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Mechanisms for Forming the Surface Structure of Steel Products During Heat Hardening

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Abstract. The paper considers the questions of strengthening of critical joints made from materials and working in complex power, temperature and high-speed operating conditions of friction parts. Production of hardened surface layers is achieved by purposeful formation of specified structural state of metal, i.e. by modification using low-temperature plasma. This method of heat treatment helps to solve the problem of increasing the wear resistance of metal products and materials for their manufacture. Particular attention is paid to the study of the conditions for the formation of the optimal microstructure and phase composition of steel in order to obtain satisfactory hardness and ductility. There are offered modes of hardening treatment, which can be used for plasma hardening of details under conditions of metallurgical production.The conducted thermophysical measurements allowed determining the heating rate of the product surface during plasma heat treatment, which was 2000 K/s. It was found that plasma hardening of a standard high-speed steel tool increases microhardness of its surface to 12000 MPa and creates a hardened layer 1-1.5 mm deep.

Keywords: low-temperature plasma, chemical-thermal treatment, hardening, microstructure.

Introduction

Improving the reliability of the equipment is one of the most important components of the product quality assurance system. It provides for reducing the number of failures due to wear of machine structural elements [1-3]. Depending on the current operating conditions, the wear process can be of a different nature: from the usual mechanical, including abrasive and fatigue, to molecular mechanical and corrosion-mechanical [4-6]. This problem requires increased attention to the possibility of creating fundamentally new materials with a given level of properties and to the development of strengthening technologies for the surface layer of products from known metal alloys. To solve it, an integrated approach is usually used. It combines the principles of forming the chemical composition of the material and then the structure by developing technological processes for its strengthening treatment during the production process or during the repair and restoration work.

In order to improve the strength characteristics and operational properties of machine parts, targeted formation of a given structural state of metal is usually carried out by chemical-thermal treatment methods, for example, nitrocementation, carbonitration, etc [7-10]. And also there are methods based on the use of highly concentrated energy sources such as ionic, plasma, laser, electro-spark, ultrasonic, high frequency induction and others [11-16]. A result of this effect is either structural changes in the original surface i.e. the modification process or the formation of a given coating on the surface.

The importance of continuing scientific investigation in the field of strengthening coatings of materials is evidenced by the analysis of recent scientific research and publications. The introduction and development of various methods of forming a given structural state of the metal leads to an increase in surface quality and service life, in particular steel parts of critical joints. Therefore, investigation of these methods and their features is an urgent task requiring continued research in the field.

At a present time it is considered perspective to use heat treatment with low-temperature plasma to strengthen the surfaces of materials. The plasma (the ionized gas) represents the directed flow of charges particles with a high concentration of energy in it. The principle of thermal treatment on the basis of plasma has its foundation in the rapid warming (=1000 Kelvin degrees per second) and the regulated cooling of the work surface, which cannot be reached by using the traditional ways of thermal treatment and which permits the creation of a specific structure with a set of specific characteristics. The plasma treatment (or the so-called surface modification) unlike the laser or ion implantation is characterized by a larger depth of the strengthened layer, the simplicity of the technological process and a high coefficient of efficiency [17-26].

This fact confirms the scientific significance regarding surface structure studying of steel pieces, which has a unique combination of mechanical, physical and chemical properties obtained using this thermal hardening method.

To realize the prospects of an innovative version of the development of production potential, it is necessary to consider and solve a number of tasks aimed at improving technologies and technical means to ensure the operable state of existing domestic and especially foreign equipment, taking into account the possibility of its import substitution. One of the main directuions identified in the process of finding solutions is the development of various technologies that allow improving the operational properties of the working surfaces of the parts of critical joints based on methods of applying a layer of material, hardening and modification.

The object of the investigation is the technological process of structure formation and specific characteristics in the process of thermal strengthening of structural steel pieces by using plasma. Medium carbon steels were selected as the test material. As the material under study there was selected steel 65G, SS 14959-2016 (analogs: G15660 – USA, 66Mn4 –

Germany, 080A67 – GB, 65Mn - China) and twist drills with the diameter of 17-20 mm made of fast-cutting steels of R6M5, R6AM5 and 11R3AM3F2 grades according to SS 19265-73 (analogs: S6-5-2 - EN 1.3343, M2 - USA).

The aim of this work is to study chemical-thermal treatment with low-temperature plasma and to obtain its optimal technological mode, which contributes to increasing wear resistance of steel blanks and tools (drills) made of high-speed steel.

To achieve the goal, it is necessary to agree on the optimal regimes of heat treatment in order to create a new form of thermal treatment which would allow for the specific changes in the steel structure. This can be represented by the block decomposition, the birth of micro-tensions and the increase in thickness of the dislocations in the surface layer.

1. Research methodology

The experimental installation consisted of an indirect arc plasmatron 1 and a steel sample 2 (Fig.1). The EDP-104-like plasmotrone, the power of which was about 9 kilowatts with the 50 ampere current, was used for the surface modifications of the steel pieces. The nozzle diameter was of 8 mm. In the central part of the steel sample and on its surface a thermocouple was stuck, and at the time the piece was in movement that thermocouple passed just above the discharge jet of the plasmotrone. The measuring of temperature at the time of the warming and cooling was allowed by the fast-acting plotter. The speed of the relative movement of the piece changed from 2 to 30 mm per second, and the distance between the nozzle cut and the work surface was changing from 17 to 30 mm. The cooling of the piece was put into practice with the use of water which was sprayed with a pneumatic jet at the time the piece was pulled out of the plasma flow.

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 spread of luminous streams up to 30 mm long on the inner surface of the sample was noted.

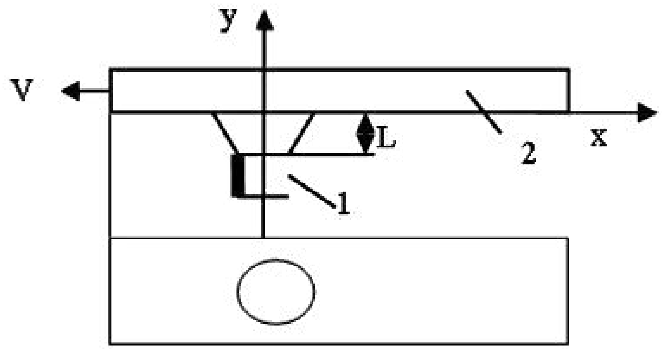


Fig.1 - Schematic diagram of the trial type: 1 – plasmatron, 2 - steel sample

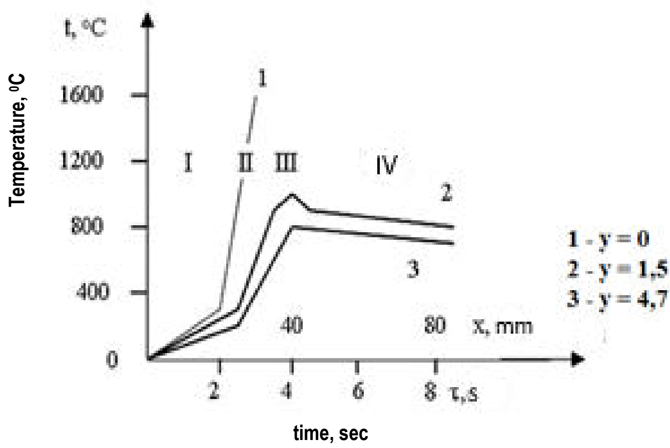
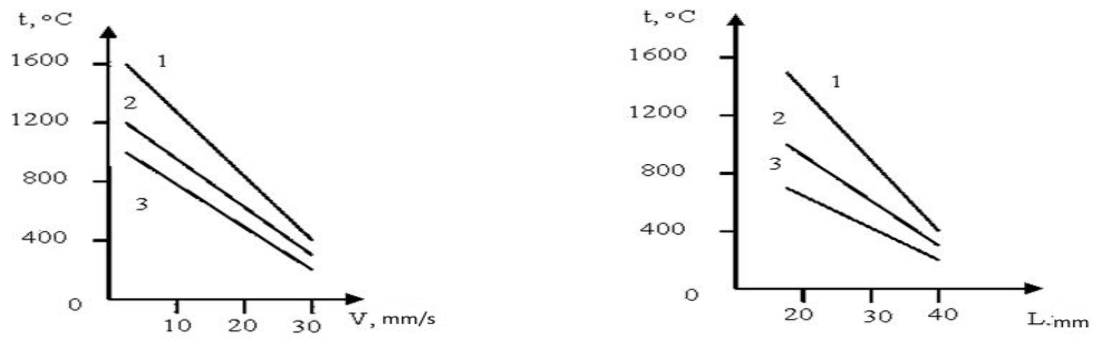


Fig.2. - Typical heating curvesV = 9 mm/s, L = 17 mm

In region I, the rate of temperature elevation for curve 2 was 80 K/s, for curve 3 - 40 K/s. In the II-zone of the heating spot, the temperature rise occurred linearly at a rate of 1700, 450 and 250 K/s for curves 1, 2 and 3, respectively. In area III, for curves 1 and 2, a temperature drop at a rate of 700 and 100 K/s was observed, and for curve 3, the temperature was kept at 700 ^{0}C. In area IV, where the sample was already moving away from the action of the plasma jet, the temperature in all sections was equalized and it was cooled at a rate of 10-15 K/s.

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



(a) (b)

Fig.3. - Temperature of the sample - speed of its movement relationship where L = 15 mm (a) and V = 8 mm/s (b)

A special attention has been paid to research the conditions of the formation of the optimal microstructure and the phase composition of steel in order to get a satisfying hardness and plasticity. Studying the steel microstructure with regard to the sample profiles after the plasma treatment has shown that the surface layers had no cracks and were pure to a high extent. According to the metallographic analysis the structure of the surface coating under the initial conditions was ferrite-pearlite, and after the plasma treatment a conversion from the structure of fine-needled martensite close to the surface to the initial sorbitic pearlite-like core structure was established. The surface layer of the sample was monitored as a white 24 mkm-thick layer which was immune to etching in the metallographic reagents. At the certain places the closest to the surface the subgrain boundaries could be seen (Fig.4).

The results of light microscopy were complemented by the electronic-microscopic analysis of the surface steel layers in the initial state and after the plasma treatment. It was necessary to prepare a few samples treated in the same conditions for getting full information about the microstructure characteristics and the change of quantity parameters subject to the distance changes between the plasmotrone nozzle and the work surface. In this case the sample's surface structure was looked into at the depth of 0.50 μm.

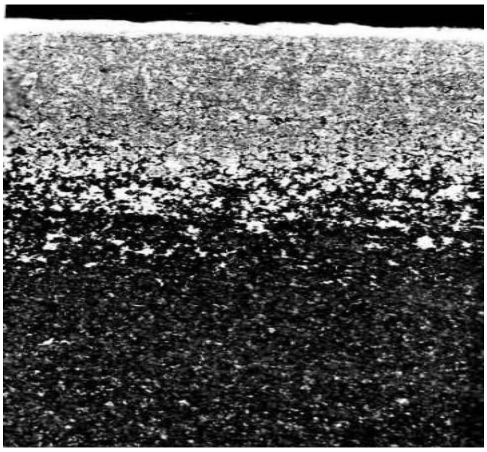


Fig.4. - Steel microstructure after surface modification, x 100 (light microscopy)

After the surface modification the foil paper was made from the sample for further electronic-microscopic analysis through the instrumentality of the electronic microscope "Tesla BS-540" (the accelerating voltage was 120 kV) with goniometric head. The dislocation thickness was measured by the means of the secant line with use of a proportion: p=2 NM/(LT).

where N – is a number of intersections of the secant line with the image of dislocations on the microphotograph;

L – is the total length of the secant line;

T – is the foil's thickness;

M – is the total zoom of the microphotography.

In the initial state the steel microstructure was represented by ferrite and pearlite (Fig.5).

The pearlite component was seen in the form of lamellar and globular modifications. The medium thickness of the cementite plates turned up to be 0.077 μm, the inter-plate distance was 0.2 μm. Within one colony the cementite plates are oriented in the same direction. Inside the ferrite the dislocations were distributed chaotically, their scalar density did not surpass 10^8 cm^{-2}.

After the air plasma treatment in the surface layers of the samples the hardened zone was formed, the dispersibility of the microstructure increased significantly. The main structural component of the hardened near-surface region of the samples was the fine-dispersed martensite of mixed morphology (Fig.6).

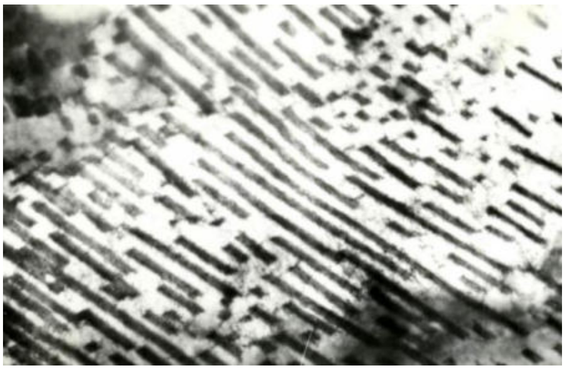


Fig.5. - Steel microstructure in initial state, x 10200

Fig.6. - Microstructure of steel surface after plasma treatment, x 10000

The quantity of residuary austenite situated between the martensite plates did not surpass 10 %. The dimensions of the martensite plates changed with regard to the plasma treatment regime within L= 1.09 – 3.15 µm, d = 0.25 – 0.74 µm.

After the plasma thermal treatment the main structural components of the hardened zone were the fine-disperse martensite of mixed morphology and the residuary austenite (up to 10 %). The dimensions of the martensite plates changed within L = 1.09 – 3.15 µm and d=0.25 – 0.74 µm.

It has been determined that with regard to the thermal treatment regimes the zone of plasma treatment upon the surface of the steel sample was up to 1.5-2.4 mm in size. The analysis of the microhardness distribution profiles throughout the depth of the hardened layer has shown that the depth of the layer with the 12640 – 13650 MPa microhardness did go up to 150 - 200 µm (Fig. 7).

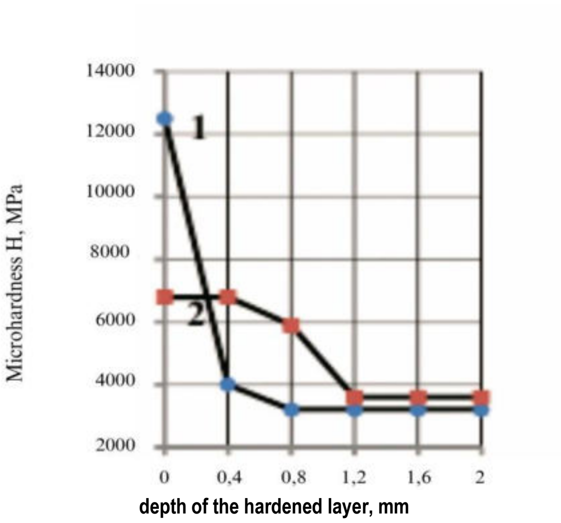


Fig. 7. - Microhardness distribution profiles by the depth of the hardened layer

2. Results and discussion

Twist drills are among the most common types of cutting tools. Currently, the use of traditional methods of heat treatment of tools made of high-speed steel grades to increase their wear resistance has been almost exhausted.

According to literature data, the use of highly concentrated energy sources, such as lasers and low-temperature plasma, can significantly increase hardness and wear resistance of products made of high-speed steels.

Plasma hardening was used for industrial cutting tools that had already undergone heat treatment (quenching and triple tempering) using a standard technology. Twist drills with the diameter of 17-20 mm made of high-speed R6M5, R6AM5, and 11R3AM3F2 steel grades, were subjected to plasma hardening for subsequent heat strengthening.

The plasma drill was fed into the heating zone with the rotation speed of 2–10 rpm. The plasma torch was positioned at the angle of 60 degrees relative to the drill axis and at the distance of 30–40 mm. The heating time varied from 2 to 25 seconds. The product was cooled with a water-air mixture under pressure. Rotation of the tool made it possible to increase the heating time and to ensure uniform heating of the drill working surface. The quality of the tool treatment was controlled indirectly by the color of the oxide film and the distribution of the microhardness numbers. This made it possible to establish the optimal parameters for plasma treatment of the products: the distance 30 mm, the rotation speed 10 rpm, the heating time 10 sec.

For all the variants of drill treating 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 zone with high microhardness not etched in acids up to 12000 MPa, the depth of which reached 0.4 mm. Next, there was a structure representing martensite and residual austenite; the microhardness of this zone was 9000 MPa. The construction of microhardness profiles showed that with increasing the distance from the surface of the product into the depth, there was decreasing hardness numbers to their values in the original structure (core).

Testing drills for durability after plasma hardening. The drills made of P6M5 steel (the diameter 17.4 mm) were used to drill a steel plate (Steel 40) 30 mm thick on a vertical drilling machine of the 2A135 modification with the speed of 250 rpm and the feed rate of 0.2 mm/rev without cooling. When drilling the plate with a drill after plasma treatment, the chips were light, i.e. their temperature was not high. When drilling with a conventional drill, i.e. not treated with plasma, the chips were dark, i.e. their temperature was high. Temper colors were observed on the main cutting blade, which indicated higher wear of the control (not treated with plasma) drill. In further studies, plasma-hardened drills made of P6M5 steel were tested as a result of treatment (drilling) cast iron samples. Plasma-hardened drills made twice as many holes as the control ones. After sharpening, the test drills also drilled twice as many holes.

1. The thermophysical measurements made it possible to determine the surface heating rate of the product during plasma heat treatment, which was 2000 K/s.
2. It was found that plasma hardening of a standard high-speed steel tool increases microhardness of its surface to 12000 MPa and creates a hardened layer 1-1.5 mm deep.
3. Tests of the test drills conducted under factory conditions, showed increasing their durability by 2 times and the possibility of multiple resharpening of the drills within the thickness of the hardened layer.
4. A technology was developed for plasma hardening (heat strengthening) of twist drills made of P6M5, P6AM5, and 11P3AM3F2 steel grades.

Conclusions

As a result of the study of the formation of the surface structure of steel pieces in the process of thermal strengthening, it was revealed that the main condition of steel strengthening under the plasma heat treatment is the formation of the fine-dispersed martensite structure in the near-surface zones. It was found that the depth of zone affected by the plasma thermal treatment reaches 1.5 – 2.4 mm and depends on the parameters of the plasma device and the heat treatment regimes. The medium-carbon steel strengthening occurs with the 12640- 13650 MPa microhardness and the 150-200 mkm depth. Thus, the obtained results make it possible to recommend the different technological regimes of plasma thermal treatment, which help to solve the problem of increasing the wear resistance of the surface layer of critical steel parts.

The conducted thermophysical measurements allowed determining the heating rate of the product surface during plasma heat treatment, which was 2000 K/s.

It was found that plasma hardening of a standard high-speed steel tool increases microhardness of its surface to 12000 MPa and creates a hardened layer 1-1.5 mm deep.

The obtained optimal hardening treatment modes for model samples were used for plasma hardening of tools in metallurgical production conditions.

Tests of pilot drills conducted in factory conditions showed increasing their durability by 2 times and the possibility of multiple resharpening of drills within the thickness of the hardened layer.

A technology for plasma hardening (heat strengthening) of twist drills made of R6M5, R6AM5, and 11R3AM3F2 steel grades was developed.

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