Abstract—The article represents the results of investigating the structure of the layers, obtained using the specimens of low-carbon steel, subjected to plasma cementation. The dependence of their structure on the percentage of graphite in the coating, which served as a carbon source, is established. The influence of the subsequent heat treatment of specimens after plasma cementation in the macro- and micro-smelting regime to form the graphite inclusions in the structure has been studied. Heat treatment consisted in conducting of annealing under different conditions.

Keywords—formation process; plasma; cementation; steel; heat treatment

I. INTRODUCTION

There are different methods of formation of the required structure on the surface of the steel articles, which would ensure the necessary properties of the article. One of the common ways is the cementation, which ensures solid wear-resistant surface of the article. However, the presence of graphite in the structure of surface layers imparts completely different properties to the steel, in particular, antifriction. Graphitized steels possess a number of the essential advantages. The main advantage is increased wear resistance because of the presence of graphite in the structure. Such steels are used for the manufacture of friction gearings, as well as products operating under conditions of high friction, etc.

The purpose of this work is to study the effect of subsequent heat treatment on the process of structure formation in the surface layers of steel that underwent preliminary plasma cementation.

II. RESULTS AND CONSIDERATION

In the present work the low-carbon steel, preliminarily subjected to plasma cementation, was used as the subject of a study. The plasmatron MULTIPLAZ 3500 was used for this
To saturate the steel surface with carbon, steam-water plasma was used. Several compositions were proposed as the plasma-forming substance. As a result of a number of experiments [1-4] the optimum composition of the plasma-forming mixture was revealed. It consisted of ethyl alcohol, benzene, and water, which makes it possible to impregnate the article surface with carbon.

As a result of the plasma cementation process, a large amount of atomic carbon is produced, and with the significant gradient of temperature it easily penetrates (diffuses) into the surface layers of metal. The advantage of this kind of treatment is that the reinforced layer is obtained in a few seconds. The depth of this layer strongly depends on the parameters of treatment and can change in wide range; however, the reinforced layer is not obtained at great depth.

The source of carbon during this process was the graphite coating, applied preliminarily to the specimens. The coating composition included the graphite powder, liquid glass, cutting compounds and water.

With the regime of surface smelting the formation of fluid bath makes it possible to considerably increase the depth of cementation.

Moreover, the directed heat removal occurs during the cooling.

When coating with graphite content of 50%, a layer having a complex structure is obtained after processing (Figure 2).

It is possible to distinguish three zones.

The first zone is formed under the effect of the smelting. It differs by significant supersaturation in carbon, whose concentration reaches 3.83 %. Its structure corresponds to the structure of white iron, which is confirmed by the results of microhardness measurement (Figure 3) [7, 8]. The eutectic component is characterized by a lamellar structure, the cementite, which is a part of it, has the appearance of very thin plates. This structure is similar to a microstructure obtained after laser treatment of cast iron [9-12] or after hardening of cast iron using an electric arc [13-16]. The formation of a eutectic consisting of cementite (in the form of columnar precipitates), residual austenite and martensite (Figure 4, a) has been recorded. The specific structural feature of the ledeburitic eutectic obtained in [5] is in the size of cementite plates. They are shorter and are thinner. The plates of cementite grow in the direction of the heat removal.

The second zone is located directly under the smelting zone (Figure 4, b). The result of simulation showed that in this zone the rate of cooling comprises 1300 °C/s, which is higher than the critical speed of quenching for steel, the carbon content in which exceeds 0.8 % [5,17,18]. Taking into account the concentration gradient of carbon in this zone, it can be estimated as heat-affected zone. Under thermal influence, heating in it occurs up to temperatures above the phase transformation temperatures of high carbon steel. In the cooling process, which was conducted at high speed as a result of heat removal by a cold metal, structures can be formed, similar to those, which appear during quenching of high-
carbon steel, what also indicate the results of the measured microhardness.

In the third zone, the concentration of carbon is declining and gradually approaching the concentration of the investigated steel.

When the concentration of graphite in the coating is reduced to 33 %, a layer is formed, which also consists of three sublayers. For this case, a layer-by-layer X-ray diffraction analysis was performed using a Shimadzu XRD-7000 diffractometer. It was found that there are α-Fe, γ-Fe, FeC, Fe₂C, Fe₃C in the structure of the cemented layer. The content of residual austenite varies non-monotonously. The maximum amount of austenite up to 55–65 % was recorded at a depth of 140–160 μm [5, 17-20].

When reducing the amount of graphite in the coating to 20 %, a layer is formed that consists of two sublayers: residual austenite and martensite. The first layer has a lower microhardness since contains a large amount of residual austenite. This may be due to a high carbon concentration in the layer at the heating stage, when the temperature of the end of the martensitic transformation decreases to negative temperatures.

When the content of graphite in the coating was 14 %, a layer with the structure of martensite and residual austenite was obtained (Figure 5a). When the concentration of graphite in the coating reaches 12.5 %, the strengthened layer consists of lamellar and needle martensite with high hardness (Figure 5, b).

Further research was aimed at studying the effect of subsequent heat treatment of specimens subjected to plasma cementation in the macro- and microsmelting modes, and at the formation of the structure of the surface layer with graphite inclusions. For this purpose, the specimen obtained with a graphite content of 50 % in the coating were used precisely because the carbon content in the layer corresponded to the area of hypoeutectic cast irons. In the case of the formation of graphite inclusions, an attractive combination of properties can be obtained: the strength properties of steels will be complemented by good antifriction properties characteristic of cast irons.

The subsequent heat treatment was annealing. The task was to assess the possibility of obtaining graphite inclusions [7, 19].

Preparation of specimens for annealing consisted in covering them with a protective coating, the composition of which was liquid glass and asbestos powder in a 1: 1 ratio. The coating was applied to the specimen surface in such a way as to carefully isolate the entire surface.

Annealing was carried out at a temperature of 900 °C, 950 °C, 1000 °C in a muffle furnace, the duration of exposure was 1, 2, 3 h. In setting the regime, the reference was the annealing temperatures of white cast irons when redistributing them into ductile iron.

As a result of the experiments of the first series (after microsmelting), it was found that the structure of the hardened layers changes after annealing. No graphite precipitates are observed, which is confirmed by the microhardness measurement. The structure of the surface layers becomes fine-grained (Figure 6). We believe that this can be due to modifying action of substances that were part of pastes applied to the surface before plasma cementation.

![Fig. 3. Results of measuring the microhardness by the depth of specimen, x100](image)

![Fig. 4. Structure of the separate zones of the surface layer: a - is the microstructure of the first zone, b - is the microstructure of zone directly under the region of smelting, x100](image)
In all cases, the surface decarburization occurs, light ferrite grains are observed. This can be attributed to carbon burnout, which suggests that the protective properties of the coating are not sufficiently high or that the diffusion layer is only 200 microns. There is an active diffusion of carbon into the specimen and, therefore, the carbon content on the surface decreases.

Regimes with a longer duration (up to 3 hours) lead to a noticeable enlargement of the structure and surface, and the core. While maintaining the ratio between the amount of ferrite and pearlite, characteristic of low carbon steel, an increase in the grain size of ferrite and pearlitic colonies occurs. There is a process of collective recrystallization.

It is established that an increase in the annealing temperature has a much greater effect on the growth of steel grains compared with an increase in the duration of exposure.

The study of samples subjected to annealing after the macro-smelting mode under different conditions, both single-stage and two-stage annealing, shows that no graphite precipitates were also observed. The absence of graphite inclusions was confirmed by the measurement of microhardness.

Thus, the subsequent heat treatment did not lead to the preparation in the hardened layer. Perhaps there might be other, a very promising way: already at the plasma processing stage, to apply such coatings that would allow obtaining a diffusion layer, the composition and structure of which would provide preferable properties. A series of pilot experiments, when chromium oxide was part of the coating along with graphite, showed that further experiments should be carried out in this direction.

III. CONCLUSION

The effectiveness of plasma cementation as the process, which forms a certain structure of the surface of steel articles, which is determined by treatment conditions and their properties, is established. The results of studying the influence of annealing on the structure of the cemented layer with the different regimes, in order to obtain graphite inclusions in the structure, showed that the stated goal was not achieved. Probably, the idea of graphitization in thin layers is doomed to failure, since the subsequent annealing after plasma cementation leads to the active draining of carbon into the deeper layers as a result of the high rate of its diffusion.

References

[1] A.E. Balanovskii, V.V. Huy, “Plasma surface cementation using graphite coating”, Letters on Materials, vol. 7(2), pp. 175-179, 2017.
[2] Wu Van Gyu, “Plasma carburizing carbon steel in solid phase using pastes”, Bulletin of Science and Education of North-West Russia, vol. 1, N 1, pp. 205-211, 2015.
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[3] A.E. Balanovskii, M.V. Grecheneva, V. Van Huy, D.A. Zhuravlev, “New plasma carburizing method”, IOP Conference Series: Earth and Environmental Science, pp. 092003, 2017.

[4] A.E. Balanovskii, M.V. Grecheneva, V.V. Huy, D.A. Zhuravlev, “Plasma surface modification in liquid environment”, IOP Conference Series: Earth and Environmental Science, pp. 092004, 2017.

[5] Gyui Wu Van, Cementation of low carbon steels using plasma heating of graphite-containing coatings and process gas environments: author's abstract of diss. of Ph.D. of Engineering Science, Komsomol'sk-on-Amur, 2018, p. 23.

[6] M.V. Konstantinova, G.V. Evsyukov, “Hardening efficiency increase metal surfaces”, Prospects for the development of technology of hydrocarbon and mineral resources: materials of VIII All-Russian sci. and pract. conf. with internat. Participation, pp. 43-46, April 2018.

[7] GOST 9450-76, Measurement of microhardness by indenting diamond tips. With amendments and changes, Moscow: Publishing house of standards, 1982, p. 35.

[8] E.A. Guseva, A.I. Khussanov, “The use of high technology in the processes diffusion saturation of the surface of metal products”, Prospects for the development of the technology of the hydrocarbon and mineral resources: the materials of VII All-Russian sci. and pract. conf. with the internat. Participation, pp. 31-33, April 2018.

[9] D.S. Stavrev, N.Ya. Nikov, “Hardening of gray cast irons at surface bleached by low temperature plasma”, Metallography and heat treatment of metals, vol. 4, pp. 15-18, 1985.

[10] Jaafar Hadi Abboud, “Microstructure and erosion characteristic of nodular cast iron surface modified by tungsten inert gas”, Materials and Design, vol. 35, pp. 677-684, 2012.

[11] Hua-tang Cao, Xian-pu Dong, Qi-wen Huang, Zhang Pan, Jian-jun Li, Zi-tian Fan, “Effect of scanning speed during PTA remelting treatment on the microstructure and wear resistance of nodular cast iron”, International Journal of Minerals Metallurgy and Materials, vol. 21 (4), pp. 363-370, 2014.

[12] E. Ramous, L. Giordano, G. Principi, A. Tiziani, “Metastable phases obtained by high power laser surface melting of cast-iron and steels”, Journal de Physique Colloques, vol. 44 (C5), pp. 501-505, 1983.

[13] V.V. Shevelyav, A.S. Trytek, G.S. Kalda, “The effect of electric arc treatment on the structure and cast iron resistance”, Problems of Tribology, vol. 2, pp. 6-11, 2009.

[14] K.Y. Benyounis, O.M.A. Fakron, J.H. Abboud, A.G. Olabi, M.J.S. Hashmi, “Surface melting of nodular cast iron by Nd-YAG laser and TIG”, Journal of Materials Processing Technology, vol. 170, pp. 127-132, 2015.

[15] D.S. Stavrev, N.Y. Nikov, “Hardening of gray cast irons at surface bleached by low temperature plasma”, Metallography and heat treatment of metals, vol. 4, pp. 15-18, 1985.

[16] V.I. Gurinovich, V.S. Golube, A.I. Pokrovskiy, N.F. Solovei “Study features structure formation ductile iron”, Casting and metallurgy, vol. 2 (65), pp. 129-133, 2012.

[17] Wu Van Gyui, A. Balanovskiy, “Study of surface surface steel after plasma cementation using carbon-containing paste”, Bulletin of Irkutsk State Transport University, vol. 21, N 4, pp. 10-21, 2017.

[18] A.E. Balanovskiy, Wu Van Gyui, “Saturation of the surface of the metal with carbon during plasma surface treatment”, Strengthening technologies and coatings, vol. 13, N 9 (153), pp. 403-415, 2017.

[19] A.E. Balanovskiy, N.A. Ivanov, “Research of processes of interaction of dispersed particles with flows of low-temperature electric arc plasma”, Bulletin of Irkutsk State Technical University, vol. 7 (47), pp. 289-295, 2010.

[20] Wu Van Guy, A.E. Balanovskiy, “Physical basic technologies of plasma surface cementation of parts on the example of a spintheon bush of a passenger car”, Bulletin of Irkutsk State Technical University, vol. 21, N 3, pp. 10-22, 2017.