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K.O. KOSTYK [1,*], **V.O. KOSTYK** [2], **and V.D. KOVALEV** [2]

[1] National Technical University 'Kharkiv Polytechnic Institute',
2 Kyrpychova Str., UA-61002 Kharkiv, Ukraine
[2] Donbas State Engineering Academy,
72 Akademichna Str., UA-84313 Kramatorsk, Ukraine
* kateryna.kostyk@khpi.edu.ua

STRENGTHENING THE SURFACE LAYER OF TOOLS WITH STATE-OF-THE-ART TECHNOLOGIES

Increasing both the service life and the wear resistance of the tool by surface hardening is an urgent issue. Its solution contributes to a significant increase in the performance of products. Available methods of surface hardening of tools, based on coating or changing the surface condition, are becoming increasingly important due to the complexity of the operation of products. Plates made of the T5K10 (85% WC–6% TiC–9% Co) and T15K6 (79% WC–15% TiC–6% Co) hard alloys as well as cylindrical samples made of the W6Mo5Cr4V2 and W18Cr4V high-speed steels are used for the study. Studies have shown that, after processing the T15K6 alloy plates with a pulsed magnetic field, the cutting tool life improved by more than 200% as compared to the untreated ones. The proposed method will increase the strength of carbide plates and stabilize the physical and mechanical properties of the cutting tool. For tools made of alloy steels, the hardening treatment is carried out by the boron method in pastes with nanodisperse powders. As shown, the thickness of the boride layer for high-speed steels increases with the duration of the process; however, its growth rate depends on the composition of the steel. An increase in the holding time of the chemical and thermal treatment leads to the growth of boride layers. The layer thickness changes quadratically (as a second-degree polynomial) with duration time. A feature of formation of diffusion layers is revealed. The dependences of both the surface hardness and the thickness of boride layer on the borating time for high-speed steels are also shown. Studies have shown that boriding in a nanodisperse medium can significantly increase the wear resistance of steels. The method of expert assessments of the maximum values of the surface properties of the studied steels is carried out. As shown, it is more rational to use W6Mo5Cr4V2 steel as a cutting tool after hardening the surface layer by boriding

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in a nanodisperse boron-containing powder. The proposed processing method demonstrates the prospects of using it to improve the performance of products. In addition, this method of hardening can significantly increase the wear resistance of materials (by ≈3.38–3.75 times) as compared to steels without processing.

Keywords: hard alloy, high-speed steel, surface hardening, magnetic pulse treatment, boriding, hardness, wear resistance.

1. Introduction

With the development of industry, the requirements for tools and machine parts are tightened, and the accuracy and quality of their manufacture are improved. To achieve an increased level of performance, new durable materials are introduced. Modern methods of surface hardening are one of the promising technologies for improving the strength, service life and operational properties of metal products for various branches of technology [1–7]. A variety of modern methods aimed at strengthening the surface layers of materials are based on coating or changing the surface condition to increase the performance of tools and machine parts. However, not always, known methods provide the necessary properties to a sufficient extent.

The surface of cutting tools undergoes increased wear during operation. Therefore, there is a need to increase the wear resistance of the surface layers of alloys, using modern methods of surface hardening. The performance of the cutting tool is strongly influenced by the properties of the material used. The optimal choice of a combination of the necessary physical and mechanical properties allows you to control the processes of tool surface wear.

Known methods for improving the physical and mechanical properties of tool materials and allow you to increase the wear resistance of the tool. However, the costs compared to the efficiency of using such methods remain significant. In many cases, they are uneconomical and impractical due to the loss of other valuable properties, in particular, for example, the strength of the tool as a whole. Therefore, the development of new progressive methods of hardening cutting tools is an important task to increase the service life of metalworking tools. This goal is particularly relevant for carbide cutting tools.

As known, hard alloys have, on the one hand, high heat resistance, which allows cutting tools to work at high cutting speeds. On the other hand, hard alloys have low strength. This limits their ability to work on previous operations. In this case, the tool experiences a shock load formed when cutting the workpiece, which is made by casting or forging methods, abrasive dust, uneven allowance, *etc*.

To increase the efficiency of tools and machine parts in conditions of friction and wear, various methods of chemical and thermal treatment (CTT) are also widely used. However, many CTT methods are quite long-term and require complex and expensive equipment [1, 8–11].

Chemical–thermal treatment combines thermal and chemical simultaneous action on the surface layer of the part in order to obtain the required composition, structure and properties [12–14]. During the chemical–thermal treatment, the metal surface is saturated with the corresponding element (carbon, nitrogen, boron, aluminium, chromium, silicon, titanium, *etc.*) by its diffusion deep into the product at high temperature in the atomic state from the external environment.

The widespread use of CTT in various fields of technology is explained by the fact that most parts of machines and various mechanisms operate under conditions of wear, cavitation, cyclic loads, corrosion at cryogenic or high temperatures, at which maximum stresses occur in the surface layers of metal. CTT of metals and their alloys both for their surface hardening and for protection against surface corrosion increases the reliability and durability of machine parts and tools [1, 10–14].

The essence of the CTT process consists in saturating the surface layers of the product with one or several elements at once in combination with a certain heat treatment, which, depending on the type of CTT, can be performed before and after saturation of the surface. Therefore, in CTT, the structure and properties of the surface of the product are predetermined both by changing the chemical composition of the surface and by heat treatment.

Thus, the actual question is the choice of a particular hardening method, which depends on many factors that determine its effectiveness and the cost of implementation in certain production conditions.

2. Analysis of the Literature Data and Problem Statement

The main known methods of increasing the wear resistance and strength of carbide tools are divided into the following groups: structural methods; mechanical hardening; application of wear-resistant coatings; chemical–thermal treatment; laser hardening; plasma-arc hardening; radiation hardening; ion alloying; magnetic–abrasive treatment, pulsed magnetic field treatment, cryogenic–erosion treatment [15].

One of the promising ways to increase the strength of the tool is the processing of working surfaces by plastic deformation (SPD): vibration, fine-jet processing [16].

At a processing SPD, a large number of impacts are applied to the cutting surfaces, resulting in plastic deformation and brittle–abrasive wear of these surfaces. All phase components of a hard alloy are plastically deformed, but to the greatest extent, it concerns the tungsten carbide. In this case, the mosaic blocks are crushed, the microdeformation of the lattice increases, and compressive stresses of the order of

100–130 N/m^2 arise. The use of SPD methods in the hardening of carbide cutters allowed increasing the feed by 1.1–1.2 times. The effectiveness of SPD methods is determined by the dependence of strength on geometric parameters, physical and mechanical properties of the material. With SPD, the cutting edges are rounded, which increases the strength of the tool. However, the rounding efficiency of the cutting edges and the optimal value of the rounding radius depend primarily on the thickness of the cut layer and the hardness of the material to be processed. This limits the usage of the SPD.

The search for a hardening method that combines the possibility of achieving optimal rounding of the edges of the cutters and the depth of the hardening caused the need to study the effect of liquid on the effect of shot blasting of carbide cutters, which turned out to be twofold. On the one hand, the liquid reduces the impact energy, and, on the other hand, removes the wear products. Thus, the intensity of plastic deformation decreases, and the intensity of rounding of edges changes to a lesser extent, which should lead to a better ratio of the value of the radius of rounding of edges and the depth of hardening. The use of liquid in fine blasting increases the maximum rounding radius by 20% . At a moment of reaching the maximum strength, the degree of deformation of the incisors of both types of processing is approximately the same, while the radius of rounding of the incisors that are treated with liquid is 10–15 percent more. This provides a 1.17-fold increase in strength. The destructive feed during hardening without liquid increases by 1.29 times, and with liquid, it increases by 1.34 times [16].

The energy of shock waves [17–18] has found application in the processing of cermet alloys to increase their strength and stability. During vibration processing, the smallest particles of the material are mechanically removed from the surface. In addition, during processing, oscillatory movements of the working elements of the abrasive filler occur, which lead to smoothing of microroughness by their plastic deformation [17]. Improving the performance properties of the carbide tool is achieved by ensuring rounding of the cutting edges and other surfaces of the cutting part because of its vibration processing. This has a favourable effect on the physical and mechanical properties of the surface layer of the material.

As a result of research, it was proved that about 60–70% of the effect of vibration hardening of the tool is achieved by rounding the edges, and 30–40% of the effect is achieved by reducing the roughness and changing the properties of the surface layer. However, the vibration treatment is very long in time and therefore requires significant costs.

The application of a hard coating [19, 20], resistant to abrasion, on carbide plates can increase the durability of the cutting edges several times compared to conventional plates or increase the cutting speed with the same durability. Plates coated with titanium carbide (TiC) with a thickness of 5–6 μm have a typical disadvantage. This is the presence of a decarburized brittle layer between the coating and the base. As a result, they can only be used for continuous cutting. Coated cutting plates, due to the advanced manufacturing technology, do not have this disadvantage. The coating thickness of these plates was increased to 7–8 μm, and special grades of hard alloy were used as a base. This made it possible to use plates for intermittent cutting [21].

Plates with a coating thickness of up to 10 μm consist of two or more thinnest layers of different composition. Titanium carbide (TiC) is most often applied to the base, and titanium nitride (TiN) or aluminium oxide (Al_2O_3) is applied to it. The use of plates with a multi-layer coating [5] allowed to increase the processing performance by 1.5 times compared to plates that have a single-layer coating (TiC). However, coated plates have a number of disadvantages. When regrinding, all the advantages compared to plates without coverage will be void. They should not be used where a very sharp cutting edge is needed, because when applying the coating, the cutting edges are always inevitably rounded. They are not suitable for processing light metals, wood and other materials with low hardness. Coated plates are unsuitable in cases where the viscosity of their base metal is insufficient for the selected processing operation [22].

The method of electrospark alloying [17, 23] of a hard alloy consists in transferring a particle of the anode material (an electrode — a material that is strengthened) to the cathode material (an instrument) by a pulse with an electric spark. The surface layer of the tool is saturated by diffusion. As the anode material, graphite or copper–graphite electrodes are most often used. When hardening in this way, the period of tool life increases by 1.5–3 times. This is due to the fact that the surface of the hard alloy is carbonized and due to heating to high (4000–10000 °C) temperature of the spark and rapid cooling, a cementation crust is formed, which protects the working surface of the tool from rapid abrasion and blunting.

Laser processing contributes to the grinding and saturation of the surface layer structure of the tool material with dislocations, which leads to an increase in hardness, and therefore, a significant increase in tool wear resistance [24]. Laser surface hardening [25] is characterized by maintaining the original purity of the upper layer of the product and ensures the locality of the process [26]. However, the technological process of surface radiation treatment is complex, depends on a number of conventions, and requires significant energy costs and a long time when irradiating a multiblade instrument [27].

The main disadvantages of surface laser hardening are as follow:

- hardening is performed only at the point where the working surface is adjacent to the cutting edge;

- simultaneous hardening of both surfaces (front and back) is unacceptable;
- the cutting edge after laser heat treatment is weakened against the action of brittle fracture forces;
- the process is long in time (when hardening a multiblade tool) and requires significant energy costs;
- when the tool is redrawn, the established layer is removed.

The advantage of these methods is that, due to changes in the chemical composition of the material surface, an enriched layer of the same thickness with certain physical and mechanical properties is obtained.

The essence of the plasma-arc hardening method consists in applying a wear-resistant thin-film coating with simultaneous plasma quenching of the surface layer [28, 29]. The coating is a product of plasma chemical reactions of substances that have passed through an arc plasma torch, quenching occurs due to the local effect of high-temperature plasma current. The effect of plasma-arc hardening is achieved by changing the physical–mechanical properties of the surface layer increases the hardness, reduces friction, and creates a compressive stress and healing of microdefects. This method allows you to increase the durability of the cutting tool up to 3 times.

Attempts to apply the method of radiation hardening of carbide plates with protons have proved its promise and can be used to improve the durability and reliability of cutting tools. As a result of proton treatment [30, 31], the physical and mechanical properties of a hard alloy can change significantly. Because of the transformation of the crystal structure, vacant nodes appear, which prevent the formation of dislocations, due to this, the material is strengthened. All these effects should affect the structure and hardness of the surface layer to some extent, and therefore, the tool life.

The method of ion implantation [12, 17] is applied to change the mechanical properties of various metals. The method consists in implanting ions of a number of elements (N^+, B^+, In^+, $Ti + N$, $Ti + B$) on the surface of carbide plates and allows applying multilayer coatings. Experiments have shown that the durability period of hard alloy plates with a multilayer coating increases by 1.4–1.8 times [32]. During this treatment, radiation defects are formed in the surface layer of the irradiated material. They lead to changes in the properties of the material, such as microhardness, strength, ductility, thermal conductivity, electrical resistance. For example, laser surface hardening is carried out by highly concentrated radiation, which is focused on a small area (from fractions to several mm). Such a complex method is limited to its use in production, as it requires protection from x-ray radiation, which occurs when working at voltages of more than 20 kV. It is also expensive and requires the use of complex equipment.

One of the most promising methods of finishing polishing and strengthening tool processing is the method of magnetic abrasive processing, implemented in conditions of large working slots, when a complex effect on the treated surface and the surface layer of parts is provided. The analysis of the interaction conditions of magnetic–abrasive processing in the conditions of large magnetic slits is primarily processing with active friction–shock interaction of the treated surface with the magnetic–abrasive tool, which is formed during processing [32]. Conventionally, such interaction can be divided into two processes: impact similar to the interaction when using jet-processing methods, friction similar to the interaction when rubbing rough surfaces. When the surface to be treated interacts with the magnetic abrasive tool, the following changes occur:

(1) change in the microrelief of the surface, which occurs either as a result of the elastic–plastic and plastic deformations of the surface and the surface layer or in the process of microcutting;

(2) change in the stress state of the surface layer of parts;

(3) structural and phase transformations in the surface layer.

The second and third groups of changes occurring in the process of magnetic abrasive treatment and experimentally confirmed are the result of effects that occur during the plastic and elastic–plastic deformations of the treated surface. The performed studies made it possible to identify clearly the processes of microcutting and plastic deformation of microroughness and the surface layer during magnetic-abrasive processing in conditions of large magnetic slits and weak magnetic fields. As shown, the process of magnetic abrasive treatment under these conditions occurs in the mode of shock–friction interaction of the magnetic abrasive tool and the surface to be treated.

One of the ways to increase the durability of a carbide tool [29] is the chemical–thermal treatment of the cutting plate. The greatest effect when using this method is achieved by nitriding in a gas medium [33, 34]. At the same time, titanium nitride (tin) is formed on the surface of the carbide plates, which has sufficient thermal conductivity, resistance to oxidation at high temperatures, relatively low brittleness, and high abrasive wear resistance.

An effective method of hardening using chemical and thermal treatment of various products is boriding (also called boronizing), *i.e.*, the process of saturating the surface of parts with boron, because of which their physical and mechanical properties change: hardness, fatigue strength, heat resistance, *etc*. of boron steels of various classes and purposes, cast iron, nickel, cobalt, and refractory alloys. As the most widespread, there is boriding in a solid, liquid, and gaseous media [35].

Many domestic and foreign scientists and engineers were engaged in the development of the theory and practice of the boron process. There are well-known scientific schools in Germany, England, France, Japan, the US, and other countries. Leading companies in the field of chemical and thermal treatment of metals and alloys: Degussa, Leybold Durferrit, Sandvik AB, Stahlwerke Röchling–Burbach, HEF, *etc.* have been engaged in the implementation of the process [36].

The authors of works [36, 37] claim that boriding can increase the wear resistance by 3–50 times compared to heat treatment and by 1.5–15 times compared to traditional CTT methods. Boriding can be subjected to pearlitic steel, ferritic and austenitic grades.

The contribution of field crystals to the energy of surface magnetic anisotropy during boriding was studied in [38]. It is noted that, in the conditions of maximum loads, which occur during the operation of a number of machines, the hardness of the transmission gears is insufficient. In order to solve this problem, it was proposed to introduce additionally silicon into the composition of the hardening mixture, which creates less brittle phases during diffusion saturation. This allows you to avoid deterioration of the hardened layer and contributes to its better run-in after boriding. In Refs. [38–40], the results of the study of the powder medium for the single-phase boriding process are presented, the structure, chemical and phase composition of the powder mixture are determined, and the properties of single-phase boride coatings are investigated.

The author of the work [40] by the method of diffusion doping with boron created new composite self-fluxing powders from waste products of cast steel and cast iron shot. The structure and properties of the initial and borated powders, the dependence of the growth of the boride layer thickness on the time of chemical–thermal treatment, and the description of the mechanism of structure formation in the process of diffusion doping are studied. Thermodynamic modelling in Ref. [41] allowed us to calculate the compositions of synthesized metallothermic powder media and determine the substances, which are sources of boron atoms during subsequent chemical–thermal treatment. In Refs. [42–46], boride coatings were obtained on steels 20, 4Cr5MoSiV, and Cr12Mo treated in a fluidized bed with a metallothermic powder medium. The phase and chemical compositions, hardness, and wear resistance of boride coatings are studied.

The analysis of the works [36–48] allowed us to classify the currently known methods and methods of boriding as follow:

solid combined method — saturation in metal–thermal mixtures when combining the processes of boron reduction from its oxides and boriding of parts;

solid separate method — saturation in mixtures during the distribution of metal–thermal reduction of boron from its oxides and subsequent use of these powder mixtures for boron parts;

contact method — carrying out boriding of parts in the container after their filling and subsequent sealing;

non-contact method — carrying out boriding in a container in which the saturating mixture is separated from the parts or is located in a special gas — prepared container (gas generator);

fluidized method — saturation in a powdery mixture in a fluidized state;

gas method of saturation in a closed volume in a process that is self-organized — saturation in a closed container, muffle or retort, the inner walls of which are lined with a saturating mixture, that is, carrying out saturation in a lined device;

electrolysis method in melts of boron-containing salts — saturation of metals with boron in melts due to their electrolysis when an electric current is passed;

electrolysis method in melts of boron-containing salts with the addition of powdered electrochemical reducing agents — saturation of metals with boron in melts to which powdered electrochemical reducing agents are added for additional formation of boron sub-ions, which are more easily reduced on the treated surface during electrolysis;

electrolysis-free method in melts of boron-containing salts with the addition of powdered electrochemical reducing agents — saturation in molten media in which the formation of boron atoms occurs in the self-organization mode during the operation of short-circuited galvanic cells;

electrolysis-free method in metal melts — liquid saturation, in which boron in the metal melt is in a dissolved or suspended state;

electrolysis-free method in melts of boron-containing salts with the addition of powdered boron-containing electrochemical reducing agents — liquid saturation in melts of salts that provide the maximum rate of formation of boron subions in the self-organization mode during the operation of short-circuited galvanic cells;

electrolysis-free method in melts of neutral salts with the addition of powdered boron-containing electrochemical reducing agents — saturation in liquid media in which the formation of boron atoms spontaneously occurs due to electrochemical mass transfer during the formation of boron subions;

electrolytic–plasma method — boriding in aqueous solutions of boron-containing salts and/or contain boron in colloidal and/or atomic states and/or in the form of compounds, due to the appearance of a spark discharge plasma in a steam jacket at the metal–solution interface when an electric current is passed;

vibration–pseudo-liquid method — saturation in a powder mixture in a pseudo-liquid state obtained either by vibration of the part, or by vibration of the container (furnace, retort, container, *etc.*) with the parts and mixture;

hot boiling — creating a pseudo-liquefied layer by feeding a powder mixture of hot gas medium into the retort from below;

cold boiling — creating a pseudo-liquefied layer by feeding a powder mixture of a cold gas medium into the retort from below, and heating the parts is provided by any known method (radiation, high frequency currents, electro contact, electric spark);

electric spark polarized heating — heating of parts due to spark discharges on the face of the powder mixture and the treated surface when passing a direct current;

nonpolarized electric spark heating — heating of parts due to spark discharges on the face of the powder mixture and the treated surface when alternating current is passed.

The above methods of increasing the wear resistance of cutting tools and machine parts can be used in combination with each other, namely combined hardening treatment. However, only a few of them have found industrial use.

Many well-known methods of processing machine parts and tools have a number of unresolved issues. Firstly, they do not provide a sufficient thickness of the hardened layer; secondly, they are long-term processes and difficult to use, time-consuming, and energy-consuming.

Therefore, it is important to improve the technological processes of processing tools and machine parts by developing new methods of surface hardening, which significantly increase the durability of the working layer and the surface of parts with a significant acceleration and simplification of surface hardening technologies.

3. Objectives of Investigation

The aim of this work is to study the effect of state-of-the-art treatments on the hardening of the surface layer of tools.

To achieve this goal, it was necessary to solve the following two tasks:

(1) to investigate changes in the properties of the surface layer of a carbide cutting tool modified by a pulsed magnetic field (PMF);

(2) to investigate changes in the properties of the surface layer of high-speed steels after boriding in the nanodispersed powder.

4. Material-to-be-Studied, Technological Regimes and Methods

As an object of the study, the plates made of hard alloys T5K10, T15K6 with a size of $15.875 \times 15.875 \times 4.76$ mm, cylindrical samples $\varnothing 12 \times 20$ mm made of W6Mo5Cr4V2 and W18Cr4V alloy steels in the amount of 20 pieces of each alloy were used.

Magnetic processing of hard alloy plates was carried out on the robotic complex of the MPT RC-1 (Ukraine) with the regime parameters: field voltage — $1.1 \cdot 10^5$ A/m; duration of the magnetic pulse treatment — 2 min; holding time after processing — 28 h; pulse frequency — 5 Hz [49].

The hardening treatment of tools was considered when the surface of steel samples was saturated with atomic boron. After annealing, the prepared samples were coated with a layer of nanodisperse powder paste up to 2–3 mm thick, which was dried in a cabinet until the paste was completely dry. The samples with a layer of paste applied were placed in a crucible and filled with a boron-containing mixture. Boriding was carried out at temperatures of 800–1000 °C with an exposure time of 15 minutes to 2 hours.

The microstructure and thickness of the diffusion layers were studied by optical microscopy on a MIM-8 microscope (RF) using a standard technique at various magnifications [50]. To measure microhardness, a PMT-3 hardness tester (RF) was used at a load of 50 g and 100 g at an exposure time of 7–15 s.

For the study of steels and alloys, diffractograms were taken on a general-purpose x-ray diffractometer DRON-3M (RF). The survey for steels was carried out in x-ray chromium radiation, and for hard alloys, copper radiation was used.

Wear tests were carried out on the machine AR 40.613.20 r 43/82 (RF). The degree of wear was determined by monitoring the weight loss of the test sample.

5. Obtained Experimental Results and Their Analysis

5.1. Magnetic Pulse Treatment (MPT) Effects on the Reliability of the Hard-Alloys-Based Cutting Tools

In connection with the intensification of production, one of the most acute problems arose in the development and application of more effective methods of hardening metalworking tools [51, 52]. Treatment with a pulsed magnetic field [53, 54] is based on the fact that the vortex magnetic field interacts with the hard alloy plate, improving the structure and properties of the latter. With this hardening, the tool is placed in the inductor, so that the centre of gravity is shifted relative to the geometric centre of the solenoid. Due to this, when the device is turned on, the tool is drawn by the field into the solenoid with acceleration and performs damped vibrations relative to its geometric centre, the amplitude of which decreases over time under the action of the friction force and is zero.

Due to the inhomogeneity of the crystal structure of the material, eddy currents are generated. In this case, the heat released is dispersed over the volume of the tool in such a way that the gradient of the thermal field is higher, the more complex and inhomogeneous the microstructure of the alloy. In places of structural heterogeneity as well as stress concentration, induced heat occurs, which increases the local temperature of overstressed areas tenfold. As a result, the tool is subjected to ‘screw compression’, in which electrodynamic forces condense and arrange the crystals of the structure, thereby reducing their internal overvoltage.

The use of magnetic fields in the processes of cutting and hardening of cutting tools is a promising direction for the development of high technologies in mechanical processing. An increase in tool life can be achieved due to the influence of a magnetic field either on the conditions of the cutting process, or on the structure and physical and mechanical properties of tool materials with ferromagnetic components. Accordingly, there are two areas of application of magnetic fields in mechanical processing. The first of them provides for an increase in tool durability when cutting in a magnetic field. The second involves increasing the resistance characteristics of the cutting tool after processing in constant, variable and pulsed magnetic fields due to changes in the structure and physical and mechanical properties of the tool material. Different researchers explain the increase in the tool durability period at the cutting in a magnetic field by removing heat from the tool due to the manifestation of the thermomagnetic Righi–Leduc effect, increasing the mechanical properties of the tool material due to the ordering of its grain size, the appearance of a force that causes bending of the chip root, reducing the chip contact area with the tool, changing the shear angle and reducing cutting performance. The effect of increasing the resistance period at the cutting in a magnetic field depends on the direction of the magnetic flux, the magnitude of the magnetic induction and cutting modes. The influence of an external magnetic field on the conditions of the cutting process allows, in addition to increasing the tool stability period, to increase the optimal cutting speed, reduce the optimal surface wear [53], and improve the quality of the treated surface.

On the other hand, as shown in Refs. [54–57], the tool that has been subjected to magnetic processing possesses an increased period of resistance even in the absence of an external magnetic field in the cutting zone. In this case, the increase in tool life is due only to changes in the structure and physical and mechanical properties of the tool material after magnetic processing. The literature provides different information about the increase in the durability period of the cutting tool as a result of magnetic processing and its causes. The increase in the resistance of high-speed steel cutters and drills after processing in constant and alternating magnetic fields is explained by the decay of residual austenite in the surface, secondary hardened steel layer formed because of tool sharpening [58–62]. The effect of increasing the durability period of a high-speed tool after processing in constant magnetic fields is associated with the polarity of its working part after magnetization. Increasing the stability period of the steel tool when processing with a static magnetic field or with a single field effect, or with the movement of the hardened tool in a magnetic field. Reduction of wear of tool steels because of remagnetization by relatively weak fields is explained in terms of changes in the structure and properties of the steel surface due to the diffusion of tungsten atoms and other elements into it from the internal volumes of the material after exposure to the field.

The most promising direction of using magnetic fields to increase the lifespan of cutting tools made of materials containing ferromagnetic components is the processing pulsed magnetic field. It allows obtaining the most stable tool life increase due to the change of physical–mechanical properties of the tool material, which is achieved because of implementation of the complex structural changes that have the magnetostrictive nature. The pulsed nature of the magnetic field in the MPT makes it easy to carry out an intense energy effect on the material using electromagnetic waves [49].

A kind of pulsed electromagnetic shaking of condensed systems with many real defects accelerates the rate of relaxation and structural adjustment in them. The selection of a pulsed magnetic field also made it possible to simplify the requirements for power sources and make the installations compact and portable. At the same time, the equipment for MPT can be installed in the machine shops of the enterprise, and the parameters of the processing modes (regimes) vary depending on the tool material in order to optimize the characteristics of the plate [63].

The change in the properties of ferromagnets after MPT is achieved due to the directed orientation of the free electrons of the substance by an external field, which results in physical prerequisites for changes in the structure and stress state of the material [64]. In the case of IMS (IP Multimedia Subsystem), a complex effect of magnetostrictive processes and mechanical deformations, thermal and electromagnetic vortex flows localized in the places of magnetic flux concentration and processes that directionally orient the spin characteristics of external electrons of atoms in the boundary zone of grain contact is realised on the material. The MPT is a combination of electromagnetic and thermodynamic methods for controlling the nonequilibrium structure of matter.

Changes in the structure of the material because of MPT can be carried out due to the force (magnetostrictive) or thermal factor. Structural changes in the material occur because of activation of dislocation or diffusion processes [65].

In the MPT of high-speed steels, the elastic field caused by magnetostrictive deformation interacts with the elastic field of the material's own real dislocation structure [62–67].

This interaction leads to the appearance of local overvoltages, in the locations of which the probability of thermal fluctuation of interatomic stress bonds increases sharply. In those places where local overvoltages exceed the elastic limit of the material, foci of plastic deformation are formed and the processes of reproduction and displacement of dislocations are intensified. With an increase in the dislocation density, the steel acquires a peculiar slope, which manifests itself in a change in the crystal-lattice parameters of martensitic systems (including nitrous martensite [68, 69]).

The increase in the mechanical characteristics of steel because of the MPT is due to the release of fine carbide particles from the metal matrix because of magnetic dispersion hardening due to the above-mentioned structural processes.

The influence of the magnetic field strength on the stability of the cutting tool and the physical–mechanical characteristics of the tool materials after MPT was noted in Ref. [49]. There is a narrow range of values of the strength of the pulsed magnetic field, processing in which improves the cutting properties of the tool. It was noted the extreme nature of dependence of physical and mechanical properties of the tool material, the wear of high-speed steels and tool on the magnetic field with the presence of a certain optimum intensity of magnetic field, which provides high hardness steel, tool life and minimum wear of steel. This confirms the theoretical statement [56] the existence for each material a certain value of the magnetic field (and hence magnetic energy) that is absorbed by the material during the time of magnetic treatment and maximizes its mechanical properties.

As the MPT duration increases to a certain limit, tool stability and physical and mechanical properties of steel increase [49]. To complete the conversion of electromagnetic energy into the energy of internal transformations in the material and to stabilize the new structure and properties acquired by the material after the MPT, it is necessary to hold the tool for a certain time at least the stabilization time. During this time, the physical and mechanical properties of the material change, which has the character of damped oscillations, which is a manifestation of the general nature of long-term relaxation of the physical parameters of condensed media after the influence of a magnetic field [57]. The influence of the magnetic state and polarity of the working part of the tool on its stability is not significant.

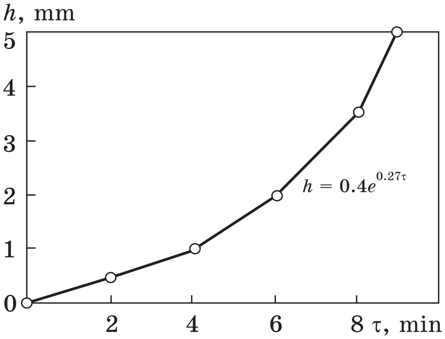
The influence of pulsed magnetic field processing on the stability of the cutting properties of the plates is evaluated. They are made of hard alloys on the example of the T5K10 alloy. The change in its microhardness before and after processing is analysed. The distribution of microhardness on the surface of the hard alloy under study is analysed. It was found that, after a pulsed magnetic field, its numerical value increases on average from 16.1 to 16.9 GPa. Besides, the coefficient of variation of microhardness values decreases from 0.13 to 0.07. A significance of differences in the mean values of the coefficient of variation was verified by the criterion described in Ref. [70].

The structures and components of the components of hard alloys in the initial state and after treatment with a pulsed magnetic field by x-ray diffraction analysis were studied. Studies have shown changes in the parameters of the crystal lattices Co and TiC after treatment. It is noted that the lines (100) Co and (220) TiC are shifted towards large angles. This indicates a decrease in the lattice parameter and distortion. This one also confirms the presence of compression deformation of the cobalt phase of the hard alloy. In addition, it indicates an increase in its strength. The propagation of a destructive crack in the VK (W–Co-based) and TTK (Ti–Ta–Co-based) hard alloys occurs almost along the binding cobalt phase. The cobalt phase of hard alloys is a solid solution of tungsten and carbon in a cubic cobalt lattice. In the TK type (Ti–Co-based) alloys, the fracture crack propagates mainly along the (Ti, W)C phase, while the cobalt component can inhibit the crack propagation. Treatment with a pulsed magnetic field leads to the rearrangement of atoms, and under the influence of a magnetic field, the properties of the cobalt phase change.

Under the influence of a pulsed magnetic field, the cobalt phase is homogenised, which leads to an increase in the stability of the cutting properties of the alloy. it was also noted that previbroabrasive treatment before a pulsed magnetic field increases the intensity of the stress transition in the cobalt phase from tensile to compressive, which leads to an increase in the strength and stability of the cutting properties of the tool [49].

Studies of the wear resistance of carbide cutting tools were carried out with the following initial data: tool material — T5K10; processed material — steel 45; processed surface — casting crust; cutting speed — 98 m/min; feed — 0.58 mm/rev; cutting depth — 2.0 mm.

Studies have shown that the kinetics of the main stage of wear during pretreatment is represented by an accelerated development of wear. Acceleration is observed, followed by deceleration of wear and delayed wear. The accelerated development of wear was characteristic of the T5K10 hard alloy cutters without MPT (Fig. 1). The predominant character of wear in this case is the brittle destruction of the cutting part of the tool. This is manifested in the separation of small particles of the cutting edge, which is largely due to surface defects of the tool material. Separation of material particles mainly occurs on the front surface,



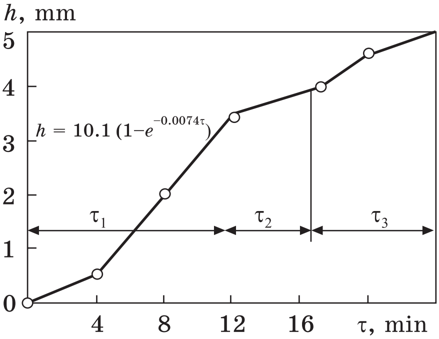


Fig. 1. Accelerated wear of the tool without magnetic pulsed treatment (MPT) [49]

Fig. 2. Change in tool wear after MPT hardening [49]

commensurate with the length of the chip contact with the front surface, and (in width) commensurate with the width of the cut layer.

At the hardening by the pulsed magnetic field, at the beginning of the running time τ_1, there is a typical increase of wear rate, and then slowing down on the second linear section τ_2, then τ_3, *etc.* (Fig. 2). Reducing the running time of the tool is due to increase in its strength and abrasive wear resistance.

Compared to untreated cutting tools, which were equipped with T15K6 hard alloy plates, the MPI-processing improves the tool life more than 200%. Such wear of the plates was characterised by the absence of plastic changes in the shape of the cutting part and the absence of cracking. Since after treatment with a pulsed magnetic field of carbide cutting plates, the stress balance in the cobalt phase is stabilised, this prevents the crack propagation and increases the strength of the product.

5.2. Formation of the Surface Layer after Boriding the Steel Tools

According to the properties and intended purpose, we can divide the boriding into the high-temperature, medium-temperature, and low-temperature ones to obtain boron layers of various structures that provide the necessary properties of the surface layers of the product. The structural features of boron layers, which are formed because of diffusion processes, determine the properties of the surface layers of tools.

The solubility of boron in iron is low. At a temperature of 1000 °C, it does not exceed 0.008%. In the process of saturation of steel with boron more than this limit, the chemical compounds of boron with iron are formed: borides FeB and Fe_2B. When a boride layer is formed, individual needle-like crystals of Fe_2B borides grow from the surface to the depth of the metal. Gradually, these crystals are combined into a solid layer, the hardness of which is 16–18 GPa. As boron is further satu-

Fig. 3. Microstructure of W6Mo5Cr4V2 steel after boriding at 1000 °C for 2 hours (×200)

Fig. 4. Microstructure of W18Cr4V steel after boriding at 1000 °C for 2 hours (×200)

rated, another layer of borides FeB is formed on the surface. Its hardness reaches 21–23 GPa. Despite their very high hardness, borides are less brittle than carbides and nitrides. A characteristic phenomenon during boriding is the formation of a zone with a high content of carbon and alloying elements under the boride layer. Boron, which penetrates the surface, pushes the carbon deep into the metal. In addition, during the formation of the boride layer, the alloying elements are redistributed both between the boride phases and between the boride layer and the transition zone. Thus, the two-phase layer consists of two zones: the boride zone and the transition zone — the zone of solid boron solution in iron. Borides have a characteristic needle-like structure. Boride FeB is located in the upper layer, and boride Fe_2B is under it. Borated layers, which are formed because of diffusion processes, determine the properties of the surface layers of the product.

Thus, the structure formation of borated layers begins already in the process of heating the part. When the surface temperature reaches a certain value, the nucleation of boride crystallites occurs. They grow perpendicular to the surface during the aging process and their growth ends with the cooling stage [1, 71]. Therefore, a more detailed study of the influence of these stages on the structure and properties of borated layers is relevant in order to obtain the necessary strength characteristics of the surface. When borating alloyed steels directly under the boride layer because of the redistribution of alloying elements, a zone is formed in which their content is first increased, and then decreases. The nature of the redistribution of elements depends on the degree of alloying of steel, carbon content and processing conditions [71].

For high-speed steels P18 and P6M5, the boron temperature was 1000 °C. Studying the microstructure in the cross-section of the samples, we see for these steels the characteristic presence of a continuous boride layer and separate rounded sections of borides under it (Fig. 3

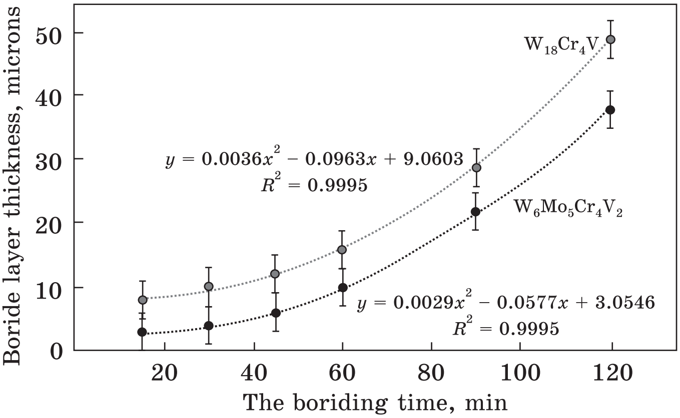


Fig. 5. Dependence of the boride layer thickness on the boriding time at a temperature of 1000 °C

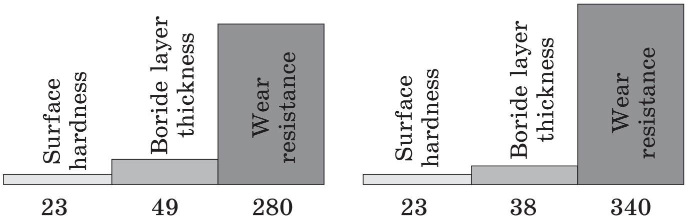


Fig. 6. Expert estimates of the maximum values of the surface properties of W18Cr4V (left) and W6Mo5Cr4V2 (right) high-speed steels

and 4). This is due to the inhibition of boron diffusion by alloying elements, which is confirmed by the layer-by-layer x-ray phase analysis. Studies have shown that borides FeB and Fe_2B are present on the surface, further into the metal from the surface borides of alloying elements Cr_2B, CrB, Cr_3B_4, Mo_2B, Mo_2B_5, MoB_2, W_2B, W_2B_5 and carbides Cr_7C_3, B_4C Fe_3C, VC, WC are formed in the diffusion transition layer. The study of the microhardness distribution from the surface deep into the metal confirms the presence of two borides, namely, FeB with a hardness of 21–23 GPa and Fe_2B with a hardness of 16–18 GPa.

Figure 5 shows the dependence of the boride thickness on the duration of the process of saturation of the surface of high-speed steels with atomic boron, obtained from experimental data.

The graphs show that the thickness of the boride layer for alloy steels increases with the duration of the process, but the rate of its growth depends on the chemical composition of the steel. An increase in the exposure time of CTT leads to an increase in boride layers, which varies by a polynomial of the second degree (the equation in Fig. 5, where y is the layer thickness (μm), x is the boriding duration (min), and R^2 is the approximation confidence value.

Studies have shown that on steel W6Mo5Cr4V2, the boride layer increases from 3–5 μm in 15 minutes to 38–40 μm in 2 hours; and on steel W18Cr4V, borides arise with a thickness of 8–10 μm in 15 min to

48–52 μm in 2 hours. The large depth of the boride layer on W18Cr4V steel is associated with the peculiarities of the formation of the diffusion layer as a whole, which practically does not have a continuous layer of borides. Alloy steel W6Mo5Cr4V2 is characterized by a zone of a solid ‘white layer’ (Fig. 1), which is a solid layer of borides. This feature of the formation of the boride layer is related to the chemical composition of each steel.

The method of expert evaluation (ranking) of the maximum values of surface properties for two steels (Fig. 6) showed that the total value of the properties of W18Cr4V (352) is higher than that of W6Mo5Cr4V2 (401). Thus, an expert assessment of the surface properties of steels showed that it is more rational to use W6Mo5Cr4V2 steel as a cutting tool after hardening the surface layer by boriding in a nanodisperse boron-containing powder.

Evaluation of the abrasive wear resistance of steels without CTT and after boriding according to the developed technologies showed a linear nature of wear of samples. Studies have shown that boriding in a nanodisperse medium can significantly increase the wear resistance of steels, namely, by 3.38–3.75 times compared to steels without chemical and thermal treatment. The wear rate of borated steels W6Mo5Cr4V2 and W18Cr4V decreases by 340% and 280%, respectively, which indicates a significant increase in the wear resistance of high-speed steels after boriding. Increased wear resistance after CTT is due to the formation of a diffusion layer on the surface with FeB and Fe_2B borides and borides of alloying elements. A significant increase in wear resistance after boriding shows the prospects of using this method to improve the performance of cutting tools.

6. Conclusions

After preliminary processing of materials of hard-alloy cutting tools, which are strengthened by a pulsed magnetic field, there is a multiple increment of the tool with several degrees of deceleration and acceleration of the wear process, which justifies an increase in their wear resistance.

For carbide cutting tools hardened by a pulsed magnetic field, at the cutting speeds that correspond to the previous processing, a decrease in the wear rate by 2–2.3 times and an increase in their stability relative to untreated ones by more than 200% is typical. The use of the proposed hardening by a pulsed magnetic field will increase the reliability of the carbide-cutting tool and stabilize its physical and mechanical properties.

Expert evaluation of the surface properties of high-speed steels has shown that it is more rational to use W6Mo5Cr4V2 steel as a cutting tool after hardening the surface layer by boronizing in a nanodisperse boron-containing powder. This will significantly increase the wear resistance of steel, namely, by 3.75 times as compared to steel without chemical and thermal treatment, which shows the prospects of using this method to improve the performance of metal-based products.

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К.О. Костик[1], *В.О. Костик*[2], *В.Д. Ковальов*[2]

[1] Національний технічний університет
«Харківський політехнічний інститут»,
вул. Кирпичова, 2, 61002 Харків, Україна
[2] Донбаська державна машинобудівна академія,
вул. Академічна, 72, 84313 Краматорськ, Україна

ЗМІЦНЕННЯ ПОВЕРХНЕВОГО ШАРУ ІНСТРУМЕНТІВ СУЧАСНИМИ ТЕХНОЛОГІЯМИ

Збільшення терміну експлуатації та зносостійкости інструменту шляхом поверхневого зміцнення є актуальним питанням, вирішення якого сприятиме значному підвищенню працездатности виробів. Наявні способи поверхневого зміцнення інструментів, які ґрунтуються на нанесенні покриттів або зміні стану поверхні, набувають все більшого значення у зв'язку з ускладненням експлуатації виробів. Для дослідження використовували пластини з твердих стопів Т5К10 (85% WC–6% TiC–9% Co) і Т15К6 (79% WC–15% TiC–6% Co), а також циліндричні зразки зі швидкорізальних криць Р6М5 (W6Mo5Cr4V2) і Р18 (W18Cr4V). Дослідження показали, що після оброблення імпульсним магнетним полем пластин зі стопу Т15К6 стійкість різального інструменту поліпшилася на понад 200% порівняно зі стійкістю необробленого. Запропонований спосіб уможливить підвищити міцність твердостопних пластин і стабілізувати фізико-механічні властивості різального інструменту. Зміцнювальне оброблення інструментів з леґованих стопів методою борування в пастах з нанодисперсних порошків показало, що товщина боридного шару для швидкорізальних криць збільшується з тривалістю процесу, одначе швидкість її зростання залежить від складу криці. Збільшення часу витримки хеміко-термічного оброблення приводить до зростання боридних шарів, потовщення яких із часом описано поліномом другого степеня.

Виявлено особливість формування дифузійних шарів, залежність поверхневої твердости та товщини шару боридів від часу борування для швидкорізальних сталей. Дослідження показали, що борування в нанодисперсному середовищі уможливлює значно підвищити зносостійкість криць. Проведені експертні оцінювання максимальних значень поверхневих властивостей для досліджених криць показали, що більш раціонально застосовувати в якості різального інструменту крицю Р6М5 після зміцнення поверхневого шару методою борування в нанодисперсному борвмісному порошку. Запропонована метода оброблення демонструє перспективність використання її для підвищення працездатности виробів і уможливлює значно підвищити зносостійкість матеріялів (у ≈3,38–3,75 разів) порівняно з крицями без оброблення.

Ключові слова: твердий стоп, швидкорізальна криця, поверхневе зміцнення, магнето-імпульсне оброблення, борування, твердість, зносостійкість.