Investigation of the microstructure of laser-deposited layers on cast-iron parts

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Abstract. The gas-powder laser surfacing process of the cast-iron parts' surfaces with the aim of increasing the wear resistance is investigated. Obtaining a coating with specified parameters (chemical composition, dimensions and quality of the rollers being deposited) depends on the irradiation regimes: power, processing speed, dimensions of the focal spot, powder consumption and the method of its delivery. St3 steel was used as a base material. Self-fluxing powders PG-C3R2, PG-PBH-6-2 and PG-US25-20Fe and their mixtures were used as a material for surfacing. The powders had a particle size of 50-160 microns. During laser heating, the structure is refined: the size of graphite plates is reduced from 150–200 µm to 20–40 µm in the melted zone, then their depth increases to the initial value. In the melted zone, graphite partially dissolves, partially burns out, forming pores. In the areas with the most complete dissolution of graphite plates, an austenite-martensitic structure with a hardness of up to 8.0–9.5 GPa is formed. In areas with a lower degree of dissolution of graphite, a martensite-sorbitol structure is formed with a hardness of 6.5–7.0 GPa. In the area of laser exposure, the hardness of the cast-iron welded parts increases by 3-4 times, which provides a significant increase in wear resistance.

1. Introduction
The microstructure of cast-iron welded parts has a different structure depending on the size and distance from the surface [1-3]. In the study of the cross-section of a cast-iron part (figure 1), it was noted that the part has a ferritic-pearlite structure (figure 2), like most parts made of cast iron [4–8]. The content of perlite in different sections ranges from 30–70 %. Graphite in the inner parts of the part has a plate-like nest shape, but closer to the surface, the width of the graphite plates increases. The amount of austenite in the structure is insignificant. During laser heating, the structure is refined: the size of graphite plates decreases from 150–200 µm to 20–40 µm in the melted zone, then their depth increases to the initial value (figure 3) [9]. In the melted zone, graphite partially dissolves, partially burns out, forming pores [10]. In the areas with the most complete dissolution of graphite plates, the austenite-martensitic structure with a hardness of up to 8.0–9.5 GPa is formed. In areas with a lower degree of dissolution of graphite, a martensite-sorbitol structure is formed with a hardness of 6.5–7.0 GPa. In this case, the initial hardness does not exceed 2 GPa. That means in the zone of laser exposure the hardness increases by 3-4 times, which provides a significant increase in wear resistance.
Therefore, when laser surfacing of surfaces that have been subjected to intensive wear, it is advisable to carry out laser hardening of those surfaces, the wear of which is possible in the process of subsequent operation [11-17].

2. Materials and methodology
To obtain coatings, a method of gas-powder laser surfacing was chosen. Obtaining a coating with specified parameters (chemical composition, dimensions and quality of the rollers being deposited) depends on the irradiation regimes: power, processing speed, dimensions of the focal spot, powder consumption and the method of its delivery.

When choosing preliminary treatment modes, St3 steel was used as the basis material. The use of steel is due to two reasons. First, the built-up parts are distinguished by the complexity of the design, different wall thicknesses, so that it is not possible to cut a sample of acceptable sizes. Secondly, the overlaying of cast iron is accompanied by an intense gas emission due to graphite burnout, and, accordingly, by an increased porosity of the coating, due to which it is difficult to draw an objective conclusion about the quality of the coating. Samples of steel St3 had dimensions of 40x40x10 mm. To refine processing modes, surfacing was performed on the details. Metallographic, durometric, and X-ray microscopic methods were used to study the deposited layer.

The microstructure, microhardness and distribution of elements over the depth of the deposited layer were studied on thin sections made in the cross section of a sample or part. The microstructure of the base was studied on non-etched thin sections and after etching in a 4 % solution of nitric acid. The study of surfacing on steel from powders PG-US25 and BH was carried out after etching in the composition reagent: 50 cm³ of silicic acid and 100 cm³ of ethyl alcohol at a temperature of 60 °C for 20-30 s. Surfacing of PG-FBH-6-2, PG-C3R2 and PG-US25 powders (cast iron base only) was electrolytically
etched in the composition reagent: 95 cm³ of ethyl alcohol, 5 cm³ of hydrochloric acid, 1 cm³ of acetic acid at a voltage of 3 V, current 100 mA for 5 s. The microhardness of the coatings was measured by their thickness on a PMT-3 microhardness meter with loads of 0.49 and 0.98 N.

The study of the distribution of elements in the deposited layer was carried out on a KAMEKA MS-46 X-ray microanalyzer with an accelerating voltage of 20 kV along the line. In this case, the spectrometers tuned to X-ray lines, the distribution of which is necessary to study. By moving the electron beam along the chosen direction (by moving the sample), the changes in the radiation intensity, that is, the concentration curves of the distribution of elements, were recorded on the potentiometer.

Laser processing of samples and an experimental batch of parts was carried out on the installation of continuous action LTI-2M with a wavelength of laser radiation of 10.6 microns. The powder from the plate type feeder in an argon flow was transported through a tube and a cyclone to the processing zone. The use of a cyclone prevents the powder from blowing off with a gas stream and increases its utilization rate. When melting, the beam was scanned along a circular trajectory, the scanning diameter corresponded to the width of the weld ring surface so that the process was carried out in one revolution of a turn. A gradual reduction in power reduces the likelihood of cracks in the deposited layer and improves the surface quality at the junction of the roller. During the welding of parts, technological inserts made of copper were used, which limit the width of the weld roll and form its side layer and improve the surface quality at the junction of the roller. During the welding of parts, technological inserts made of copper were used, which limit the width of the weld roll and form its side layer and improve the surface quality at the junction of the roller.

As a material for surfacing, self-fluxing powders, their mixtures, as well as additives to them of iron powder grade PG1 were used. The powders had a particle size of 50-160 microns. The chemical composition of the deposited powders (by mean values) is given in table 1. Before the overlaying, the powders were dried at a temperature of 100-150 °C for 1 hour.

| Type          | The content of elements, % by weight |
|---------------|-------------------------------------|
|               | C  | Ni | Cr  | Si | Fe | Mn  | B   | Ti  | N  |
| PR-Ni77Cr15C3P2 | 0.47 | main | 15  | 3.15 | 5  | -   | 2.1 | -   | -  |
| PR-Ni77Cr15C3P2-4TiCr | 0.45 | main | 14.4 | 3.02 | 4.8 | -   | 2.01 | 4  | -  |
| PR-Ni77Cr15C3P2-Fe | 0.46 | main | 14.55 | 3.05 | 7.85 | -   | 2.03 | -  | -  |
| BH            | 0.65 | -   | 37.5 | 0.75 | main | -   | 8   | -   | -  |
| FBH-6-2       | 4.5  | -   | 34.5 | 1.75 | main | 2.75 | 1.65 | -   | -  |
| FBH-6-2/PN55T45 | 3.42 | 13.7 | 25.9 | 1.31 | main | 2.06 | 1.23 | 11.25 | 0.025 |
| PG-US25       | 4.9  | 1.4 | 38   | 2.1  | main | 2.5  | -   | -   | -  |
| PG-US25-20Fe | 3.92 | 1.12 | 30.4 | 1.68 | main | 2.0  | -   | -   | -  |

*a* 4% (by weight) of metallic titanium iron powder was introduced into the composition.

*b* Powders were mixed in a ratio of 3/1 by weight.

To study the structure and properties of the deposited layer, the preparation of the part to be restored was wrapped around the surfaces “I”, “3”, “N” (figure 1). The workpiece was fixed in a three-cam rotator chuck along the outer cylinder, technological plugs from copper were inserted into the holes. When processing the “I” surface, liners were used for the inner and outer diameters, while the liners were somewhat 1.5–2.0 mm above the “I” surface so that the powder was fed precisely into the groove. The powder was transported by argon or carbon dioxide under a pressure of 50 MPa and poured in front of the beam or directly into the zone of radiation exposure. The latter is possible when using powders

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**Table 1. Chemical composition of researched powders.**

| Type          | The content of elements, % by weight |
|---------------|-------------------------------------|
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| PR-Ni77Cr15C3P2 | 0.47 | main | 15  | 3.15 | 5  | -   | 2.1 | -   | -  |
| PR-Ni77Cr15C3P2-4TiCr | 0.45 | main | 14.4 | 3.02 | 4.8 | -   | 2.01 | 4  | -  |
| PR-Ni77Cr15C3P2-Fe | 0.46 | main | 14.55 | 3.05 | 7.85 | -   | 2.03 | -  | -  |
| BH            | 0.65 | -   | 37.5 | 0.75 | main | -   | 8   | -   | -  |
| FBH-6-2       | 4.5  | -   | 34.5 | 1.75 | main | 2.75 | 1.65 | -   | -  |
| FBH-6-2/PN55T45 | 3.42 | 13.7 | 25.9 | 1.31 | main | 2.06 | 1.23 | 11.25 | 0.025 |
| PG-US25       | 4.9  | 1.4 | 38   | 2.1  | main | 2.5  | -   | -   | -  |
| PG-US25-20Fe | 3.92 | 1.12 | 30.4 | 1.68 | main | 2.0  | -   | -   | -  |

*a* 4% (by weight) of metallic titanium iron powder was introduced into the composition.

*b* Powders were mixed in a ratio of 3/1 by weight.
of the same fraction with a particle size of at least 50 microns. The rotator provided adjustment of speed from 0.4 to 20 rpm. The powder consumption was regulated by the gap of the feeder within 1-10 g / min.

3. Results

The parts deposited with PG-C3R2, PG-FBH-6-2 and PG-US25-20Fe powders are investigated. The microstructure of the cladding powder PG-C3R2 (figure 4). The deposited layer has a dendritic structure, the predominant orientation of the axes of the dendrites is absent, the pore size reaches 120 μm. The source of the formation of pores is graphite.

When the surface layer is melted, the undissolved graphite inclusions coagulate and float to the surface and burn out, eliminating vapor-gas channels in the form of voids and microcracks (figure 5). Therefore, as a rule, graphite is absent in the melted part layer (figure 5, a). Between the coating and the substrate is visible light layer, the depth of which reaches 0.3 mm. In this zone there are pores up to 120 microns in size. The layer is a transition zone, which is a continuous series of solid solutions from the iron to the nickel base. The iron content in the transition zone is up to 10 % and remains on average the same over the entire thickness of the cladding with segregation from 6.5 to 16 %.

The coating structure is uniform throughout the thickness; it is chromium-based carbide and carboboride, a γ-solid solution, and a eutectic γ + Ni3B. The solid solution is highly supersaturated with alloying elements.

Due to the homogeneity and fine dispersion of the structure obtained, the hardness of the cladding is fairly uniform in depth and is 6–7 GPa (figure 6), when slight mixing with the substrate is observed (on
average 10 % of iron, instead of 5 % by grade composition).

When surfacing the PG-FBH-6-2 powder from worn surfaces of the part, layers of different quality were obtained.

![Figure 6](image1)

**Figure 6.** The microhardness of the coating of powder PG-C3R2, power 1.2 kW, surface: a – diameter 58 mm; b – diameter 38 mm.

The main defect is the presence of pores, the number and location of which depends on the processing modes and the thickness of the fused layer. Surfacing of the surface “G” was carried out according to the mode: power 1.2 kW, rotation speed 2 rpm, powder consumption 7 g / min. The thickness of the deposited layer on the surface “G” was 1.2–1.3 mm with a heat-affected zone (HAZ) 0.6 mm, on the “Z” surface a surfacing of 1.5 mm, HAZ - 0.6 mm, on the “N” surface, 0.6 mm surfacing, 0.9 mm. With the same processing conditions, the cladding has similar defects. So, on the “G” and “Z” surfaces, the thickness of the hardfacing and HAZ has similar values, pores form at the boundary of fusion of the coating with the base metal, and cracks are formed in some cases (figure 7). The reasons for the formation of cracks are not clear, but, in any case, the porosity at the boundary of fusion has a significant effect, since some cracks are channels of gas outlet.

![Figure 7](image2)

**Figure 7.** Surfacing of PG-FBH-6-2 powder (×130): a – general view; b – transition zone.

With a small thickness of the coating (surface “N”), the gases formed during the burning of graphite, have time to emerge and retire from the surface, while crystallization cracks were not detected.

With a coating height of 1.3 mm, the depth of the transition zone is 0.35 mm. The transition zone is a continuous series of solid solutions in which the iron content decreases monotonically, while chromium and manganese increases. On average, the transition zone contains about 55 % iron, 34 % chromium, 4 % manganese, 1.1 % silicon.

Starting from the transition zone to the edge of the sample, the coating structure is dendritic, and the size of the dendrites increases from the transition zone to the edge of the coating. Accordingly, with an
increase in the size of dendrites, interdendritic segregation increases. Data on the content of elements in the axes of the dendrites and interdendritic gaps are given in Table 2.

Table 2. Distribution of elements in surfacing powder PG-FBH-6-2.

| Zone                | The content of elements, % of mass |
|---------------------|-----------------------------------|
|                     | Fe  | Cr  | Si  | Mn |
| Dendrite axes       | 40  | 50  | 0   | 4.0-4.6 |
| Interdendritic layers | 60  | 17-26 | 2.6 | 4.0-4.6 |

From the concentration distribution curves of the elements, it can be seen that manganese is evenly distributed in the coating. In the axes of the dendrites, the silicon content drops to zero, the iron drops to 40 %, and the chromium content increases to 50 %. In the interdendritic gaps, on the contrary, the chromium content drops to 17-26 % (depending on the size of the dendrite), and iron and silicon increases (Fe up to 60 %, Si up to 2.6 %).

Despite the interdendritic segregation, since the size of dendrites is rather small, the microhardness of the coating is distributed sufficiently evenly (excluding the transition zone) and is 10.2–11.7 GPa (Figure 8).

![Figure 8](image)

Distance from the surface, mm

In order to reduce the carbon content in the deposited layer to prevent crystallization cracks, PG-US25 added 20 % of iron powder PG1. Surfacing of the guide vane was carried out according to the mode: power 1.2 kW, part rotation speed 1 rpm, powder consumption 2.0-2.2 g / min, scan diameter 3.5-5 mm (corresponding to the width of the weld ring). The quality of the weld bead powder of such a composition is better than PG-C2RZ and DG-FECH-6-2. The weld beads mainly had a high-quality formation. Pores on the fusion boundary were formed in the case when the height of the deposited bead exceeded 1.5 mm. Obviously, at such a height of the roller, the upper layers have time to harden, and the gases do not have time to stand out. Figure 9 represents the microstructure of the transition zone from the base metal to the weld. In the HAZ at a considerable distance from the fusion line, pores have already formed, but in the transition zone itself, there are no pores. With a significant thickness of the roller in the transition zone, pores remain. Qualitative formation of the roller occurs in cases where a transition zone of variable composition is formed with a gradual change in the content of chemical elements.
When surfacing with iron-based powders, a dendritic structure is usually formed. During the growth of dendrites in the process of crystallization, interdendritic segregation of elements occurs, which is well illustrated by the concentration curves of the distribution of elements (figure 10).

In the axes of the dendrites we have a solid solution of chromium with iron based on chromium. In the interdendritic gaps, iron is eliminated in phase with nickel and silicon. Manganese is uniformly distributed over the coating, its content is 1.5%. The content of silicon and nickel in the axes of the dendrites drops to zero.

The distribution of elements in the surfacing of the surface “Z” is presented in table 3.

| Zone                | The content of elements, % of mass |
|---------------------|-----------------------------------|
|                     | Fe      | Cr      | Mn      | Si      | Ni      |
| Dendrite axes       | 20-30   | 55      | 1.5     | 0       | 0       |
| Interdendritic layers | < 70   | 10-12   | 1.5     | Up to 3 | 2.7-3.0 |

When surfacing a similar powder on the surface “N” with a diameter of 68 mm with the same modes of surfacing, a coating 0.4 mm thick was obtained. From the results of X-ray microanalysis, it follows that during the deposition there was a strong mixing with the base. Likvatcionnye processes for the thickness of the weld is not observed. The elements are uniformly distributed, while the chromium content increases monotonically from the fusion line to the edge of the sample, while the iron content decreases. The uniform distribution of elements is determined by the dispersion of the structural components. With a smaller layer thickness, the cooling rate is higher, the dendrites are smaller and with different directions of the axes.

Surfacing of such a composition is characterized by high hardness, primarily due to the formation of chromium carbides. The bead deposited on the “Z” surface (diameter 38 mm), in the absence of mixing
with the substrate, has a hardness of 8–9 GPa (figure 11). HAZ is also characterized by increased solidity. Here is the dissolution of graphite and the formation of a hardened structure as a result. Depending on the regimes, martensite, austenite, carbides are formed in different ratios and distributions. The undissolved graphite inclusions are crushed and a dispersed structure is formed.

4. Conclusion
During laser heating, the structure is refined: the size of graphite plates is measured in the melted zone, then their depth increases to the initial value. In the melted zone, graphite partially dissolves, partially burns out, forming pores. In the areas with the most complete dissolution of graffiti plates, the austenite-martensitic structure with a hardness of up to 8.0–9.5 GPa is formed. In areas with a lower degree of dissolution of graphite, a martensite-sorbitol structure is formed with a hardness of 6.5–7.0 GPa.

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In the area of laser exposure, the hardness of the cast-iron welded parts increases by 3–4 times, which provides a significant increase in wear resistance.

References
[1] Marest G, Fontes A, Jeandin M, Fayeulle S, Vardavoulias M and Frainais M 1998 Exclusive laser processing *Hyperfine Interactions* **112** (1–4) 39–42
[2] Alexandrov V D, Shashkov D P and Pishchulin D N 2006 Laser processing of cast iron products *Bulletin of the Moscow Automobile and Road Institute* [in Russian – Vestnik Moskovskogo Avtomobilno-Dorozhnogo Instituta] **6** 28-35
[3] Zhou H, Sun N, Shan H, Ma D, Tong X and Ren L 2007 Biographed by laser *Applied Surface Sci.* **253** (24) 9513–20
[4] Benyounis K Y, Fakron O M A, Abboud J H, Olabi A G and Hashmi M J S 2005 Surface melting of the nodular iron and tir *J. of Materials Processing Technology* **170** (1-2) 127–132
[5] Gureev D M, Mednikov S I, Yamshchikov S V and Balashov I A 1993 Laser ultrasonic alloyed iron *Physics and Chemistry of Material Processing* [in Russian – Fizika i Chimiya Obrabotki Materialov] **3** 109–116
[6] Gao W, Glorieux C, Van De Rostyne K, Laurieks W, Thoen J, Kruger S E and Gusev V 2001 Ultrasonic surface wave spectroscopy *Mater. Sci. and Eng. A* **313** (1–2) 170–179
[7] Tesker E I, Gur'ev V A, Savchenko A N and Durosov V M 2002 Laser treatment *Physics and Chemistry of Material Processing* [in Russian – Fizika i Chimiya Obrabotki Materialov] **2** 18–20
[8] Zhou H, Zhang P, Sun N, Wang C-T, Lin P-Y and Ren L-Q 2010 Wear graphite graphite line with bioni c units processed by laser wc Applied Surface Sci. 256 (21) 6413–19

[9] Kolmakova T G and Ivanov A S 2018 The use of gas-powder laser surfacing in agricultural technology Proc. Int. Conf. “Theory and Practice of Modern Agrarian Science” (Novosibirsk) pp 182-185

[10] Zhang J, Liu J-C, Yan C, Yang L-S, Ni L-B and Zhang F-Q 2010 Fe-Cr-Si-B coating by laser cladding on nodular cast iron Cailiao Rechuli Xuebao 31 (5) 133-137

[11] Tokarev A O 2012 Improving the tribotechnical characteristics of gray cast iron by laser treatment Metal Processing (Technology, Equipment, Tools) [in Russian – Obrobotka Metallov (Technologiya, Oborudovanie, Instrumenty)] 1 69-73

[12] Tokarev A O, Ivanchik S N, Makagon L D, Ivanchik I S and Gurin A M 2012 Improving the tribotechnical characteristics of gray cast iron by laser treatment Scientific Problems of Transport in Siberia and the Far East [in Russian – Nauchnye Problemy Transporta Sibiri i Dalnego Vostoka] 1 287–291

[13] Chen Z-K, Zhou T, Zhao R-Y, Lu S-C, Yang W-S, Zhou H and Zhang H-F 2015 Improved wear resistance by cast iron by localized laser carburizing Mater. Sci. Eng. A 644 1-9

[14] Zhang Y and Liu F 2016 Laser-induced domino ex-ironing in spheroidal graphite cast iron Surf. Coat. Tech. 285 235–241

[15] Gilev V G, Torsunov M F and Morozov E A 2016 Laser alloying of cast iron nireist CHN16D7GH by feeding powder VT-20 to the reflow zone Metalworking [in Russian – Metalloobrabotka] 5 (95) 25–30

[16] Liu H, Hao J, Han Z, Yang H, Yu G and He H 2016 J. Mater. Process. Tech. 232 153–164

[17] Minakov N V, Bloshanevich A M, Rudyk N D, Puchkova V Yu and Khomenko G E 2011 The effect of laser treatment on the properties of HF40 cast iron Strengthening Technologies and Coatings [in Russian – Uprochnyaschie Technologii i Pokrytiya] 10 12–14