Selection of rational modes of laser powder cladding

A N Gots*, D S Gusev, A B Lukhter and A V Zavitkov
Vladimir State University named after Alexander Grigoryevich and Nikolay
Grigoryevich Stoletov" (VlSU), Vladimir, Russia

*hotz@mail.ru

Abstract. A brief overview of the surfacing used on the working surfaces of industrial
equipment parts is given. The most universal method of laser surfacing is considered laser
powder cladding. The results of experimental studies on the choice of parameters of surfacing
modes for a single track are presented: laser power, mass flow rate of powder for deposition,
and surfacing speed. Samples made of 08H18N10T steel were used as a substrate for testing.
Laser powder cladding was performed on a robotic complex with an ytterbium fiber laser and a
coaxial powder feed. When measuring macrogeometry, the quality of a single track was
evaluated by its geometric dimensions: height, width, and depth of the layer mixing of the
surfaced and base materials (substrate). Variable parameters of the surfacing process were the
output power of laser radiation, processing speed, and mass flow rate of the powder. The
quality of a single clad track was evaluated by its geometric dimensions: height, width, and
depth of the layer mixing of the surfaced and base materials (substrate). It is shown that the
value of d depends on the mass flow rate and the power of the laser radiation: when increasing
mass flow rate, it is necessary to increase power of the laser radiation to ensure a constant
value of depth of the layer mixing. The shape of the deposited clad track is close to a half-
ellipse only when the laser power not more than 1000 W and mass flow rate 15 g/min. The
height of d depends on the value of mass flow rate and the laser power: when increasing mass
flow rate, an increase in laser power is required in approximately the same ratio. The width of
the surfacing with increasing mass flow rate at a constant power of laser radiation decreases
due to the fact that the cooling rate of the liquid phase of the metal melt is very high and only
superheated melt can increase the width of the clad track.

1. Introduction
To increase the wear resistance of friction pairs, metal or composite coatings are applied to the
working surfaces of critical parts, which have increased characteristics: mechanical, corrosion and
radiation resistance, heat resistance, wear resistance; good anti-friction properties [1-4]. Obtaining
such surfacing is relevant for the entire spectrum of heavy industry, shipbuilding, energy, oil and
and mining industries, Metalworking, paper and others. In principle, the use of coatings to increase the
durability of parts has been known for a long time – remember the period of mass shortage, when for
the transport ice was carried out surfacing on the main and connecting rod necks of the crankshaft by
electric arc method. During this time, various methods of applying surfaced coatings have appeared
and developed, while, of course, there are differences in the final results. Recently, pulsed laser
radiation has been used for surfacing. Note that the use of this type of surfacing, the duration of which
is milliseconds, allows you to obtain minimal heat affected zone, which does not exceed a few tens of
micrometers [5-7]. The minimum volume of the melt and the minimum heat input to the part while
welding significantly reduce thermal distortion and thereby to maintain the dimensions of the part that is surfacing in the field of tolerance of a few micrometers [8-11]. The accuracy of the guidance and locality of the laser beam allows you to apply coatings on strictly defined geometric areas of the part (even curved), providing a minimum allowance for machining, which is 0.2...0.5 mm [12-15]. It is known that when pulsed laser surfacing compared with other surfacing heat affected zone is very small, the substrate remains almost cold, and the cooling rate of the liquid phase of molten metal large [16-18].

In gas-powder laser surfacing, coatings are obtained by forcing the powder flow directly into the laser radiation zone [17-19]. The powder particles are heated in the laser radiation zone and fall on the treated surface (substrate). When the substrate is heated, its surface layer melts and it dissolves in the molten layer of the surfacing, and as a result of diffusion processes at the interphase boundary, a significant part of the base (substrate) components passes into the surfacing [16, 17].

When surfacing, it is important to ensure the height and width of the deposited track. It is believed that a slight mixing of the surfaced and basic materials, as well as a large contact angle on both sides of the clad track, allows us to predict the production of defect-free coatings when successive surfacing of the tracks with some overlap [6]. At an acute contact angle, the deposited clad track is formed unsatisfactorily – with large fluctuations in the height, width, and depth of the mixing layer.

The surfaced layer must not contain such defects as: pores, shells, hairlines (a fine grid of cracks), and also have a good adhesion strength of the surfaced layer to the substrate. It is possible to achieve the election of rational modes of laser cladding using powders.

The paper considers the results of experimental studies when the feed of the additive material was carried out by forcing it directly into the melt bath of the substrate material. This method allows automating the process and has high reproducibility [15-17].

Studies of gas-powder laser surfacing were carried out for a single track, for which its height and width were determined, and then later, when using the obtained materials for surfacing, the overlap value and the depth of penetration in the substrate should be determined [18-21].

Conducting experimental studies with a single track allows you to choose the most effective modes of laser surfacing on parts, as well as predict its shape.

It is to determine the effect of surfacing modes: laser power, W, optical head movement speed, mm/s, mass flow rate supplied to the powder processing zone q, g/min, on the linear dimensions of the clad track in mm: height h, width b, and layer depth mixing of the surfaced and base materials d.

To achieve this goal, the following tasks were set:

- determine the rational modes of laser surfacing when changing the mass flow rate of the powder fed to the processing zone based on the results of experimental studies;
- determine the surfacing modes that meet the requirements of the shape of the surfaced tracks, the height and width of the clad track.

2. Materials and methods of research

To conduct experimental studies on the choice of laser surfacing modes, a laser robotic complex of surfacing (LRC-S) was used, which includes: a 6-axis industrial robot manipulator FANUC M710iC-50, a single-column powder feeder GTV PF 2/1LC, designed for metered supply of powder material to the surfacing head; a laser surfacing head with a module for feeding powder from four sides IPG Photonics Corporation. To distribute the powder through four channels, a four-string powder distributor is used. The radiation source was an ytterbium fiber laser YLS-3 with a power of up to 3 kW by IPG Photonics Corporation. To ensure the safety of the researchers, the experiments were conducted in a modular protective cabin.

The surfacing material used was a metal powder of erosion-resistant alloys PR-08X17H8C6G (TSN-6L) produced by JSC "Polema" with a particle size of 63 ... 125 microns made according to TU 14-22-250-2013, deposited on a substrate of steel 08H18N10T. Gas-sprayed powders are characterized by a spherical particle shape, high fluidity, and microcrystalline structure [10]. The hardness of the surfacing using PR-08X17N8C6G powder after heat treatment is 30-39 HRC. The
largest mass fraction in the powder: Fe-about 66%; alloying components: Cr - 17.7%, Ni - 7.97%, Si - 5.55%, Mn - 1.93%, and the remaining components (C, Co) - hundredths of a percent.

Laser surfacing was performed using continuous laser radiation in the medium of protective and transporting argon gas (Ar 99.998%), flowing at a speed of 6 l/min and 25 l/min, respectively.

To evaluate the microgeometry of the track, planks were cut from the surfaced tracks, which were processed by grinding, polishing and etching. Studies of surface geometry was conducted on the metallographic microscope Leica DM ILM. Cross-sections of the deposited tracks and layers were photographed using x50 magnification.

During the experiment, the following technological parameters were varied: the laser power $P_l$ in the range of 400 to 2000 W, the surfacing speed $V$, mm/s, and the mass flow rate of the powder $q$, g/min—mainly at two levels: for $V$ - 4 and 6 mm/s, and $q$ - 15 and 21 g/min. The length of the surfaced track was 100 mm.

To check the dependence of geometric parameters (height $h$, mm; width $b$, mm, layer depth mixing of the surfaced and base materials $d$, mm), an experiment was conducted at $q$ from 6 and 28 g/min and laser power in each experiment from 1000 to 2000 W in increments of 200 W and a constant surfacing speed $V=6$ mm/s.

When choosing the parameters for laser deposition to ensure the most satisfactory shape of the track, the main attention was paid to the choice of the laser deposition power $P_l$, W and the mass flow rate of the powder was $q$, g/min. The choice of laser radiation power is important for obtaining the quality of surfaced coatings.

After laser cladding was prepared the thin sections from the weld paths and layers for evaluation of surface geometry by means of electro-erosive cutting, grinding, polishing and etching. Studies of surface geometry was conducted on the metallographic microscope Leica DM ILM. Cross-sections of the clad tracks and layers were photographed using X50 magnification.

3. Results and Discussion

Fig. 1 shows cross-section of the deposited track after laser surfacing of the PR-08H17N8S6CG powder. As estimates of the parameters of the geometry of deposited bead choose: $h$ - height of the cushion; $b$ - width; $d$ - depth of the layer of mixing of the filler and the base material (substrate); $\beta$ is a contact angle between the tangent to the surface of the track and the plane of the substrate. This cross-section is used for surfacing with a laser power of $P_l=1000$ W at a surfacing speed of $V=4$ mm/s and a mass flow of powder $q=15$ g/min.

![Figure 1](image-url)  
**Figure 1.** Cross-section of a single track of laser surfacing powder PR-08H17N8S6G: $h$ – height of the track; $b$-width of it; $d$ – depth of the layer mixing of the surfaced and basic materials; $\beta$ –contact angle between the tangent to the surface of the track and the substrate

Fig. 2 shows graphs of changes in the surfacing height, width and depth of the layer mixing of the surfaced and basic materials depending on the mass flow of the powder $q$ at a constant surfacing speed $V=6$ mm/s (for the entire test period) and constant laser radiation power $P_l$: 1000 (1), 1200 (2), 1400 (3), 1600 (4), 1800 (5), 2000 (6) W (numbers in parentheses indicate the test sequence for analyzing the curves in figure 2); the mass flow rate of powder $q$ was 6, 12, 18, 22 and 28 g/min. At $P_l=1000$-1400 W, the powder consumption $q=28$ g/min was not used due to insufficient thermal radiation for
melting. At $P_l = 1600-2000$ W, the powder consumption $q$ = 6 g/min was not applied due to large overheating.

Let's analyze the results. In Fig. 2a,b,c, the curves obtained at a single constant power of laser radiation are indicated by the same numbers. Thus, curve 1 – shows the trend line of changes in the height of the deposited track $h$ (see Fig. 2a) at $P_l = 1000$ W after approximation by polynomial dependence and smoothing; in Fig. 2b, curve 1 – the same for width $b$; in Fig. 2c, curve 1 – the same for the depth of the layer mixing of the deposited and basic materials $d$. This designation allows you to evaluate the change in the selected indicators only from the mass flow rate of the powder $q$, g/min during surfacing.

**Figure 2.** Changing the height (a) of the track $h$, its width (b) and-the depth of the layer mixing of the surfaced and basic materials (c) depending on the mass flow of the powder $q$, g / min at a constant surfacing speed $V$ = 6 mm/s: indicated 1 - $P_l$ = 1000 W; 2 - $P_l$ = 1200 W; 3 - $P_l$ = 1400 W; 4 - $P_l$ = 1600 W; 5 - $P_l$ = 1800 W; 6 - $P_l$ = 2000 W

First of all, it can be noted that increasing the mass flow rate of powder in 3...3.5 times height $h$ is increasing also in this times (see Fig. 2,a), irrespective of laser power $P_l$. At the same time, with laser radiation power up to $P_l$ = 2000 W, the height gain is significant (see Fig. 2,a).

At the same time, when the consumption of powder $q$ increases during surfacing, regardless of the laser power, the width of the track decreases (on average by 10..14%, (see Fig. 2,b). This change in the value $b$ can be explained by the fact that the amount of heat supplied is apparently sufficient for the melt of the applied increased mass of powder, but since the thermal influence zones are very small during pulsed laser surfacing, the substrate remains practically cold, and the cooling rate of the liquid phase of the metal melt reaches $10^2$...$10^3$ deg/s [17, 18], the melt does not overheat. Therefore, the liquid melt does not spread and does not increase the width of the track. Only when the laser power is 2000 W, the width of the track changes slightly [18, 19].

Fig. 2,c shows the trend lines for changing the depth of the layer mixing of the surfaced and basic materials $d$. The graphs show that when the mass flow rate of the powder $q$ increases, the depth of the layer mixing of the surfaced and basic materials $d$ decreases (only at $P_l$ = 2000 W, the value of $d$ changes slightly). Apparently, with increasing $q$, a greater amount of heat is required to heat and melt
the powder supplied to the melt zone, and, as mentioned above, with a small zone of thermal influence, the substrate does not warm up.

Let's now consider the influence of the laser radiation power $P_l$ on the geometric parameters of the deposited track. From Fig. 1 it can be seen that the correctly formed track has a shape close to a half-ellipse on the sections. In this case, the track has the highest height $h$ with a significant width $b$ and the contact angle $\beta$ between the tangent to the surface of the track and the substrate plane compared to other forms (there is no spreading on the surface).

Take as the evaluation parameter of the quality of the forming track $k_1$ is the ratio of actual cross-sectional area of the deposition surfacing $S$ to the area ellipse, taking half the width $b/2$ and the height $h$ of the tracks after surfacing as the half axes of the ellipse.

Half of the cross-sectional area of the ellipse, the major axis of which is equal to half the width of the track $b/2$, and the small-the height $h$, we determine by the formula:

$$S_{0.5el} = \frac{\pi hb}{4}.$$  \hspace{1cm} (1)

The actual cross-sectional area of the surfacing $S$ in mm$^2$ is determined by examining the structure on micro-sections.

Then the estimated parameter of the quality of forming the track $k_1$ as the ratio of the actual cross-section area of the surfacing $S$ to the area of the half-ellipse calculated by the formula (1) is equal to:

$$k_1 = \frac{S}{S_{0.5el}}.$$  \hspace{1cm} (2)

The actual cross-sectional area of the surfacing $S$ depends on the change in the width $b$ and height $h$ of the surfacing (at a large depth of the layer, mixing of the surfaced and basic materials $d$, the height $h$ decreases due to the spreading of the surfaced material). Therefore, it is interesting to see how the ratio $b/2h$ (the ratio of the large and small half-axis of the ellipse) changes depending on the power of the $P_l$ laser radiation. When the power of the laser radiation $P_l$ increases and the mass flow of the powder $q$ increases, the depth of the layer mixing of the surfaced and basic materials $d$ must also change. In this regard, we will determine experimentally how the $d/h$ ratio changes with an increase in the mass flow rate of the powder $q$.

Results of processing experimental data for the following powder consumption $q$: experiments 1 – 15; 2 – 21; 3 – 6; 4 – 12; 5 – 18; 6 – 22; 7 – 10 g / min and surfacing speeds $V$: 1, 2 – 15; 3...6 – 6; 7 – 10 mm/s, shown in Fig. 3 (the laser radiation power is visible from the graphs, the designation of the curves corresponds to the experiment number).

Analyze the results. First of all, it turned out that the closest to the shape of the half-ellipse are the tracks, which were surfaced at a speed of $V = 4$ mm/s and the mass flow rate of the powder $q = 4$ and 21 g/min (see Fig. 3,a, curves 1 and 2). Indeed, the average value of the ratio $(S/S_{0.5el})$ m or the estimated parameter of the quality of forming the roll $k_1$ at a laser power of 400 to 1000 W is close to one ($k_{1m} = 1.008$ and 1.002). We can recognize a satisfactory result of the quality of the surfacing track at the deposition rate $V = 6$ mm/s, as well as $q= 18$ and 22 g/min at a laser power of 1000 to 2000 W (see Fig. 3, a, curve 6, the average coefficient $k_{1m} = 0.92$ and curve 7, $k_{1m} = 0.854$). For all other surfacing modes, the quality parameter for surfacing the track $k_1$ is 0.85.

However, note that when building-up curves for the conditions in experiments 1, 2, 6 and 7, which form a separate track close to ellipse, the average value of the ratio of the major and minor axes of the ellipse $b/2h$ is just: curves 1, 2 – 1.5; curves 6,7 and 1.9 and 1.3 (see Fig. 3,b).

Average $b/2h$ ratio for curves: $4 – 6.0; 3 – 7.1; 5 – 4.7$ at $P_l \approx 1400...1500$ W. In other words, if the surfacing modes correspond to the laser power $P_l \approx 1400...1500$ W, then $k_1 \approx 0.91$ at a sufficiently large ratio $b/2h$.

Consider how the $d/h$ ratio changes – the ratio of the depth of the layer mixing of the surfaced and basic materials to the height of the track when the laser radiation power changes.
First of all, we note that for curves 1 and 2 (see Fig. 3, c), the average value of the ratio of the depth of the layer mixing of the surfaced and basic materials to the height of the track \(d/h\) is the smallest and is only 0.125 and 0.091. The highest average value of \(d/h = 2.98\) when surfacing with parameters \(q = 18\) g/min; \(V = 6\) mm/s; \(P_l = 1000...1800\) W (see Fig. 3, curve 5). For other curves: curves 3, 4 \(\approx 1.8\) (\(P_l = 600...1400\) W); curves 6, 7 (\(P_l = 1000...2000\) W) \(\approx 1.0\). In experiment 7, the powder consumption was \(q = 10\) g/min; \(V = 10\) mm/s.

From the obtained graphs in Fig. 3, c, curve 5 is highlighted (\(q = 12\) g/min; \(V = 6\) mm/s) At \(P_l = 1800\) W, the height of the track is only \(h = 0.3\) mm, but the depth of the mixing layer of the surfaced and base materials is \(d = 1.37\) mm (see Fig. 2,a and Fig.2, c, curve 5). At high power of laser radiation, the heat generated is not only used for melting the supplied powder, but also for heating and melting the substrate.

Note that if the value of the depth of the mixing layer of the surfaced and basic materials \(d\) is tenths of a millimeter, it means that the surfacing has a minimal thermal effect on the base metal (substrate). This is especially important for materials undergoing structural and phase transformations; in addition, the resulting residual temperature deformations do not have any effect on the strength and durability of the deposited parts. The minimum melting depth of the base is achieved when the base and filler metals are heated separately, as well as when a sufficient amount of powder is fed to the melting zone (see curves 6 and 7, Fig. 3, c).

4. Conclusions
As follows from the analysis of two independent results of experimental studies: first, at constant laser radiation power \(P_l\), surfacing speed \(V\) (in one test) and variable values of powder mass flow \(q\); and also at constant in one test \(V\) and \(q\) with a variable value \(P_l\), the following results were obtained:
the surfacing height \( h \) depends on the mass flow rate \( q \) and the laser power \( P_l \): increasing \( q \) requires approximately the same ratio of increasing \( P_l \);

the surfacing width \( b \) decreases with increasing mass flow \( q \) at constant laser power \( P_l \) due to the fact that the cooling rate of the liquid phase of the metal melt is very high and only superheated melt can increase the width of the track;

the depth of the layer of mixing of the filler and base materials \( d \) also depends on the mass flow rate \( q \) and the laser output power \( P_l \); with increasing \( q \) to ensure a constant value \( d \) is needed to increase \( P_l \); shape filler track close to ellipse is only possible when the laser output power \( P_l \leq 1000 \) W and \( q = 15 \) g/min.

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.

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