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EXPERIMENTAL STUDIES OF OPERABILITY OF HARDENED CUTTING EDGES OF PARTS

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The operability of machine and tool parts is often determined by the state of the working surface. It is on the surface that cracks arise, wear and corrosion processes begin. The presence of defects, the degree and depth of hardening, the level of residual internal stresses, the structure, the nature of the transition to the base material, most often determine the reliability and service life of parts and structures. Based on a critical review of hardening methods, it was found that one of the promising ones is the effect on the treated surface of a plasma jet of different power density. To ensure wear resistance of the working edges, the surface was treated with low-temperature plasma at an indirect arc plasmatron installation. The work investigated the phase and structural transformations after plasma coating on model samples of steel 65G, studied the structure and built microhardness profiles. Optimal parameters of plasma processing of articles are determined: distance from plasmatron - 30 mm, rotation speed - 10 s^{-1}, heating time - 10 s. The established optimal modes of hardening treatment were used for plasma hardening using the example of an instrument (spiral drills made of steel grades R6M5, R6AM5 and 11R3AM3F2) under production conditions. For all types of drills, it was possible to obtain a hardened layer of 1-1.5 mm deep from the surface. According to the results of metallographic analysis, the microstructure of the hardened layer contained a white, non-etchable in acids zone with a high microhardness of up to 12000 MPa, the depth of which reached up to 0.4 mm; then there was a structure consisting of martensite and residual austenite with a microhardness of up to 9000 MPa. Tests of experimental drills for resistance, carried out in production conditions, showed an increase in their resource by 2 times compared to a tool that did not undergo plasma hardening, confirmed the possibility of multiple regrind within the hardened layer.

Keywords: thermo-hardening, plasma, modes, parts, cutting edge, spiral drill, resistance.

INTRODUCTION

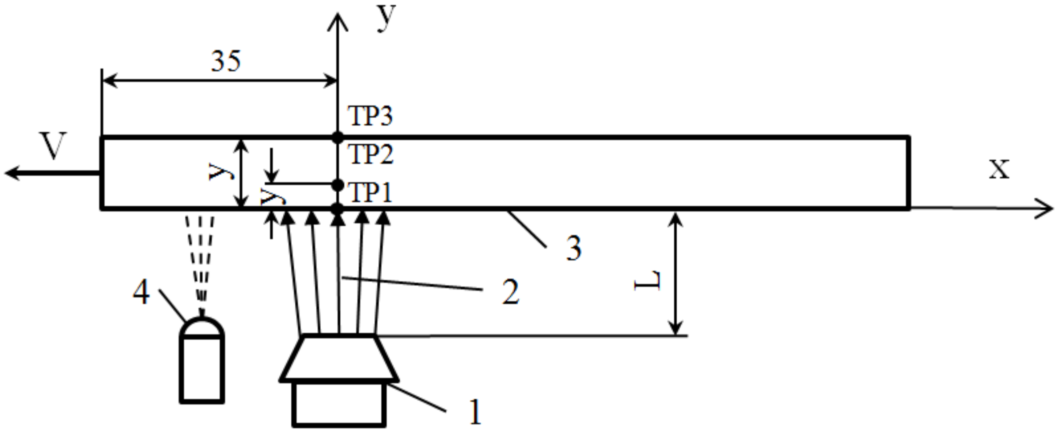
The technical modernization of the agro-industrial complex, currently, provides for its renewal with competitive agricultural equipment, and its service base with equipment and technical facilities of a high technical and technological level, which are not inferior to the products of leading manufacturing companies in the industry (Bochtis et al. 2014, Burak et al. 2019, Pastukhov et al. 2021). New and modernized agricultural machinery technologies and tools are being developed to improve the renewal rate of the fleet of machines and their quality (Burak et al. 2019, Pastukhov et al. 2021). The most effective technological measure to increase the operability of cutting edges of working elements and tools is their hardening (Callister, Wiley, 2007, Sharaya, 2020). Among the methods of surface hardening of the tool, the most promising is heat treatment using low-temperature plasma (Callister, Wiley, 2007, Klyucharev et al. 2008). Plasma (ionized gas) is a directed stream of charged particles with a high energy concentration. The essence of the plasma thermal hardening process is based on rapid (≈1000 K/s) heating and regulated cooling of the treated surface, which ensures the formation of structure and properties that are unattainable with traditional heat treatment methods (Yakovlev et al. 2010, Pastukhov et al. 2018). Plasma heat treatment, in contrast to laser and ion implantation, is characterized by a greater depth of the hardened layer, simplicity of the process, high efficiency (Sun, 2005, Aizawa et al. 2019, Bogdanov, Chernov, 2019, Tong et al. 2014).

The object of research is the technological process and the results of hardening of cutting edges of parts and working elements by low-temperature plasma.

The purpose of the research is to determine optimal thermophysical modes of hardening with low-temperature plasma, to study their structure, to develop thermal hardening technology and evaluate the operability of parts.

MATERIALS AND METHODS

The object of the study was steel samples 65G GOST 14959-2016 (analogs: G15660 – USA, 66Mn4 – Germania, 080A67 – GB, 65Mn - China) and spiral drills with a diameter of 17-20 mm, made of fast-cutting steels of grades R6M5, R6AM5 and 11R3AM3F2 according to GOST 19265-73 (analogs: S6-5-2 - EN 1.3343, M2 - USA). The micro- and fine structure was examined using optical microscopes (Neophot-21) and transmission electron (EM 125) microscopes. The microhardness measurement was carried out on a PMT-3M solid. Modification of samples and tools was carried out on the instalation (Yakovlev et al. 2010), consisting of indirect arc plasmatron and steel sample (Figure 1).



1 - a plasmatron head; 2 - plasma jet; 3 - shows a machined plate; 4 - pneumatic nozzle;
y - depth of thermocouples welding TP1, TP2, TP3; L - processing distance; V - feeding speed of the part.
Figure 1. Scheme experimental installation:

Samples of the analysed materials in the form of a plate with a size of 87×30×4.7 mm moved over the output electrode of the arc heater at a speed of V=5-30 mms^{-1} with a processing distance of L=5-40 mm (Figure 1). At a distance of 35 mm from the front edge of the sample, three thermocouples were welded to it along the longitudinal axis of symmetry at a depth of y=0 (TP1), y=1.5 mm (TP2), y=4.7 mm (TP3) from the inner (jet-facing) surface of the sample (Figure 1). The temperature change was recorded by a fast-acting amplifier N338-4P with an operating frequency of 150 Hz.

Heat treatment of the materials was carried out without surface melting, since the sample was cooled by a stream of water sprayed by an air nozzle. A typical heating curve of the sample surface layer is shown in Figure 2. The beginning of the temperature rise coincided with the moment of contact of the sample edge with the plasma jet. At the same time, the propagation of luminous streams 2-3 sm long on the inner surface of the sample was noted.

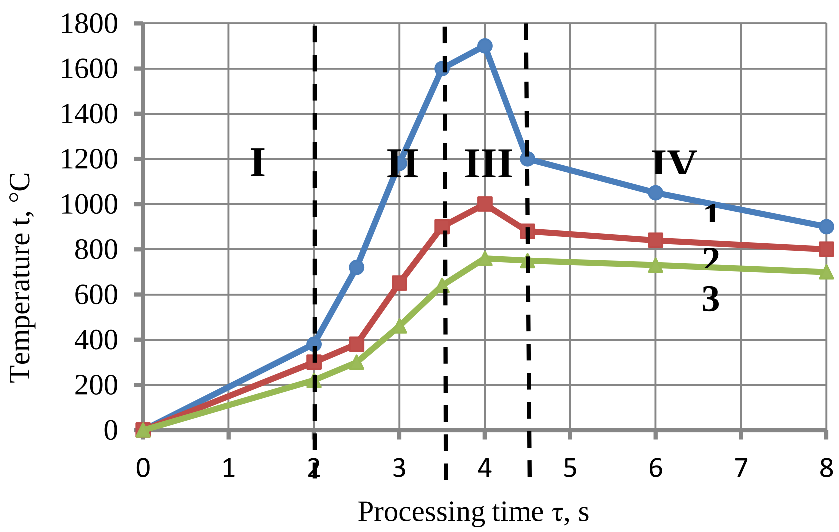


Figure 2. Graphical dependencies of sample heating at P=20 kW, V=9 mms^{-1}, L=17 mm:
depth of thermocouples welding in plate 1 - y=0, 2 - y=1.5 mm, 3 - y=4.7 mm.

In area I, the temperature rise rate for curve 2 was 80 Ks^{-1}, for curve 3 - 40 Ks^{-1}. In area II, the heating spot zone, the temperature rise occurred linearly at a rate of 1700, 450 and 250 Ks^{-1} for curves 1, 2 and 3, respectively. In area III, for curved 1 and 2, a temperature drop of 700 and 100 Ks^{-1} was observed, and for curved 3, the temperature was kept at

700 °C. In area IY, where the sample was already moving away from the action of the plasma jet, the temperature in all areas was equalized and it was cooled at a rate of 10-15 Ks^{-1}.

The dependence of the maximum temperature of the sample on the processing distance and the speed of its movement is shown in Figure 3.

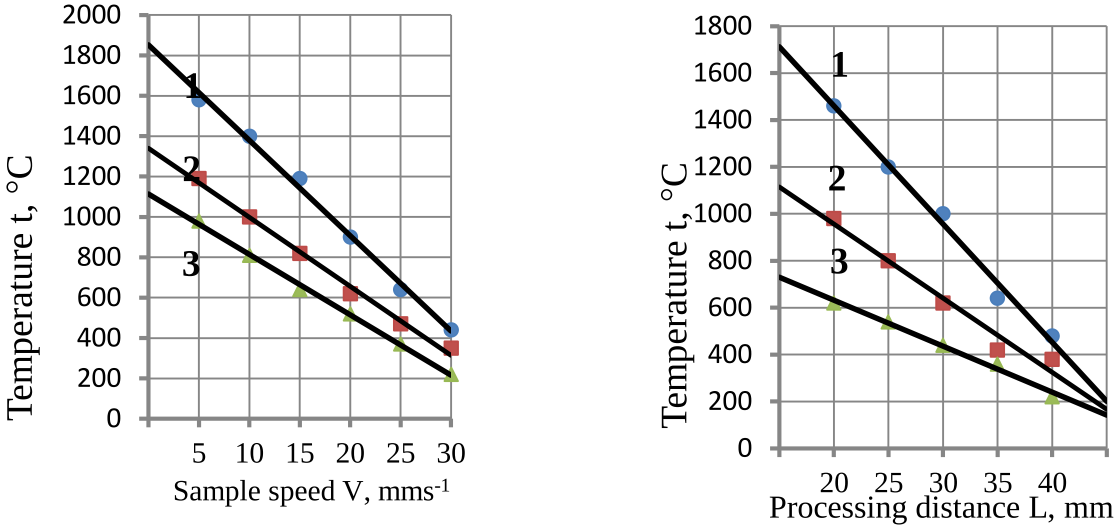


Figure 3. Temperature dependence of a sample on speed of its movement at L=15 mm (*a*) and on processing distance at V=8 mms^{-1} (*b*): depth of thermocouples welding in plate 1 - y=0, 2 - y=1.5 mm, 3 - y=4.7 mm.

It can be seen that the thickness of the phase change area δ varies from about 1.5 mm at V=9 mms^{-1} to zero at V=23 mms^{-1}. Thus, the thickness of the phase change area varied from 1.5 mm at L=15 mm to zero at L=30 mm. The thickness of the phase change zone was inversely proportional to L at V=const and V at L=const. From the point of view of achieving a higher efficiency to increase the thickness of the thermally strengthened layer, it is preferable to reduce the processing distance, and to reduce it, to increase the speed of movement of the sample. Obviously, the optimum mode will be achieved at a maximum temperature on the surface of the sample equal to the melting point of the metal.

RESULTS AND DISCUSSION

Plasma quenching of products of various grades of steel is one of the ways to significantly increase the reliability and durability of equipment and tools, when it is impossible to harden by volumetric heat treatment, surfacing or other methods (Aizawa 2019, Afriansyah et al. 2019, Erokhin et al. 2020). Despite the difference in the physical processes underlying a particular method of surface hardening of metals (plasma, laser, electron-beam, etc.), everyone has a common feature - phase and structural transformations occur under conditions far from equilibrium. Therefore, it is of particular interest to study the structure and properties of steels after hardening by low temperature plasma treatment. (Farghali, Aizawa, 2017).

The thin structure of the steel of the prototype (brand 65G) according to the results of electron microscopic analysis (Sharaya, Dakhno, 2012, Bogdanov, Chernov, 2019, Farghali, Aizawa, 2017, Vasilenko et al., 2021) in the initial state (before treatment with a plasma jet) was represented by a ferrite-pearlite mixture. The perlite component at large magnifications of the microscope was observed in the form of lamellar and globular modifications. The average thickness of the cementite plates was 0.077 mkm, the distance between the plates was 0.2 mkm. Within one colony of cementite, the plates were oriented in one direction. In ferrite, randomly distributed dislocations, scalar density, which did not exceed 10^8 sm^{-2}, were observed.

After treating the surface of steel samples 65G with a plasma jet, metallographic analysis revealed the formation of several structural zones: the surface is a modified white layer with a size of 8-24 mkm (1), then a thermal influence zone with a depth of up to 240 mkm (2) and a transition to a ferrite-perlite core structure (3) was observed (Figure 4, *a*).

Figure 4,*b* shows the change in microhardness H in the depth of the strengthened layer: the microhardness profile had several sections that corresponded to certain structural states of steel. Microhardness in the near-surface layer varied from 8400 to 12500 MPa depending on plasma treatment modes.

Electron microscopic examination of the surface layers of steel after plasma treatment showed an increase in the dispersion of structural components and a clear picture of the formation of a hardened zone (Sharaya, Dakhno, 2012). The main structural components of the hardened near-surface zone of steel 65G was fine martensite of mixed morphology; the amount of residual austenite located between the martensite plates did not exceed 10%, the dimensions of the martensite plates varied depending on the plasma heat treatment modes in the range *l*=1.09…3.15 mkm and d=0.25…0.74 mkm.

The established optimal modes of hardening treatment of model samples were used for plasma hardening of the tool under production conditions. As a tool, spiral drills were selected, which are among the most common types of cutting tools. Currently, the use of traditional heat treatment methods for tools made of high-speed steel grades in order to increase their wear resistance has been practically exhausted. According to the literature, the use of highly concentrated energy sources, such as lasers and low temperature plasma, can significantly increase the hardness and wear resistance of products made of high-speed steels.

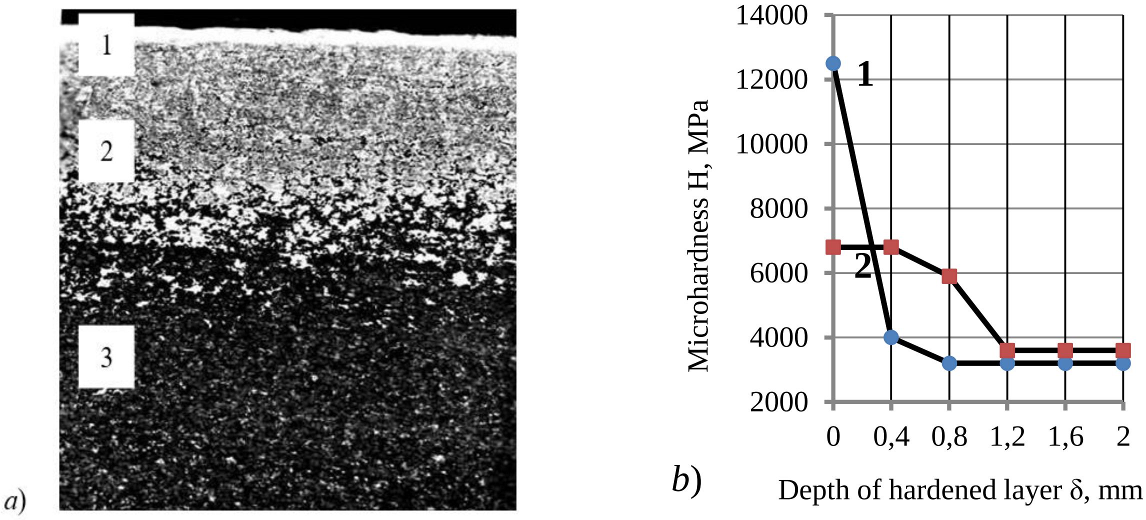


Figure 4. The microstructure of steel 65G after treatment with low-temperature plasma, an increase of ×100 (*a*) and a distribution of microhardness over the depth of the hardened layer with the number of heating cycles n: 1 - n=1; 2 - n=3 (*b*)

The industrial cutting tool, which had already undergone thermal treatment (quenching and three-fold tempering) according to standard technology, was subjected to plasma quenching. Spiral drills of diameter 17-20 mm made of fast-cutting steels of grades R6M5, R6AM5 and 11R3AM3F2 were subjected to plasma quenching for the purpose of subsequent thermohardening.

The plasma drill was fed to the heating zone at a rotational speed of 2-10 s^{-1}. The plasmatron was located at an angle of 60 with respect to the axis of the drill and at a distance of 30-40 mm. The heating time varied from 2 to 25 s. Cooling of the product was carried out with a water-air mixture under pressure. Rotation of the tool made it possible to increase the heating time and ensure uniformity of heating of the working surface of the drill. The processing quality of the tool was monitored indirectly by the color of the oxide film and the distribution of microhardness numbers. This made it possible to establish the optimal parameters of plasma processing of products: distance - 30 mm, rotation speed - 10 s^{-1}, heating time - 10 s.

For all variants of the drills treatment modes, it was possible to obtain a hardened layer 1-1.5 mm deep from the surface. According to the results of metallographic analysis, the microstructure of the hardened layer contained a white acid-free zone with a high microhardness of up to 12000 MPa, the depth of which reached up to 0.4 mm. Then there was the structure, which is martensite and residual austenite; microhardness of this zone - up to 9000 MPa. The construction of microhardness profiles showed that with an increase in the distance from the surface of the product in depth there was a decrease in hardness numbers to their values in the original structure (core).

The presence of a hardened layer on the working edges of the drills, a sufficient depth, with high microhardness values, a smooth transition to the base structure are prerequisites for increasing the wear resistance of the tool in operation. In this work, the drills were tested for resistance after plasma hardening. The durability of the tool is its ability to maintain its service purpose during operation until criterion wear. The tool operation time between its two consecutive regrind (replacements) is called the persistence period. The persistence period can also be determined by the number of processed parts.

Drills made of steel P6M5 (diameter 17.4 mm) drilled a steel plate made of steel 40 (GOST 1050-88) with a thickness of 30 mm on a vertical drilling machine of modification 2A135 at a rotation speed of 250 min^{-1} and a feed of 0.2 $mmrev^{-1}$ without cooling. When drilling the plate with a drill after processing with plasma, the chips were light, i.e. its temperature was not high. When drilling with a conventional, i.e. not plasma-treated drill, dark chips were formed, i.e. its temperature was high. On the main cutting blade, benevolent colors were observed, that indicated a greater wear of the control (non-plasma treated) drill.

During further studies, tests were carried out on plasma-hardened drills made of steel R6M5 and 11R3AM3F2 as a result of processing (drilling) of cast iron samples. Plasma-hardened drills drilled 2 times more holes than control ones. After sharpening, experimental drills also made it possible to drill a double rate of holes.

CONCLUSIONS

1. The heating rate of the surface of steel samples and articles during plasma heat treatment, which was 2000 Ks^{-1}, was determined, as well as the optimal modes of plasma processing of articles: distance from the plasmatron - 30 mm, rotation speed - 10 s^{-1}, heating time - 10 s.
2. Phase and structural transformations after plasma coating were investigated on model steel samples 65G and microhardness profiles were constructed.

3. It has been found that plasma quenching of a standard tool made of fast-cutting steel increases the microhardness of its surface to 12000 MPa and creates a hardened layer with a depth of 1-1.5 mm.
4. Tests of experimental spiral drills made of fast-cutting steels of R6M5, R6AM5 and 11P3AM3F2 grades for resistance were carried out in production conditions and showed an increase in their resource by 2 times and the possibility of multiple regrind within the thickness of the hardened layer.
5. The technology of plasma hardening of parts has been developed, which can be used for thermohardening of cutting edges of working elements of agricultural machines.

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