Analysis of microstructure and properties of multilayer coatings produced by laser cladding

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Abstract. Purpose of the work is to prepare multilayer coatings corresponding to specified requirements to recovery and improvement of surface details. Requirements to coatings: providing durable and reliable adhesion base and filler materials, absence of pores, cracks, delaminations, reducing mixing metal base and cladding. We used iron-based PR-10R6M5 and tungsten carbide Hoganas 44712 powders. Experimental determination of the optimal technological mode of application of the single track, the coefficient of overlapping tracks to create a full layer, the angle of the second cladding layer, relative to the first one and, finally, the determination of the optimal additive tungsten carbide to achieve increased durability were produced to fulfill these requirements.

1. Introduction
The technology of the recovery process and the application of protective coatings using the fiber laser is one of the priority technologies in mechanical engineering, with great prospects and require more extensive research [1]. During application of cladding coatings it is necessary not only to take into account the whole set of parameters that affect the quality of the coating, but also the economic feasibility when choosing one of them [2]. Processes affecting the quality of the deposited coatings are not fully known. The study of these processes allows more efficient to select process conditions to ensure the specified quality of the applied coating. Used powder PR-10R6M5 was made by spraying molten gas. It is usually used for the restoration and consolidation of punching tools, the creation of the working surfaces of cutting tools, hardening roll cold rolling welding and other purposes [3]. Powder Hoganas 44712 is agglomerated powder WC-Co and has spherical particles given more uniform distribution of carbide in the matrix [4].

2. Experimental equipment
Photo of experimental setup is shown in figure 1a. The equipment consists of a filler unit (1) (view inside is shown in figure 1b), the controller (2), a powder feeder SulzerMetco Twin 10-C (3) for feeding a metal powder with a particle size of 5 to 200 µm. We used a fiber laser LS-3.5 (4) with a power of up to 3.5 kW, the wavelength $\lambda = 1069$ nm, the fiber diameter of 100 µm. Cladding head in figure 1b consists of a collimating and focusing optical system, water cooling system optics and nozzle, delivery system of filler powder and shielding gas.

The metal powder is provided in the treatment zone via a coaxial nozzle symmetrically from all the sides, under laser radiation it is heated and melted (figure 2). Simultaneously, the substrate
surface is melted. When the relative motion of the nozzle relative to the substrate after cooling is formed on the surface of the track. The sequential application of tracks with some overlapping formed a new layer.

3. Experimental results

3.1. Forming one track

It was necessary to prepare the filler material before cladding. Grain size of PR-10R6M5 is in the range up to 140 µm. Sieving through a flat sieve was performed for improving the properties of the cladding. The cell size varied from 63 to 100 µm. The powder became more homogeneous, without large teardrop-shaped beads after screening (fig. 3).

It is different forming tracks during cladding with different modes of laser power, speed,
laser power, speed, powder flow, gap between nozzle and substrate surface different tracks are forming. Deep penetration of the filler material into the substrate can be seen in a technological window of these parameters, this results in a significant mixing of materials and the deterioration of coating properties. Coating, produced under the other process parameters window with a small penetration of filler material into the substrate, will have insufficient adhesion. One track geometrical parameters were measured for proper selection of cladding technological window: width, height and depth of penetration of the substrate, depending on adjusting of the following parameters: laser power, speed, powder flow, gap between the nozzle and the substrate. The measurement results are shown in figure 4.

The measurements evidenced that a change of the laser power has the most crucial impact on

![Graphs showing geometric parameters of cladded tracks on laser power, powder feed rate, linear speed, and gap between nozzle and substrate](image)

**Figure 4.** Dependences of geometric parameters of cladded tracks on laser power (a), powder feed rate (b), linear speed (c) and gap between the nozzle and substrate (d).

...the width of the cladding track and depth of penetration of filler material in the substrate and the powder feed rate - on the height of the tracks. The most appropriate mode was selected for further research on the following parameters: uniformity of track form, absence of pores and cracks, the least gauge of mixing substrate materials and powder, and a minimal depth of penetration of filler material in the substrate with good adhesion of the coating to the substrate without delamination from it.

A study of topography and microstructure of the surface was carried out under the electron microscope (SEM) Carl Zeiss EVO 50 XVP, determined the elemental composition of the samples by the method Vickers on the setup HVS-1000 with automatic loading of the indenter to the
load at 1 N. The dwell time at load has been chosen to 20 s. The results showed (figure 5a) that
the HAZ is 300 µm, cladding structure - equiaxed mesh, near the boundary with the substrate -
dendritic structure, grain boundaries are enriched in heavy elements (Mo, W). The structure
of the HAZ - milled grain ferrite-pearlite with traces of partial martensitic transformation. The
structure of the substrate - polyhedral (equiaxed) grains of ferrite and pearlite. The boundary
of the substrate and facing a clear, there is no peeling, cracking and porosity. Microhardness
(figure 5b) changes at the boundary of the substrate and cladding (points 3 and 4) from 5700 MPa
(cladding) to 2000 MPa (substrate material).

![Figure 5](image)

Figure 5. One track producing by optimal regime (a) and change of microhardness over the
cross section (b).

3.2. Forming one layer

Single-layer coatings were formed by depositing sequential tracks with different coefficients of
overlapping by width: 0.33, 0.5, 0.6. The temperature distribution of the substrate was also
measured during the deposition. The measured distribution determined the distance in the
transverse direction, which is a significant decrease in temperature. Measurements demonstrated
that the change in the surfacing (laser power, deposition rate, flow rate of the powder, gap
between the nozzle and substrate) influences the maximum temperature in the vicinity of the
melting of the metal. The distance in a transverse direction, at which crucial attenuation of
temperature in all cases happens, may be taken as 5 mm.

Next, a single-layer coating was performed considering the temperature distribution of the
substrate (figure 6). After application of the track 1 (figure 7) substrate material was displaced
at the distance D where thermal field of one track falls significantly. On the basis of the analysis
devoted to the measured distribution of substrate material temperature within welding the value
of D = 5 mm was chosen. Then track 2 was applied, and once again shift at the distance D
happened, track 3 was applied. Further substrate material was turned back to the track 1 and
was moved in direction of the track 1 at the pace L = 0.33W, and after that the layers 4, 5 and 6
were applied. The procedure was repeating, until the whole layer was completed.

Figure 8 show images of produced coatings obtained due to electron microscope, and figure 9 -
the measurement results of their microhardness. For all coatings structure - equiaxed mesh,
near the boundary with the substrate - dendritic structure, grain boundaries are enriched in
heavy elements (Mo, W). The structure of the HAZ - milled grain ferritepearlite with traces of
partial martensitic transformation. The boundary of the substrate and facing a clear, there is
no peeling, cracking and porosity. Microhardness changes at the boundary with the cladding
and the substrate 6000 MPa (cladding) to 2000 MPa (substrate material). The Fe content in the powder is 80% and about 98% in the substrate. The resulting coating with overlapping 0.33 contents 86% Fe, with an overlap of 0.5 - 85%, with overlapping 0.66 - 83%, with overlapping 0.66 and considering the temperature distribution - 81.5%. Cover with a large overlap ratio has minimal mixing of substrate materials and powder that indicates improved quality. Coatings by strategy based on the temperature distribution, have the best characteristics concerning the mixing of substrate materials and the powder, the highest microhardness, but penetration of substrate and coating thickness are uneven at the site of the last series of tracks.

3.3. Forming two layers

The bilayer coatings were produced under different conditions. Initially the first layer was created by sequential application of tracks with overlapping 0.66. Next, a second layer was formed with the same mode, but with different directions of the tracks: along the first layer, at an angle of 45° and 90°. Structure of coatings is presented in figure 10 and change of microhardness over the cross section this bilayer coatings in figure 10d.

Coatings have equiaxed mesh, near the boundary with the substrate - dendritic structure, grain boundaries are enriched in heavy elements (Mo, W). The width of the HAZ 300 m, its structure - the crushed grain ferrite-pearlite with traces of partial martensitic transformation. The iron content in the three cases was 85%. The microhardness increased to 7,000 MPa (figure 10d), its dependence is more uniform in the case with the direction of the clad layers of 0°. Since measured the remaining coating characteristics are the same, one can conclude the best quality in the event of cladding layers at an angle of 0°.
Figure 8. Cross-sections of one layer with overlapping 0.33 (a), 0.5 (b), 0.66 (c), 0.66 and considering thermal field (d).

Figure 9. Change of microhardness over the cross section of one layer.

3.4. Forming high wear resistance coatings
Coatings with additives of tungsten carbide-based 44712 Hoganas powder were created under obtained technological regime. Additives ranged from 3 to 9% by weight. The coating, containing 9% Hoganas 44712 powder cracked, so did not participate in further tests. Another samples were tested for wear resistance by standard Brinell-Haworth with a rubber disc and sand. The experiment is based on the current method of comparative evaluation of steel and alloys tribological characteristics (weight loss) by dry friction. Steel disk with a rubber rim is rotating at 200 rpm and is pressed against the fixed sample with a force of 15 N during 10 min. Between the disk and the sample is fed from the bunker by gravity silica sand. Addition of 7% of the powder based on tungsten carbide resulted in an increase in wear resistance of the alloy layer 2 times in comparison with cladding iron-based powder (figure 11).
Figure 10. Bilayer coatings with direction of second layer $0^\circ$ (a), $45^\circ$ (b), $90^\circ$ (c) and change of microhardness over the cross section (d).

Figure 11. Dependence of wear resistance in content powder Hoganas 44712.

4. Conclusion
The greatest influence on the height of cladding track has the powder feed rate and on the width of the cladding track and depth of penetration of filler material in the substrate of the tracks - change of the laser power. Monolayer coatings with a coefficient of 0.66 overlapping tracks have lower gauge of mixing powder material and the substrate than coatings with a coefficient of 0.33 and 0.5. This is a consequence of smaller area thermal effects on the substrate. Bilayer coatings with the direction of the clad layers $0^\circ$ are more uniform than in the case when a direction angle of $45^\circ$ and $90^\circ$. Differences in the ratio of mixing for the three different directions are not observed. Addition of 7% powder Hoganas 44712 improved wear resistance 2 times in comparison with
cladding iron-based powder. The coatings can be used to restore worn-out and manufacture of new machine parts and mechanisms: the body parts of various internal combustion engines, electrical and crank shafts, valves, pulleys, flywheels, wheel hubs, etc.

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