt and bond a metal powder to a substrate, with the mechanical properties of the cladding layer and substrate being approximately the same [1,2]. Laser cladding is carried out at low heat input, which reduces residual stresses compared to other types of surfacing. In arc surfacing, for example, deep heating occurs, which leads to large deformation, and are highly susceptible to hydrogen cracking [1]. However, there is a large penetration depth, which increases the adhesion strength.

The surfacing quality is characterized by the following indicators: the absence of pores, cracks, undercuts during visual inspection of the surface and in the cross section on the thin section, the adhesion strength of the layer to the substrate, and also the clad height [3-6].

Laser cladding can be optimized for these indicators by changing the following process parameters: laser power P, kW, travel speed S, mm/s, powder mass flow rate F, g/min [7-11].
For the effective application of laser surfacing in production conditions, it is necessary to develop repeatability of processes that provide the required coating quality. In this regard, studies were conducted for a single track [12-14], for which its height and width were determined, and then in the future, the amount of overlap, the penetration depth in the substrate were determined.

Conducting experimental studies with a single track allows to choose the most effective modes of laser cladding on the part, as well as to predict its shape [15-18].

During cladding, the surface layer consists of two zones. The first zone is the deposited layer, the second zone is the penetration zone of the substrate. The second zone provides mainly the strength properties of the deposited layer [19-22].

The purpose of this study is to identify patterns of change in the linear dimensions of the deposited track and layers from the technological modes of laser powder cladding.

To solve this goal, the following tasks were set:
- experimentally determine the effect of cladding on the linear dimensions of the deposited tracks;
- determine the laser cladding modes that satisfy the requirements of the shape of the clad beads;
- experimentally select overlap of tracks when creating layers of surfacing;
- determine the proportion of non-fusion in the cross section of the deposited layer;
- to study the adhesion strength of the deposited layers with the substrate.

2. Materials and methods

As the surfacing material, was used metal powder of erosion-resistant alloys PR-08X17N8S6G (CN-6L) manufactured by JSC Polema with a particle size of 63-125 microns manufactured according to TU 14-22-250-2013. This powder has a spherical particle shape and has good flowability. The hardness of surfacing after heat treatment is 30-39 HRC. Table 1 shows the elemental composition of the powder.

| Value (mass fraction) by elements,% | Fe | C | Cr | Co | Ni | Si | Mn | S | O2 | P | N2 |
|-----------------------------------|----|---|----|----|----|----|----|---|----|---|----|
| base                             | 0.096 | 17.7 | 0.08 | 7.97 | 5.55 | 1.92 | 0.014 | 0.02 | 0.03 | 0.09 |

Laser cladding was carried out on a laser robotic cladding complex which includes: 6-axis industrial robot manipulator (FANUC M710iC-50), powder feeder (GTV PF 2 / 1LC) designed to supply powder material to the surfacing head; four-nozzle laser cladding head (IPG Photonics Corporation).

The radiation source was an YLC-3 ytterbium fiber with laser power of 3 kW (IPG Photonics Corporation). For safe experiments, a modular protective cabin was used. The general view of the complex is shown in Figure 1.

Laser cladding was performed using continuous laser radiation in an argon shielding gas (Ar 99.998%). The metal powder was deposited on a substrate made of corrosion-resistant heat-resistant steel 08H18N10T (AISI 321).
After laser cladding, thin sections of deposited tracks and layers were prepared for evaluating macrogeometry by cutting, grinding, polishing and etching. Macrogateometry studies were performed on a Leica DM ILM metallographic microscope. Photographing the cross sections of the tracks and layers was carried out at a magnification of x50.

Mechanical tests of the deposited layers were carried out on a test machine R-20. The bond strength obtained by melting the substrate and the deposited material was determined by stretching the test samples with a layer deposited over the entire surface, in accordance with GOST 6996-66.

The deposited layer during the tensile test before reaching the yield strength should not have cracks, shells, pores and other defects on the surfacing surface.

3. Results and discussion
During the experiment, the following technological parameters were varied: laser power $P$ from 400 to 1200 W, travel speed $S$ and mass flow rate $F$ were at two levels: for $S$ – 4 and 6 mm/s, and $F$ – 15 and 21 g/min. The length of the deposited track was 100 mm.

Figure 2 shows the recorded linear dimensions of the deposited track: clad height $h$, clad width $w$, penetration depth $b$.

Analyzing the results obtained, which are presented in figures 3 and 4 in the form of graphs and histograms.
Figure 3. Effect of laser power $P$ on the width $w$ of the deposited layer and the dilution $d$, $S=4 \text{ mm/s}$:

1 – $F=15 \text{ g/min}$, 2 – $F=21 \text{ g/min}$.

With an initial increase in laser power $P$ from 400 to 800 W, there is a linear increase in both the clad width $w$ (fig. 3a) and clad height $h$, however, the penetration depth $b$ is minimal (fig. 4), which characterizes a very low dilution level $d$ (fig. 3b), determined as

$$d = b / (h+b), \quad (1)$$

which casts doubt on the presence of a good metallurgical bond.

Figure 4. Effect of laser power $P$ on the clad height $h$ and the penetration depth $b$, $S = \text{const} = 4 \text{ mm/s}$:

a – $F = 15 \text{ g/min}$, b – $F = 21 \text{ g/min}$.

When evaluating the effect of laser power $P$ on the dilution level $d$ at $F=15 \text{ g/min}$, there is a sharp increase in the laser power of 900 ... 1000 W. Obviously, at a certain heat supplied by laser radiation $E_{\text{laser}}$, the metal powder melts and the substrate heats up. Further increase in $E_{\text{laser}}$ leads to the penetration of the substrate, the value of which depends not only on the heat input, but also on the mass flow of the powder $F$ (see fig. 4).

When the mass flow rate of the powder increases to $F=21 \text{ g/min}$, the transition to the process of penetration of the substrate shifts toward a higher laser power $P$.

Based on the obtained data on the effect of the laser power on dilution level (see fig. 3b), the ranges of cladding conditions were determined: $P = 800, 1000$ and $1200 \text{ W}$, $S = 4$ and $6 \text{ mm/s}$, $F = 15$ and $21 \text{ g/min}$, corresponding to $d = 0.10 \ldots 0.15$.

The cross section of the deposited beads in the indicated ranges is shown in Figures 5 and 6, and are grouped by a constant laser power $P$. The total fraction of non-fusion in the cross section for the presented modes didn’t exceed 1% of the total surfacing area in the cross section.
Figure 5. Macrogeometry of the tracks at $P = 1000$ W.

Figure 6. Macrogeometry of the tracks at $P = 1200$ W.

An increase in the travel speed $S$ from 4 mm/s to 6 mm/s reduced the linear dimensions of the tracks, as well as the penetration depth $b$, which is clearly shown in Figure 7.

With an increase in laser power $P$ from 800 W to 1200 W or a mass flow rate of powder $F$ from 15 g/min to 21 g/min, an increase in the clad width $w$ and clad height $h$ is observed. The penetration depth $b$ with a sufficient amount of heat input increases slightly, and at a processing speed of $S = 6$ mm/s, boundary positions were obtained in the lack of heat flow ($E_{\text{laser}}$) for penetration of the substrate, as indicated earlier.

A greater contribution to the increase in the clad width $w$ is made by the laser power $P$, to the clad height $h$ – the mass flow rate of the powder $F$.

Figure 7. Effect of travel speed $S$ on height $h$, width $w$ and penetration depth $b$: 1 – at $F = 21$ g/min, 2 – at $F = 15$ g/min.
Preparation of tensile samples experimentally selected overlap between the tracks when creating coatings, the results of which are shown in table 2. It is known that the amount of overlap of the tracks (how much the next track overlap the previous one relative to its width) should be in the range from 30 to 50% [23]. Based on the smaller incomplete fusion, track overlap of 40% was selected, and samples for tensile tests were made.

### Table 2. Selection of track overlap.

| Overlap, % | Cross section layers | Incomplete fusion, % |
|------------|----------------------|----------------------|
| 50         | ![Image]             | 0.34                 |
| 46         | ![Image]             | 0.12                 |
| 43         | ![Image]             | 0.27                 |
| 40         | ![Image]             | 0.02                 |
| 36         | ![Image]             | 0.24                 |
| 33         | ![Image]             | 0.13                 |
| 30         | ![Image]             | 0.20                 |

The results of the mechanical characteristics of the deposited layer are analyzed and shown in table 3.

### Table 3. Results of mechanical testing of samples with a deposited layer.

| Laser power $P$, W | Scanning speed $S$, mm/s | Feed powder $F$, g/min | Dilution $d$ | Ultimate tensile strength, MPa | Tensile strength of clad, MPa | $k_{clad}$ |
|--------------------|--------------------------|------------------------|--------------|-------------------------------|------------------------------|------------|
| 1000               | 4                        | 15                     | 0.171        | 482                           | 385                          | 0.80       |
| 1000               | 4                        | 21                     | 0.153        | 498                           | 395                          | 0.79       |
| 1000               | 6                        | 15                     | 0.055        | 526                           | 402                          | 0.76       |
| 1000               | 6                        | 21                     | 0.070        | 482                           | 353                          | 0.73       |
| 1200               | 4                        | 15                     | 0.203        | 437                           | 398                          | 0.91       |
| 1200               | 4                        | 21                     | 0.242        | 431                           | 404                          | 0.94       |
| 1200               | 6                        | 15                     | 0.125        | 499                           | 412                          | 0.83       |
| 1200               | 6                        | 21                     | 0.099        | 463                           | 370                          | 0.80       |

To assess the quality of the deposited layer relative to the substrate strength, the following ratio was determined:
\[ k_{\text{clad}} = \frac{\text{TS}_{\text{clad}}}{\text{UTS}_{\text{sample}}}, \]  

(2)

where \( \text{TS}_{\text{clad}} \) – tensile strength of clad layer, MPa; 
\( \text{UTS}_{\text{sample}} \) – ultimate tensile strength control sample, MPa.

The first cracks that appeared in the deposited layer have \( \text{TS}_{\text{clad}} \) strength significantly higher than the yield strength, which indicates a good metallurgical bond of the deposited layer with the substrate material.

The strength of the deposited layer correlates with dilution level (fig. 8), the higher the dilution level, the higher the strength of the deposited layer.

![Figure 8](image_url)

\textbf{Figure 8.} Effect of dilution on tensile strength of clad (\( k_{\text{clad}} \)).

In the dilution range from 0.2 to 0.25, the appearance of cracks in the deposited layer occurs in the range of 0.91-0.93 of the tensile strength of the substrate.

4. Conclusions

Based on the studies established:

1) The linear dimensions of the deposited tracks is mainly affected by laser power, however, the clad height is more dependent on the mass flow rate of the powder.

2) The maximum clad height excess of 1 mm and a width of more than 3 mm was obtained in the following modes: laser power of 1200 W, a travel speed of 4 mm/s and a powder mass flow rate of 15 and 21 g/min.

3) The smallest amount of incomplete fusion (0.02\%) in the layer at the borders of the tracks was obtained with overlap of tracks of 40\%.

4) The strength of the deposited layer correlates with dilution, the higher the dilution, the higher the strength of the deposited layer, in the dilution range from 0.2 to 0.25, the appearance of cracks in the deposited layer occurs in the range of 0.91-0.93 of the tensile strength of the substrate.

Acknowledgments

This work was supported by the Ministry of Science and Higher Education of the Russian Federation, grant agreement No. 075-15-2019-1833 dated December 03, 2019. The unique identifier of the applied scientific research is RFMEFI60419X0245.

References

[1] Sexton L, Lavin S, Byrne G and Kennedy A 2002 Laser cladding of aerospace materials \textit{J. Mater. Process. Technol.}

[2] Vilar R 2001 Laser cladding \textit{Int. J. Powder Metall. (Princeton, New Jersey)}

[3] Liverani E, Toschi S, Ceschini L and Fortunato A 2017 Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel \textit{J. Mater. Process. Technol.}

[4] Li R, Shi Y, Wang Z, Wang L, Liu J and Jiang W 2010 Densification behavior of gas and water atomized 316L stainless steel powder during selective laser melting \textit{Appl. Surf. Sci.}
[5] Peng L, Taiping Y, Sheng L, Dongsheng L, Qianwu H, Weihao X and Xiaoyan Z 2005 Direct laser fabrication of nickel alloy samples Int. J. Mach. Tools Manuf.
[6] Yu J, Rombouts M and Maes G 2013 Cracking behavior and mechanical properties of austenitic stainless steel parts produced by laser metal deposition Mater. Des.
[7] Reddy L, Preston S P, Shipway P H, Davis C and Hussain T 2018 Process parameter optimisation of laser clad iron based alloy: Predictive models of deposition efficiency, porosity and dilution Surf. Coatings Technol.
[8] Alvarez P, Montealegre M, Pulido-Jiménez J and Arrizubieta J 2018 Analysis of the Process Parameter Influence in Laser Cladding of 316L Stainless Steel J. Manuf. Mater. Process.
[9] Bykovskiy D P, Petrovskiy V N, Dzhumaev P S, Polskiy V I and Yermachenko V M 2016 Analysis of microstructure and properties of multilayer coatings produced by laser cladding Journal of Physics: Conference Series
[10] Zhu G, Li D, Zhang A, Pi G and Tang Y 2012 The influence of laser and powder defocusing characteristics on the surface quality in laser direct metal deposition Opt. Laser Technol.
[11] Goodarzi D M, Pekkarinen J and Salminen A 2017 Analysis of laser cladding process parameter influence on the clad bead geometry Weld. World
[12] de Oliveira U, Ocelik V and De Hosson J T M 2006 Residual stress analysis in Co-based laser clad layers by laboratory X-rays and synchrotron diffraction techniques Surf. Coatings Technol.
[13] Ocelik V, de Oliveira U, de Boer M and de Hosson J T M 2007 Thick Co-based coating on cast iron by side laser cladding: Analysis of processing conditions and coating properties Surf. Coatings Technol.
[14] Gusev D S and Lyukhter A B 2018 Influence of technological parameters on the geometry of single-track laser clad nickel based alloy on grey cast iron substrate Journal of Physics: Conference Series
[15] Lian G, Zhang H, Zhang Y, Tanaka M L, Chen C and Jiang J 2019 Optimizing processing parameters for multi-track laser cladding utilizing multi-response grey relational analysis Coatings
[16] Nenadl O, Ocelik V, Palavra A and De Hosson J T M 2014 The prediction of coating geometry from main processing parameters in laser cladding Physics Procedia
[17] Ju J, Zhou Y, Kang M and Wang J 2018 Optimization of process parameters, microstructure, and properties of laser cladding Fe-based alloy on 42CrMo steel roller Materials (Basel).
[18] Liu H, Qin X, Huang S, Jin L, Wang Y and Lei K 2018 Geometry Characteristics Prediction of Single Track Cladding Deposited by High Power Diode Laser Based on Genetic Algorithm and Neural Network Int. J. Precis. Eng. Manuf.
[19] Telasang G, Dutta Majumdar J, Padmanabham G, Tak M and Manna I 2014 Effect of laser parameters on microstructure and hardness of laser clad and tempered AISI H13 tool steel Surf. Coatings Technol.
[20] Yadollahi A, Shamsaei N, Thompson S M and Seely D W 2015 Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel Mater. Sci. Eng. A
[21] Lin C M, Chandra A S, Morales-Rivas L, Huang S Y, Wu H C, Wu Y E and Tsai H L 2014 Repair welding of ductile cast iron by laser cladding process: Microstructure and mechanical properties Int. J. Cast Met. Res.
[22] Sun S Da, Liu Q, Brandt M, Luzin V, Cottam R, Janardhana M and Clark G 2014 Effect of laser clad repair on the fatigue behaviour of ultra-high strength AISI 4340 steel Mater. Sci. Eng. A
[23] 33258-2015 G 2015 GOST 33258-2015. Interstate standard