Plasma carburizing with surface micro-melting

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Abstract. This paper presents carburizing the surface of 20 low carbon steel using electric arc and graphite prior. A carbon black solution was prepared with graphite powder and sodium silicate in water. A detailed analysis of the phase structure and the distribution profile of the sample hardness after plasma treatment were given. The hardened layer consists of three different zones: 1 – the cemented layer (thin white zone) on the surface, 2 – heat-affected zone (darkly etching structure), 3 – the base metal. The experimental result shows that the various microstructures and micro-hardness profiles were produced depending on the type of graphite coating (percentage of liquid glass) and processing parameters. The experiment proved that the optimum content of liquid glass in graphite coating is 50–87.5%. If the amount of liquid glass is less than 50%, adhesion to metal is insufficient. If liquid glass content is more than 87.5%, carburization of a metal surface does not occur. A mixture of the eutectic lamellar structure, martensite and austenite was obtained by using graphite prior with 67% sodium silicate and the levels of the hardness layer increased to around 1000 HV. The thickness of the cemented layer formed on the surface was around 200 µm. It is hoped that this plasma surface carburizing treatment could improve the tribological resistance properties.

1. Introduction
The use of concentrated heating sources for surface hardening has increased substantially in recent years. The concentrated heating makes it possible to obtain special structures in a surface layer, which could increase wear resistance of workpieces. One of the promising fields of surface treatments is carburizing using laser [1-3], electronic beam [4], plasma arc [5-7]. These methods have a number of advantages over the traditional methods of carburizing (short processing time, special structure, possibility of local hardening).

Carburizing with carbon-containing pastes was described in [1-5]. As a metal surface heating source, a laser, an electronic beam, a plasma electric arc were used. The method involves application of carbon-containing paste on the workpiece surface which is melted when exposed to concentrated energy flow (laser, electronic beam, plasma arc or jet). Under gas-dynamic force of the plasma arc or jet, intensive mixing of liquid metal and carbon occurs. After crystallization, the alloyed layer of carbon is formed. The works [1,7] show that plasma surface carburization based on the electric arc of the solid phase is followed by surface melting. The workpiece of such wise hardening should be necessary to carry out mechanical processing, and it increases production costs. The authors developed a new composition of the carbon-containing mixture (liquid glass and graphite) which is applied on workpiece surfaces. It enables one to carbonize metal surface without weld pool formation [8-10].
2. Materials and methods
Steel 20 was chosen as the base material for the experiment. It was made in the form of block sized 80x40x10 mm. Fig. 1 shows a scheme of plasma carburization. The paste is made of graphite, liquid glass, water and oil. Plasma carburizing was carried out using a TIG welding machine. A welding speed was set at the level of 5 mm/s. As shielding gas argon was used during a plasma carburizing process, a flow rate was set at 8 L/min. The tungsten electrode was 2.4 mm in diameter and 150 mm long. The distance between tungsten electrode to specimen surface was kept at 5 mm.

![Figure 1. Plasma treatment](image)

1– Welding power source; 2– Balloon argon; 3– Oscilloscope; 4– Control block; 5– Electrical engine; 6– Sample with coating; 7– Tig welding torch; 8– Camera; 9 – Infrared thermometer

The microstructure was studied using OLYMPUS GX51 microscopes having magnification of 100x and 500x. Electronic and microscopic analysis of metal sample surfaces was carried out with a scanning electron microscope LV-4501. Micro-hardness was measured with the HMV-2T (Shimadzu) micro hardness tester under load of 2–5 N. Layer depth was taken as a distance from the sample surface to the point of base hardness. X-ray crystallography was carried out with the ShimadzuXRD-7000 x-ray diffractometer.

3. Results
The carbon saturation steel process can occur in two ways: 1 – the diffusion of carbon atoms into the surface layers, when the layer structure is transformed into austenite, 2 – dissolution of carbon in liquid steel. In the second case, the saturation process is faster [8]. In this case, the surfaces can have traces of micro-melting without molten pool formation in the form of a thin layer after carburizing. The formation of a liquid film on the surface accelerates the diffusion of carbon into metal and metal surface roughness Ra is < 5 µm after plasma treatment. Fig 2 shows the plasma carburizing process using graphite coating in both cases: with surface melting (macro-melting) and with traces of melting (micro-melting). In the case of micro-melting during the arc welding process, a layer of iron carbides is formed on the surface. This carbide layer has a melting point from 1200 to 1500 °C. Therefore, the carbide layer is pre-melted and a liquid film is formed on the sample surface.
Metal samples are subjected to grinding before the plasma carburizing to remove the oxide layer. On the surface, alternating depressions and protrusions are formed after removing the oxide layer as a result of the phenomenon of micro-cutting by particles of a grinding disc with the sample surface. Fig. 3 shows the surfaces after grinding. Surface roughness is $Ra = 0.7$-$0.9 \, \mu m$. The grinding sample after applying a graphite coating is subjected to a plasma arc treatment (coating layer thickness was constant at 0.25 mm). Fig. 4a shows the effect of arc current on the carburizing process when using a coating with 50% graphite.

The saturation process will begin until the current of the plasma arc reaches 95A. After that, an increase in the carburizing current increases the depth of the carburizing layer. When the arc current is greater than 120 A, a weld pool is formed (macro-melting).
Similar tests were conducted for other coating compositions; the result is shown in Fig. 4b. The experiment proved that the optimum content of liquid glass in graphite coating is 50–87.5%. If the amount of liquid glass is less than 50%, adhesion to metal is insufficient. If liquid glass content is more than 87.5%, carburization of a metal surface does not occur.

It can be seen that the depth of carburizing layer after plasma treatment with surface micro-melting is independent of the coating composition and reaches 180-200 µm. After plasma treatment, significant depressions and protuberances disappeared as a result of the micro-melting of the surface and other depressions and protrusions are formed, and cementitic plates are observed on the surface (Fig. 5).

![Figure 5. The surface after plasma carburization (67% liquid glass)](a - x25; b - x1700; b - 3D surface)

Research has shown that the degree of micro roughness in the hardened track decreases from the center to the edges. In the middle of the track, the microroughness varies from -5 to 5 µm (in comparison with the base surface) and in the marginal zones from -10 to 20 µm (Fig 6). This corresponds to the temperature distribution of the cathode spot of the arc during processing. It is known that in the process of plasma heating in the center of the heating spot, the temperature is maximum; therefore, the formation of a liquid layer (Fe₃C, SiO₂ and Na₂O) occurs more intensively. The formed micro-droplets of the liquid spread over the surface, thereby creating a smooth, uniform surface in the middle of the hardened track, and the roughness of this zone is smaller than the marginal zones. Due to this, the degree of micro roughness decreases with increasing amount of liquid glass in the coating (Fig 7).

![Fig. 6. 2D-Surface profilogram](image)
After deep etching, a cross section of a plasma-treated sample is shown in Fig. 8. The hardened layer consists of three different zones: 1 – cemented layer (thin white zone) on the surface, 2 – heat-affected zone (darkly etching structure), 3 – base metal.

If liquid glass content is 50%, a carburized layer consisting of two layers: 1 – eutectic lamellar structure, 2 – retained austenite and martensite (Fig. 9). Microhardness of the first layer is 900–1200 Hv. Microhardness of the second layer having small thickness of 15–25 µm is 600–800 Hv.

The microstructure of the eutectic structure is shown in more detail in Fig. 10. The eutectic structure has a lamellar form consisting very fine plate cementite with a thickness 0.5 µm and lengths more than 2 µm. Plates cementite grow mainly in two directions: perpendicular and parallel to the direction of heat input. This type of structure is similar to the microstructure of white cast iron after laser hardening [11-13], laser carburization [1] or after hardening of cast iron by electric arc [14], a fibrous-lamellar eutectic consisting of columnar cementite and residual austenite. The difference between the ledeburite eutectic obtained in this work from the dendritic cementite of other works after hardening of cast iron is the size, the cementite plate is thinner and shorter. Increasing the dispersion of the
ledeburite eutectic and the presence of residual austenite reduces the likelihood of the formation of cracks, which often appear after quenching of cast iron.

With increasing content of liquid glass up to 67%, hardened surface consists of 3 sub-layers (Fig. 11): 1 – Large amounts of the eutectic lamellar structure (lamellar iron carbide – light-etching fine crystals, austenite) retained austenite + martensite; 2 – retained austenite + plate martensite + eutectic lamellar structure (Fig. 12); 3 – retained austenite + martensite. Fig. 11 shows the results of microhardness measurement by the depth of a carburized layer after plasma carburizing with the coating of 33% liquid glass.

After plasma surface carburizing with graphite paste consisting of 20% graphite (80% liquid glass), a hardened surface consisting of two layers (retained austenite and martensite) is formed (Fig. 13a).
The first layer cannot be etched and has low microhardness of 400–550 Hv. Fig. 13b shows the microstructure of the carburized layer after plasma carburizing with graphite paste consisting of 14% graphite, the amount of martensite in the carburized layer increases. Microhardness of the layer is 500–750 Hv. By decreasing amount of graphite to 12.5%, the hardened layer consists of lath martensite with high hardness of 900–1100 Hv and retained austenite (Fig. 13c). It is explained that the decreasing amount of graphite in the coating leads to lower concentration of carbon in the cemented layer and an increase of the starting temperature for martensite transformation.

![Figure 13. Microstructure of the carburized layer in different modes](image)

Figure 13. Microstructure of the carburized layer in different modes
a – 20% graphite; b – 14% graphite; c – 12.5% graphite

In order to have a clearer knowledge what kind of phase structure forms between these elements and the block material in the surface, the authors used an X-ray diffractometer (Shimadzu XRD) to analyze the physical phase of the carburized layer after plasma treatment with 67% liquid glass. The results are shown in Fig. 14a. Fig. 14a indicates that in the carburized layer, there are α-Fe (martensite), γ-Fe (austenite) and Fe3C, Fe5C, etc. The content of retained austenite was identified by correlation and intensity of X-ray maximums of austenite (111) and martensite (110). Fig. 14b presents distribution of retained austenite and iron carbide by the carburized layer depth. The quantity of retained austenite (RA) in the surfaces of steel 20 varies extremely. The maximum quantity of austenite is 60–65% at a layer depth of 150–170 µm. The amount of iron carbide reaches maximum on the surface and decreases to zero at a distance of 180 from the surface.

![Figure 14. X-ray diffraction patterns and distribution of retained austenite and iron carbide](image)

Figure 14. X-ray diffraction patterns and distribution of retained austenite and iron carbide:
a – X-ray diffraction patterns at the sample surface (with 30% liquid glass); b – Distribution of retained austenite and iron carbide by the carburized layer depth

Due to positive properties of the developed coating (high conductivity, mechanical and thermal stability), the arc burns in a sustained way on the graphite coating. When the surface of the sample has traces of micro-melting without molten weld pool formation in the form of a thin layer, carbon diffusion coefficient increases; therefore the carburizing process is accelerated. The advantage of the
method is due to the fact that this method enables carburizing workpiece surfaces for several seconds without significant surface fusion; after that the surface roughness Ra is < 5 µm. Thus, the cemented surface can be subjected only to shallow grinding (10-30 µm).

4. Conclusion
The carburized layer on the surface of steel 20 can have a depth of 180-200 µm and micro-hardness of 400-1200 Hv. By controlling components of the carbon coating, it is possible to achieve different degrees of finite surface roughness and control depth and structure of a carburized layer.

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