Ministry of Education and Science of Ukraine
Donbass State Engineering Academy

PULSED MAGNETIC FIELD PROCESSING OF THE CEMENTED CARBIDE CUTTING TOOLS

Monograph

Kramatorsk-Ternopil
DSEA
2024

UDC 621. 9.01

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Viktor Kovalov, Yana Vasylchenko, Maksym Shapovalov, Andrey Manokhin. Pulsed Magnetic Field Processing of the Cemented Carbide Cutting Tools: monograph – Kramatorsk-Ternopil, Ukraine : DSEA, 2024. – 78 p.

ISBN 978-617-7889-84-6

The monograph analyzes the current state of the problem of improving the tooling of new machine tools for high-precision productive machining of hard-to-machine materials. The conditions for machining large-sized parts at heavy engineering enterprises, methods for determining the rational parameters of the cutting process on heavy machine tools, and the use of the modern methods of tool hardening are analyzed. Methods for studying the stability of carbide cutting tools that have been treated with a pulsed magnetic field using forced test methods are presented. The influence of pulsed magnetic field treatment on the physical and mechanical factors that determine the cutting ability of hard alloys during pretreatment of products is considered. The results of operational production tests of carbide cutting tools after pulsed magnetic field treatment and the impact on improving the efficiency of the cutting process are presented.

UDC 621.9.01

ISBN 978-617-7889-84-6

CONTENT

INTRODUCTION

To manufacture heavy machinery that is competitive in the global market, the challenge is to improve the strength of the relevant structural materials, the performance and service life of large parts by applying new efficient technologies, equipping machine-building enterprises with modern technological equipment and cutting tools based on the results of research and development. As the industry develops, the requirements for machines are becoming more stringent, as is the accuracy and quality of their manufacture, and the introduction of new durable materials that make it possible to achieve an increased level of performance. An important task is to improve the tooling of new machine tools for high-precision productive machining of hard-to-machine materials by applying the latest tool hardening methods. One of the most promising technologies for improving the strength, service life and performance properties of metal products for various engineering sectors is pulsed electromagnetic field treatment.

This task is particularly relevant for carbide cutting tools. As you know, carbide grades have, on the one hand, high heat resistance, which allows cutting tools to operate at high cutting speeds. On the other hand, hard alloys have low bending strength, which limits their ability to work in preliminary, roughing operations, where the tool is subjected to a shock load generated by the workpiece, which is made by casting or forging, abrasive dust, uneven allowance, etc. Therefore, the study of these issues is an urgent scientific and technical task.

1. THE ANALYSIS OF THE FACTORS LEADING TO THE CUTTING TOOLS DAMAGE WHILE MACHINING ON THE HEAVY MACHINE TOOLS. THE OVERVIEW OF THE PHYSICAL-MECHANICAL METHODS OF THE CUTTING TOOLS IMPROVEMENT AND THE METHOD OF THE PULSED MAGNETIC FIELD PROCESSING (PMFP)

1.1 Working conditions of cutting tools at heavy engineering enterprises

Statistical studies have shown that when machining on heavy machines, the cutting force allowed by the machine mechanisms, torque (Fig. 1.1), are not restricted by cutting conditions and can reach extremely high values. The maximum values of forces up to 10 times exceed their average value, which is usually used to calculate the design parameters of cutting tool.

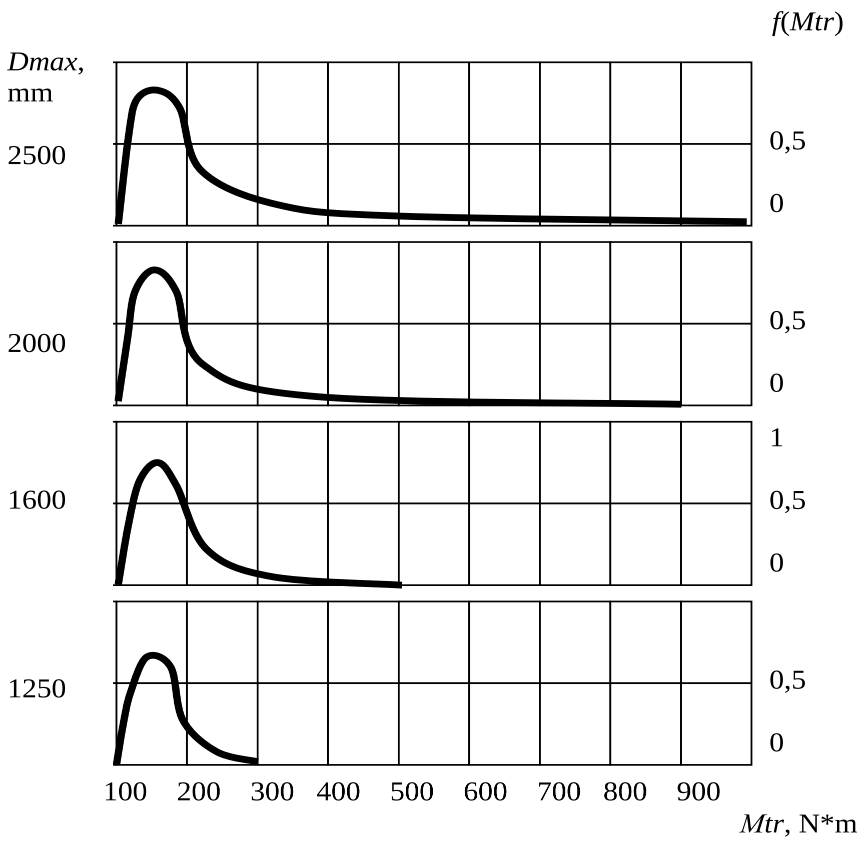


Figure 1.1 - Distributions of torque f (Mtr) values as a function of working part diameter

A significant limitation on the modes of cutting when machining existing structures on heavy machines is the weight of the part, which does not allow in some cases to increase the speed [6; 32].

The efficiency of the cutting tool is also affected by variable loads, the quality of its manufacture, scattering of physical and mechanical properties, etc. Ultimately, the combined effect of many random factors can lead to unforeseen failure due to catastrophic wear or accidental destruction of the tool.

The decrease in the average cutting speed while processing on heavy machines compared to medium and small machines, in addition to the increased cross section, is due to the fact that these speeds require in some cases the use of spindle speed, which is on the verge of power of machines (Fig. 1.2).

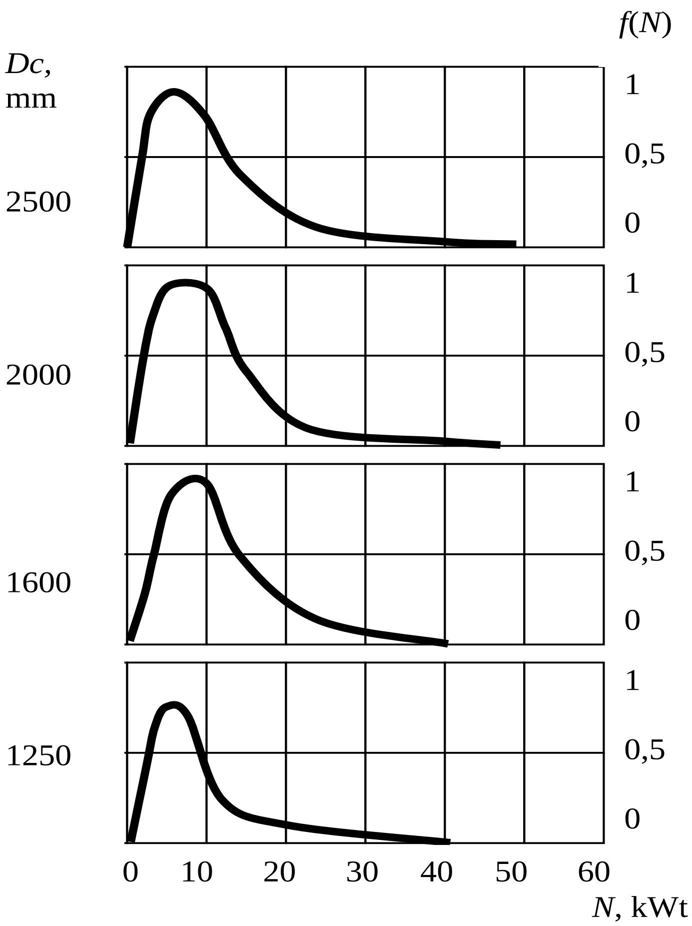


Figure 1.2 - Distributions of cutting power f (N) per carriage of a heavy lathe

Figure 1.3 shows the distribution of the applied speed n of the spindle of heavy lathes. The restriction zone covers a different part of the spindle scattering field for machines with different Dmax values, which is due to the design features of the machines and once again confirms the need to take into account the size of the machine when determining rational operating regulations.

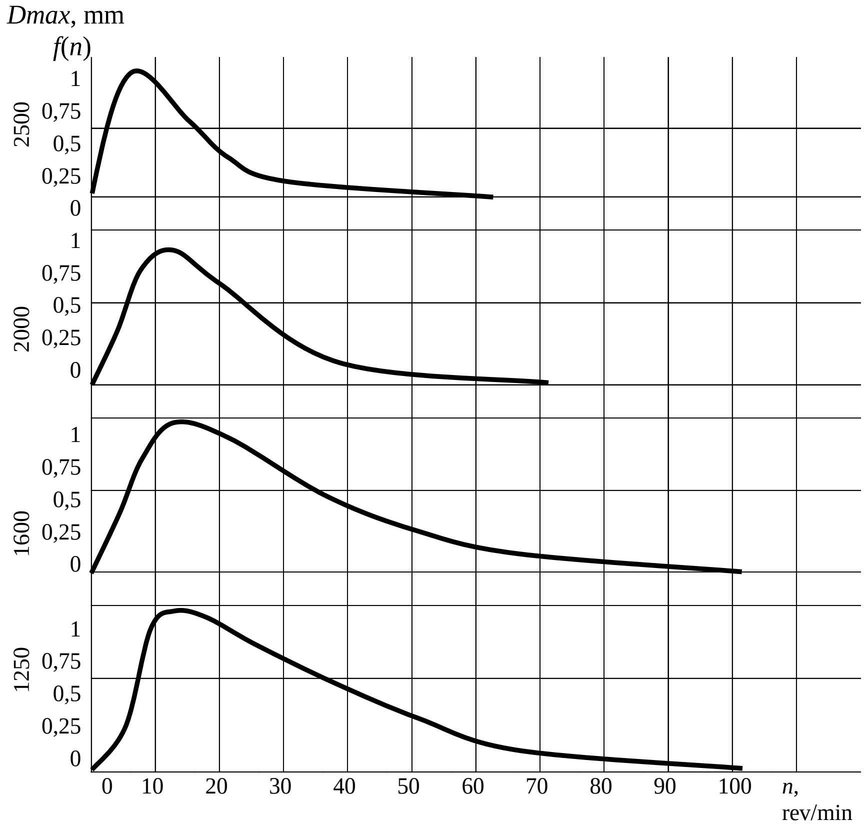


Figure 1.3 - Spindle speed distribution f (n) used on heavy lathes

t

o

o

t

o

h

t

6

m

a

6

a

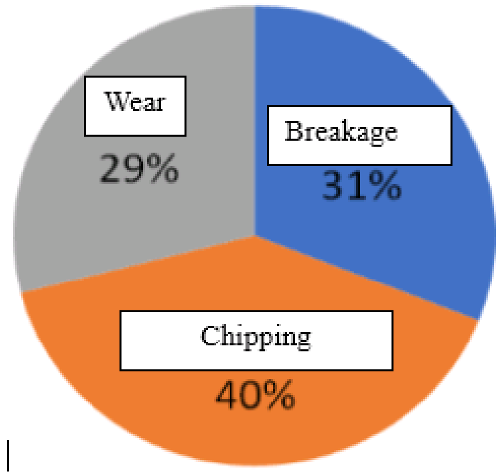


Figure 1.4 - Distribution of failures of cutting tools when turning parts on heavy machines (in general)

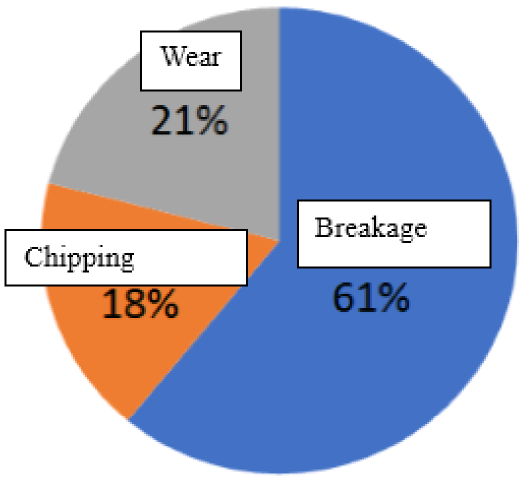


Figure 1.5 - Distribution of failures of cutting tools during machining on heavy machines (pre - processing)

The analysis of tool failures also revealed the heterogeneity of the degree of degradation of different parts of the indexable inserts of turning inserts and milling tools, inherent for heavy machines (Fig. 1.6).

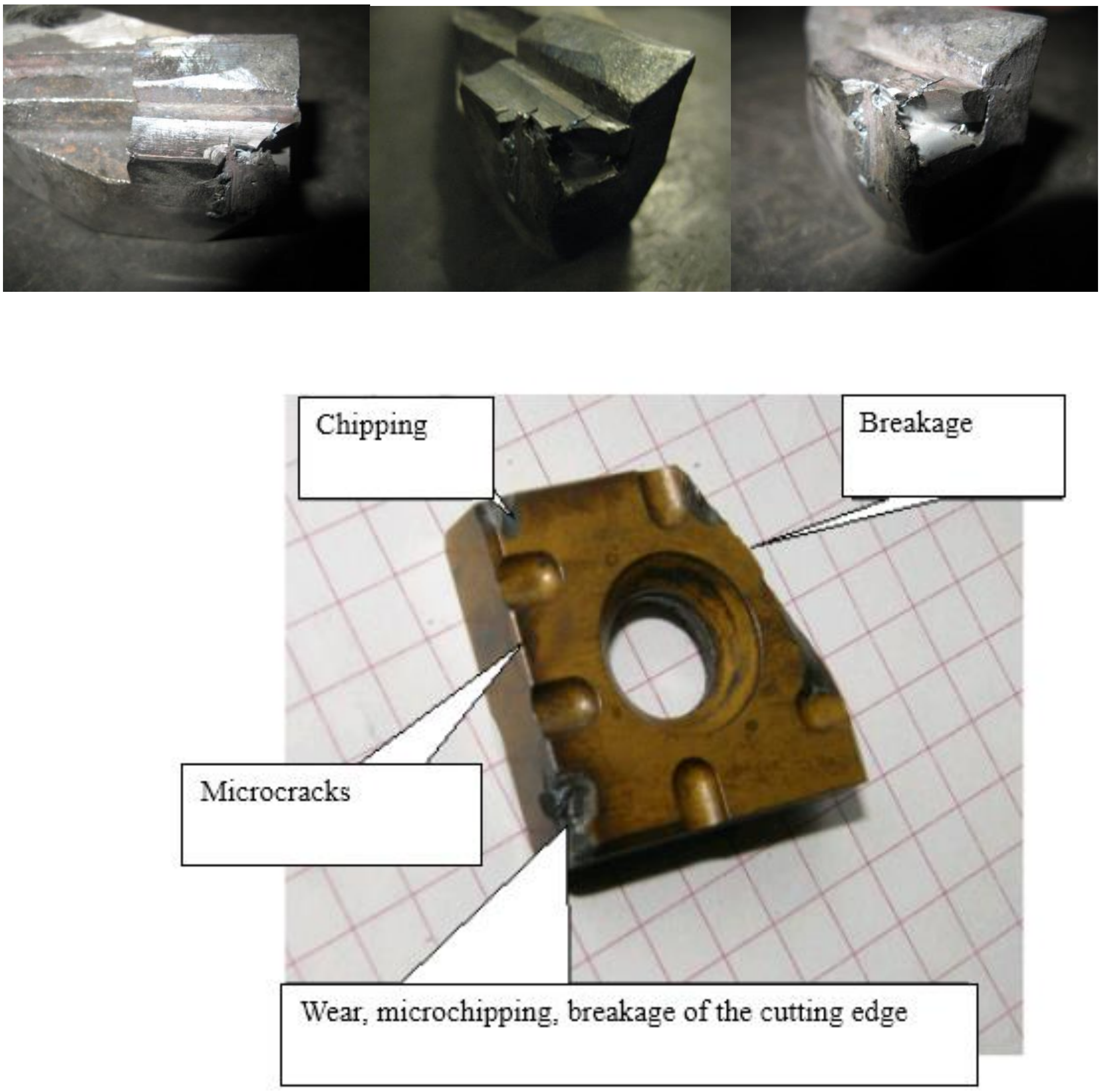


Figure 1.6 - Types of damage and destruction of indexable inserts

Failures, including unforeseen, are due to random fluctuations in the physical and mechanical properties of the material being processed, especially during rough turning in the presence of crusts.

The efficiency of the cutting tool is also affected by the scattering of physical and mechanical properties of the tool material, its defect in the form of agglomerates of carbide grains and pores, which leads to instability of bending strength and hardness of tool cemented carbides.

The destruction of carbide inserts when machining on heavy machines is due to the fact that large values of the undeformed chip thickness cause an increase in the magnitude and distributiob tensile stresses on the front surface of the tool.

The presence of tool failures significantly affects the efficiency of turning large parts, because there is a need to spend unplanned time and money to restore them.

Therefore, the urgent problem is to optimize the technology of materials and elements for extreme conditions in terms of strength and performance. Thus, the direction in solving the problem of extending the life of tools for heavy engineering is to increase surface and bulk strength and also its hardness. Ways to obtain tool materials with a set of characteristics required in the conditions of processing on heavy machines should be considered surface modification technologies that control the defects and strength of the surface layers of tool materials, as well as volumetric modification of cutting tool material.

1.2 Methods of improving the physical and mechanical properties of carbide tool materials

There are ways to improve the physical and mechanical properties of tool materials, although they can increase the wear resistance of the tool, but the costs compared to the efficiency of such methods remain significant, and in many cases uneconomical and impractical due to loss of other valuable properties. Therefore, the development of new advanced methods of strengthening the cutting tool is an important task to increase the service life of metalworking tools.

This task is especially relevant for carbide cutting tools. It is known that cemented carbides have, on the one hand, high heat resistance, which allows cutting tools to work at high cutting speeds. On the other hand, cemented carbides have low strength, which limits their ability to work in previous operations, where the tool has a shock load formed during processing of the workpiece, which is made by casting or forging, abrasive dust, uneven allowance, etc.

The main known methods of increasing the wear resistance and strength of carbide tools can be divided into the following groups: design methods; strengthening by mechanical shot blasting (peening); application of wear-resistant coatings; chemical and thermal processing; laser hardening; plasma arc hardening; radiation strengthening; ionic doping; magnetic abrasive processing, pulsed magnetic field processing.

The choice of a method of hardening depends on many factors that determine its effectiveness and cost of implementation in certain production conditions.

Among the design methods should be noted [14; 17]:

- rounding of cutting edges, which leads to a change in the direction of cutting forces and reduce oscillations;

- increase in the sizes of dangerous section of a indexable inserts or its thickening;

- increasing the stiffness of the support of the cutting insert in the holder, grinding or finishing the supporting surface of the plate, hardening of the holder, reducing the rear corner of the insert;

- application of substrates with high modulus of elasticity and resistance to compression at the temperature arising at a support.

These methods do not lead to an increase in production costs, but their efficiency depends on certain operating conditions (material being processed, cutting mode, characteristics of equipment, devices, etc.).

One of the promising ways to increase the strength of the tool is the processing of working surfaces by plastic deformation (SPD): vibration, shot peening [5; 19; 48; 51].

When processing SPD is applied, a large number of blows are applied on cutting surfaces, resulting in plastic deformation and brittle-abrasive wear of these surfaces. All phase components of the cemented carbide are plastically deformed, but to the greatest extent - tungsten carbide. At the same time, the mosaic blocks are crushed, the microdeformation of the lattice increases and compressive stresses of the order of 100–130 N/m2 occur.

The use of SPD methods in the strengthening of carbide cutting tools allowed to increase the supply by 1.1-1.2 times.

The effectiveness of SPD methods is determined by the dependence of cutting tool strength on geometric parameters, physical and mechanical properties of the material. At SPD there is a rounding of cutting edges that increases durability of the tool.

However, the efficiency of rounding of the cutting edges and the optimal value of the radius of rounding depend primarily on the thickness of the cut layer and the hardness of the material being processed. This limits the application of SPD.

The search for a method of hardening, which combines the ability to achieve optimal rounding of the edges of the cutting tools and the depth of hardening, led to the need to study the effect of fluid on the effect of shot blasting carbide cutters, which proved to be twofold. On the one hand, the fluid reduces the impact energy and, on the other hand, removes wear products. Thus, the intensity of plastic deformation decreases, and the intensity of rounding of the edges changes to a lesser extent, which should lead to a better ratio of the radius of rounding of the edges and the depth of hardening.

The use of liquid in shot blasting increases the maximum radius of curvature by 20 percent. At the moment of reaching the maximum strength, the degree of deformation of the cutters of both types of processing is approximately the same, while the radius of curvature of the cutters, which are treated with liquid, is 10-15 percent higher. This provides an increase in strength by 1.17 times.

Vibration processing is a mechanical process of removing the smallest particles of material from the surface to be machined, as well as smoothing of micro-irregularities by their plastic deformation by the working elements of the abrasive filler, which performs oscillating movements [19].

Improving the performance of carbide tools as a result of its vibration processing is achieved due to the fact that the latter provides rounding of cutting edges and other surfaces of the cutting part, a favorable change in physical and mechanical properties of the surface layer of the cemented carbide. As a result of research it was proved that about 60-70 percent of the effect when vibrating the tool is achieved by rounding the edges and 30-40 percent - by reducing the roughness and changing the properties of the surface layer. Vibration processing is very time consuming and therefore requires significant costs.

Shock wave energy [20; 64; 94] has found application in the processing of metal-ceramic alloys to increase their strength and stability.

The cutting insert made of VK8 alloy was placed in a lead container, the choice of which as a pulse "trap" was due to the relative equality of the acoustic stiffness of the alloy VK8 and lead. The formation of a flat detonation front was performed by a plane-wave generator. The "running" on the surface of the detonation front, forms an oblique shock wave in the material, the intensity of which decreases as it passes - deep into the environment. With such a spread of the impact front in the material, favorable shear conditions are created in terms of thermodynamics, which lead to a marked strengthening of compact materials and inevitably cause the destruction of fragile media. This fracture accounted for 60 percent of the volume of the cemented carbide. The conditions for the complete preservation of the plate were achieved by means of the experimentally found law of attenuation of plane shock waves in copper.

Studies of the microstructure showed significant grinding of tungsten carbide grains and refinement of the cobalt bond due to its deformation, which led to an increase in microhardness by 1.4 times. As a result of tests, it was found that the tool life increased by 2 times. This is due to the grinding of tungsten carbides, the strengthening of the cobalt bond and the appearance of compressed stresses on the surface of the plate.

Applying a hard coating [1; 16; 41; 48; 62; 66], resistant to abrasion, on carbide inserts can increase the durability of cutting edges several times compared to conventional inserts or at the same durability to increase the cutting speed.

Titanium carbide (TiC) coated plates with a thickness of 5–6 μm have a typical disadvantage: the presence of a decarburized brittle layer between the coating and the substrate. As a result, they could be used only for continuous cutting.

Coated cutting inserts did not have this disadvantage due to the advanced manufacturing technology. The coating thickness of these inserts was increased to 7–8 μm, and special grades of cemented carbide were used as a basis. This allowed the use of inserts for interrupted cutting.

Inserts having a coating thickness of up to 10 μm consist of 2 or more thin layers of different composition. Titanium carbide (TiC) is most often applied to the base, and titanium nitride (TiN) or alumina (Al2O3) is applied to it. The use of inserts with a multilayer coating [2] allowed to increase the productivity of processing by 1.5 times compared to inserts with a single layer coating (TiC).

However, coated inserts have a number of disadvantages. When regrinding, all advantages over uncoated inserts are nullified. They should not be used where a very sharp cutting edge is required, as the cutting edges are always inevitably rounded when applied. They are not very suitable for light metals, wood and other materials with low hardness. Unsuitable coated inserts in cases where the viscosity of their base metal is insufficient for the selected machining operation.

One of the ways to increase the stability of the carbide tool [48; 55; 73; 80; 92] is the heat processing of the cutting plate. The greatest effect when using this method is achieved by heat processing in a gaseous medium: N2 (40-60%), CO (15-20%), H2 (30-35%)

Titanium nitride (TiN) is formed on the surface of carbide inserts, which has sufficient thermal conductivity, resistance to oxidation at high temperatures, relatively low brittleness and high abrasion resistance.

Laser processing helps to grind and saturate the dislocations of the structure of the surface layer of the tool material, which leads to increased hardness and, consequently, a significant increase in wear resistance of the tool. Laser surface hardening is characterized by maintaining the original purity of the upper layer of the product and ensures the locality of the process [48; 50; 65; 67; 77; 83; 86; 97]. But the technological process of surface beam processing is complex, depends on a number of conventions, requires (when irradiating a multi-blade tool) significant energy costs and time-consuming.

Note the main disadvantages of surface laser hardening:

- hardening is carried out only at the junction of the working surface to the cutting edge;
- simultaneous strengthening of both surfaces (front and rear) is unacceptable;
- the cutting edge after laser heat processing is weakened against the action of brittle fracture forces;
- the process is long in time (when strengthening the multi-blade tool) and requires significant energy costs;
- when regrinding the tool, the established layer is removed.

Ion implantation method [45; 48; 81; 95; 96] is used to change the mechanical properties of various metals. The method consists in implantation of ions of a number of elements (N^+, B^+, In^+, (Ti + N), (Ti + B)) on the surface of carbide inserts and allows to apply multilayer coatings [2]. Experiments have shown that the tool life of cemented carbide inserts with a multilayer coating increases by 1.4-1.8 times.

One of the promising methods of finishing polishing and hardening processing of the tool is the method of magnetic abrasive processing (MAP), when a comprehensive impact on the processed surface and the surface layer of parts is carried out. The analysis of MAP interaction conditions in the conditions of large magnetic slits is first of all processing at active frictional-shock interaction of the processed surface with the magnetic-abrasive tool (MAT) formed in the course of processing [38; 100]. In the implementation of the processes of predominant microcutting or microplastic deformation of the treated surfaces, a significant factor is the size, geometric characteristics and shape of the particles of magnetically abrasive powder materials. It is shown that MAP of drills after their regrinding with the use of round equilibrium powders provides opportunities to strengthen the surface layer, reduce the roughness of the working surfaces of the tool and increase their stability by more than 1.7 times.

However, due to the intensification of production, one of the most acute problems in the development and application of more effective methods of strengthening metalworking tools.

Pulsed magnetic field processing [34; 48; 57; 58; 82; 101] is based on the fact that the vortex magnetic field interacts with the carbide insert, improves the structure and properties of the latter. With this hardening, the tool is placed in the inductor so that the center of gravity is shifted relative to the geometric center 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 relative to its geometric center damped oscillations, the amplitude of which decreases over time under the action of friction and is zero.

Due to the heterogeneity of the crystal structure of the material, eddy currents are generated. In this case, the heat released is dissipated over the volume of the tool so that the thermal field gradient is higher, the more complex and heterogeneous the microstructure of the alloy. In places of structural inhomogeneity, as well as the concentration of stresses there is a reduced heat, which increases tenfold the local temperature of overstressed areas. As a result, the tool is subjected to "screw compression", in which electrodynamic forces compact and order the crystals of the structure, thereby reducing their internal overvoltage.

The use of magnetic fields in the processes of cutting and strengthening the cutting tool is a promising direction in the development of high technology in machining. Increasing the stability of the tool can be achieved due to the influence of the magnetic field or the conditions of the cutting process, or the structure and physical and mechanical properties of tool materials with ferromagnetic components. Accordingly, there are two directions of application of magnetic fields in machining. The first involves increasing the stability of the tool when cutting in a magnetic field, the second involves increasing the stability characteristics of the cutting tool after processing in constant, variable and pulsed magnetic fields due to changes in structure and physical and mechanical properties of tool material. Various researchers explain the increase in the period of tool life during cutting in a magnetic field by the removal of heat from the tool due to the manifestation of the thermomagnetic effect of Riga - Ledyuk, increasing the mechanical properties of the tool material due to the ordering of its grain size [26], the emergence of forces that cause bending of the chip roots, reducing the area of contact of the chips with the tool, changing the shear angle and reducing cutting forces. The effect of increasing the period of resistance to cutting in a magnetic field depends on the direction of magnetic flux, the magnitude of the magnetic induction [25] and cutting modes. The influence of the external magnetic field on the conditions of the cutting process allows, in addition to increasing the tool life of the tool, to increase the optimal cutting speed, reduce the optimal surface wear [25; 58; 82], to improve the quality of the treated surface [24; 28].

On the other hand, in the works [22; 26; 27 et al.] it is shown that the tool, which is subjected to magnetic processing, has an increased tool life and in the absence of an external magnetic field in the cutting zone. In this case, the increase in the 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 various information about the increase in the tool life of the cutting tool as a result of magnetic processing and its causes. The increase in the stability of cutting tools and drills made of high-speed steels after processing in constant and alternating magnetic fields is explained by the decay of residual austenite in the surface, re-hardened layer of steel formed by sharpening the tool [58; 63; 75]. In the works [24; 27] the effect of increasing the tool life of the high-speed tool after processing in constant magnetic fields is associated with the polarity of its working part after magnetization. In the works [4; 26; 27] the increase of the tool life of the steel tool at processing by a static magnetic field or with one-time influence of the field, or with the movement of the tool which is strengthened, in a magnetic field is specified. In [3] the reduction of wear of tool steels as a result of remagnetization by relatively weak fields is noted, which is explained by the authors in terms of changes in structure and properties of steel surface due to diffusion of tungsten atoms and other elements from internal volumes of material after field exposure.

The most promising direction of using magnetic fields to increase the tool life of the cutting tool from materials containing ferromagnetic components is pulsed magnetic field processing (PMFP), which allows to obtain the most stable increase in tool life by changing the physical and mechanical properties of tool material.The pulsed nature of the magnetic field in PMFP allows you to easily make an intense energy impact on the material with the help of electromagnetic waves. A kind of pulsed electromagnetic shaking of condensed systems with many real defects accelerates the rate of relaxation and structural adjustment in them. The choice of a pulsed magnetic field has also simplified the requirements for power supplies and made installations compact and portable. In this case, the equipment for PMFP can be installed in the mechanical shops of the enterprise, and the parameters of the processing modes vary depending on the tool material in order to optimize the characteristics of the plate [18; 44].

The physical foundations of PMFP in relation to the tool of high-speed steels were formulated by S.M. Postnikov and representatives of his scientific school. The basis of the theory of PMFP processes is the fundamental principles of the physics of magnetism.

The change in the properties of ferromagnets after PMFP is achieved due to the directed orientation of the free electrons of matter by the external field, as a result of which there are physical preconditions for changes in the structure and stress state of the material. Based on the works [47; 48] it can be argued that the PMFP has a complex effect on the material of magnetostrictive processes and mechanical deformations caused by them, thermal and electromagnetic vortex fluxes localized in places of magnetic flux concentration and directionally oriented processes, spin characteristics of outer electrons of boundary zone atoms. PMFP is a combination of electromagnetic and thermodynamic methods of controlling the imbalance structure of material. Changes in the structure of the material as a result of PMFP can be due to force (magnetostrictive) or thermal factor. Structural changes in the material occur as a result of activation of dislocation or diffusion processes.

According to S.M. Postnikov, at the PMFP of high-speed steels there is an interaction of the elastic field caused by magnetostrictive deformation with the elastic field of the material's own real dislocation structure. This interaction leads to the appearance of local overvoltages, in the locations of which the probability of thermofluctuation rupture of interatomic stress bonds increases sharply. In those places where local overstrains exceed the limits of elasticity of the material, sources of plastic deformation are formed and the processes of reproduction and displacement of dislocations are intensified. With increasing dislocation density, the steel acquires a kind of slander, which is expressed in changes in the parameter of the crystal lattices of martensite. The increase in the mechanical characteristics of high-speed steel as a result of PMFP is due to the release from the metal matrix of fine carbide particles as a result of magnetic dispersion hardening due to the above structural processes. It is Postnikov's concept of magnetostrictive hardening and magnetically dispersion hardening of high-speed steels that is the only integral scientific theory of the PMFP of a cutting tool.

The results of studies of the influence of PMFP on the tool life of the cutting tool and the physical and mechanical properties of tool materials are presented in [34 – 36; 46, etc.].

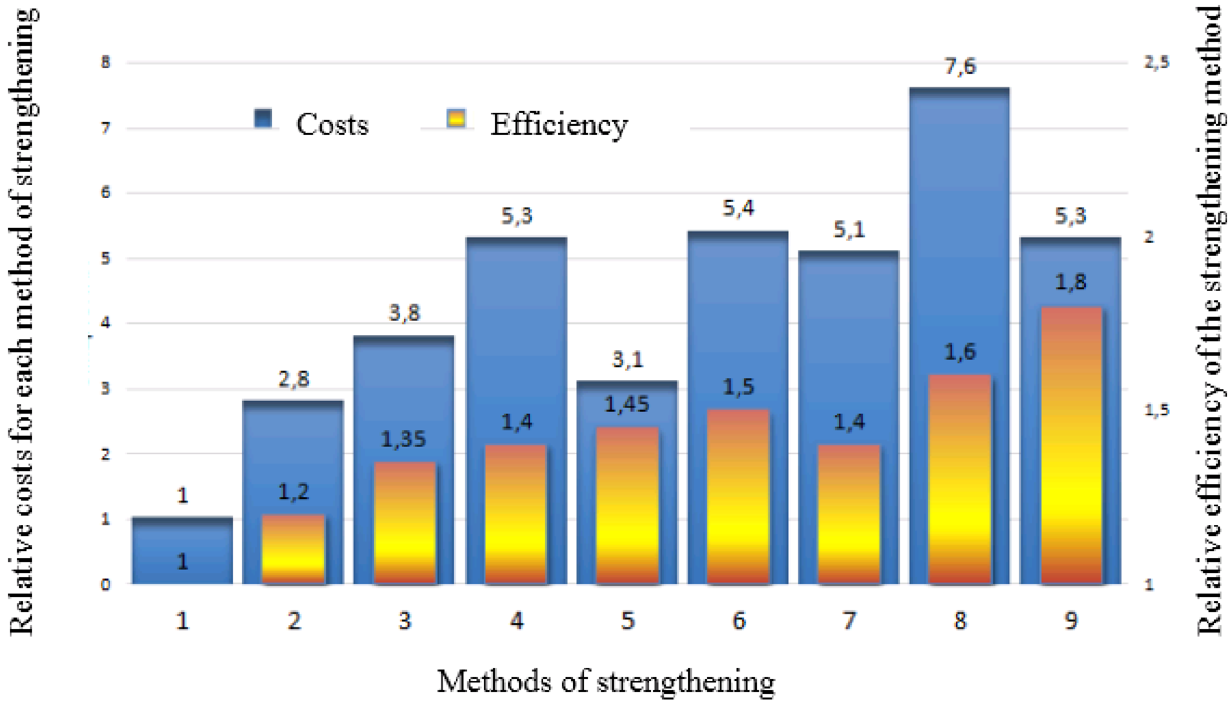
The magnitude of the effect of increasing the mechanical properties of the tool material, as well as the magnitude of the effect of increasing the tool life of the cutting tool, depends on PMFP modes (pulsed magnetic field strength, PMFP duration, exposure time after PMFP), with magnetic field strength.

The influence of magnetic field strength on the tool life of the cutting tool and the physical and mechanical characteristics of tool materials after PMFP noted in [36]. There is a rather narrow range of values of the pulsed magnetic field strength, the processing of which improves the cutting properties of the tool. The extreme nature of the dependence of physical and mechanical properties of tool material, wear of high-speed steels and resistance of cutting tools on magnetic field strength with a certain optimum magnetic field strength, which provides maximum steel hardness, tool life and minimum steel wear. This confirms the theoretical statement of B.V. Maligin [39] on the existence for each material of a certain value of the magnetic field strength (and hence the value of magnetic energy), which is absorbed by the material during the time of magnetic processing and maximizes its mechanical properties.

As the duration of the PMFP increases to a certain extent, the stability of the tool and the physical and mechanical properties of steel increase [34]. To complete the conversion of electromagnetic energy into energy of internal transformations in the material and stabilize the new structure and properties acquired by the material after PMFP, the tool must be kept for a certain time not less than the stabilization time t_{st}, which changes physical and mechanical properties of the material. And in its turn this is a manifestation of the general nature of long-term relaxations of physical parameters of condensed media after exposure to magnetic fields [26; 68; 70; 85]. The influence of the magnetic state and polarity of the working part of the tool on its stability is not significant [23].

The question of the influence of cutting modes on the stability of the tool subjected to PMFP or which is in the external magnetic field. In addition to increasing the length of the cutting path, there is an increase in the optimal cutting speed as a result of PMFP.

As can be seen from Figure 1.9, the best combination of cost and production efficiency is observed in the method of pulse magnetic field processing. The high efficiency is due to the volumetric nature of the hardening, as a result of which the increase in stability persists after regrinding. For other post-regrinding methods, reinforcement must be repeated to increase stability.



1 - constructive methods; 2 - strengthening by mechanical blasting; 3 - application of wear-resistant coatings; 4 - pulsed laser processing; 5 - plasma arc hardening; 6 - radiation hardening; 7 - ionic doping; 8 - surface laser hardening; 9 - pulsed magnetic field processing.

Figure 1.9 - Dependence of costs and production efficiency on methods of strengthening cutting tools from a cemented carbide VK6

2. DEVELOPMENT OF THE METHODS OF THE RESEARCH: WAYS OF ESTIMATION OF PMFP IMPACT ON THE STRENGTH AND WEAR RESISTANCE OF THE CUTTING TOOLS.

2.1 Experimental setup

At the Department of Computerized Mechatronic Systems, Instruments and Technologies of Donbas State Machine-Building Academy, pulsed magnetic field (PMFP) processing of carbide cutting inserts is carried out at an installation consisting of a pulse generator, power supply and inductor.

For processing of small parts the inductor is established on a horizontal dielectric diamagnetic surface (plastic, a tree, rubber, etc.), the axis of the inductor has to be vertical. The products are placed in the middle of the inductor and a processing session lasting 120 s is carried out.

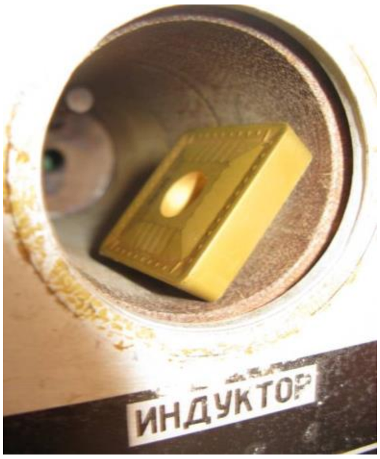
Technical characteristics of the generator and inductors are given in table. 2.1–2.2. The technological parameter of the unit control is the operating voltage of the installation (capacitor discharge voltage, magnetic field pulse generation circuits), displayed on the front panel of the generator unit (Fig. 2.1, a).

Various designs of the magnetic inductor are developed for realization of processing (fig. 2.1, b). The analysis of the geometry of solenoids for magnetic inductors in terms of their optimality and ability to provide the required values of magnetic field strength and pulse frequency. As the length of the solenoid increases, there is a weakening of the magnetic field in the working gap.

Table2.1 - Brief technical characteristics of the complex for PMFP

Complex parameter	Parameter value
Magnetic field strength range, A/m	0.2·105–2.2·105
Operating voltage	100–900V
Inductor inductance	225 μH
Pulse frequency, Hz	1–10
Impulse time, ms	60

A)



B)

C)

a - generator unit b, c - design of the magnetic inductor

Figure 2.1 – Experimental setup for generating a pulsed magnetic field

The magnetic field strength in the center of the inductor is determined by the formula:

$$H = \mu_0 I_0 \frac{W}{l}, \quad (1.8)$$

where I is the current in turn, A;

L - inductance, H;

W - number of turns;

l is the length of the winding, mm;

$\mu 0$ is the magnetic constant (for vacuum $\mu 0 = 4\pi \cdot 10^{-7}$ H/m).

Table 2.2 - Brief technical characteristics of inductors

Inductance, μH		
Internal diameter of the inductor, mm		

2.2 Methods of laboratory research

For preliminary assessment of the effect of pulsed magnetic field processing on the wear resistance of carbide tools, express test methods were used. Unlike full durability tests, express tests reduce test time, tool costs, and material being processed.

At the heart of the express methods are the physical principles of reliability theory, namely: Sedyakin's principle, Miner's hypothesis. The basic physical principle of reliability is based on the fact that the real system loses performance due to various influences, at the same time, each element of the system and the system as a whole before operation has some margin of safety - resource. During operation, this resource is consumed at a certain rate due to the modes and conditions of operation.

Sedyakin's principle takes place under the following conditions:

- with the transfer of the tool from one mode of operation to another it should not be a radical change in the processes occurring in the material of the tool;

- the same destructive factors must operate in different modes of operation of the tool, and only the intensity of these factors can change.

The principle of load extrapolation for carbide tools can be implemented by stepwise (gradual) increase in feed rate and by methods of stepwise and stepless (end turning) increase in cutting speed. In the first case the influence of gradual increase of loading on characteristics of durability of tool material is investigated, and in the second - intensity of wear of material at various range of speeds of cutting

2.2.1 The method of step-increasing conditions of cutting

Tests for wear resistance under the method of step-increasing cutting speed were to determine the cutting speed at which wear reached the normative wear criterion [98].

The initial cutting speed V_1 was set equal to the normative value for specific grade of the tool material which is tested. During tests, V_1 will be increased in steps. The coefficient of geometric progression of a number of cutting speeds φ_{st} was taken equal to 1.26 in accordance with the design of the gearbox of the machine tool mark 1K62.

The speed was adjusted so that the number of stages of cutting speeds before wear was equal to 3-5. The duration of work on the step was assumed to be equal to 60 seconds. The minimum number of experiments is n = 7.

After each cutting step, wear was measured on the main clearance face. During the tests, the cutting speed at which wear reaches the specified criterion of wear land width was recorded.

According to the test results, we calculated the average value of the cutting speed at which wear occurred for each batch of cutting tools and the wear rate, which was defined as the ratio of the increase in wear to the time during which this increase occurred:

$$V_3 = \frac{\Delta\delta}{\tau_i}, \qquad (2.1)$$

where $\Delta\delta$ is the increase in wear over time τ_i.

The main idea of the strength tests of the cutting tools by the method of step-increasing feed consisted in determination of the feed, the achievement of which causes the destruction of the cutting tool.

The tests were performed as follows. The feed was set equal to the standard for roughing of structural steel, and then increased in steps. The coefficient of geometric progression of a feed values was taken be equal to 1.21. Based on the diameter of the workpiece and the height of the toolholder, the initial feed rate was taken equal to 0.58 mm/rev. The cutting speed was assumed to be 18–24 m/min.

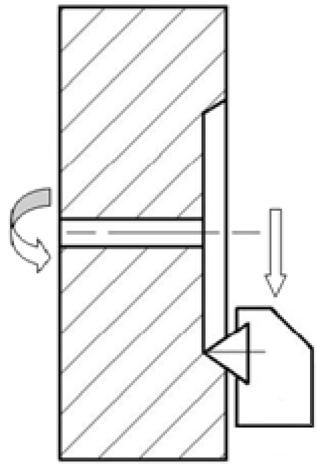
The choice of cutting depth was made taking into account the size of the toolholder, the size of the machine tool, the maximum and minimum diameter of the workpiece and the thickness of the indexible insert. In our case, the depth of cut was taken to be 2 mm.

The tests were performed in the same sequence as in the tests by the method of step-increasing speed of cutting. That feed, during which the cutting tool was chipped or broken, was accepted as the limit.

2.2.2 Method of continuous increase of cutting speed

The methods of continuous increase of cutting speed include the method of end face turning [69; 74; 90]. When tested by this method it is possible to reduce the error of the results in comparison with the method of stepwise increase of the cutting mode, however, the duration of the tests increases [44].

Tests of cutting tools were carried out on cylindrical samples (Figure 2.2), which are fixed in the chuck of the lathe.



i

$$D_i = D_н \cdot \varphi_i, \tag{2.2}$$

where φ – coefficient of proportionality;

i – number.

The number of sections and the diameter of the last ring D_k was equal to the outer diameter of the workpiece. The diameter D_n is determined so that the initial velocity Vp correlated with the normative V, as

$$\frac{V_п}{V} = 0,5 \ldots 0,7. \tag{2.3}$$

Tests of the cutting tools were performed by turning the end surface of the workpiece from the center to the periphery of each section. The spindle speed for each pass of the end surface was determined by the formula:

$$n_q = n_{n1} \cdot \varphi_1^{q-1}, \tag{2.4}$$

де q – number of the passage during end turning;

n_{n1} – number of revolutions for the first pass;

During the tests there was a monotonic increase in cutting speed, so after turning of each ring, it was measured wear of the cutting tool on its clearance face. Turning of the end surface was carried out until the wear of the cutting tool on the clearance face reached the established criterion of the tool wear. If the wear of the cutting tool on the clearance face didn't meet the established criterion in the first pass, the turnig began again from the center to the periphery (second pass) with the spindle speed determined by formula (2.4) and so on. The speed at which the cutting tool reached the established criterion of the tool wear was considered the limiting speed *Vgr*, which was taken as a parameter of wear resistance of the tool.

The brands of cemented carbides inserts which were tested: T5C10, T15C6, WC8, WC6OM, TT20C9.

2.2.3 Methods of testing the tool life and performance of cutting inserts, which are reinforced by PMFP and combined technologies in the laboratory

The cutting tools were selected from a batch of 18-20 pieces, hereinafter referred to as the sample.

The strength test of the cutting tools was intended to determine the feed, the achievement of which causes the destruction of the cutting insert. The feed was set at the normative level for pre-treatment and further increased by degrees.

The coefficient of geometric progression of the series of feeds φ_{st} is taken equal to 1.21 or closest according to the design of the feed box of the machine tool. Initial feeds are given in table. 2.3.

The workpieces were installed in the chuck and rear center to ensure maximum rigidity of the technological system of machining. Duration of work at each stage t_{st} = 6 s.

Table 2.3 - Values of initial feeds when testing cutting tools for strength

Toolholder height *H*, mm	40	50	63	80
Minimal diameter of workpiece *Dmin*, mm	400	500	600	700
Initial feed rate, mm/rev.	1,1–1,5	1,5–1,8	1,8–2,0	2,0–2,2

According to the current values of the cutting speed at which the wear occurred, and the destructive feed obtained by the number of experiments equal to 7, calculate the average values of the cutting speed at which the wear took place v_u and destructive feed *Sp*:

$$\bar{v}_u = \frac{1}{n}\sum_{i=1}^{n} v_{u_i}. \quad (2.5)$$

Coefficient of variation of cutting speed

$$V_{v_u} = \sigma_{v_u}/\bar{v}_u, \quad (2.6)$$

where σ_{v_u} – standard deviation of the cutting speed.

$$\sigma_{v_u} = \sqrt{\frac{\sum_{i=1}^{n}\left(v_{u_i} - \bar{v}_u\right)^2}{n-1}}. \quad (2.7)$$

Confidence intervals for cutting speed

$$\overline{v_u} \pm \Delta, \quad (2.8)$$

where $\Delta = \pm t_k \sigma_{v_u}/\sqrt{n}$, t_k – Student's criterion which equal 1.94 for $f = n - 1 = 6$ and $p = 0.9$.

Where f – degree of freedom, P – confidence level.

In the comparative assessment of the wear resistance of batches, the significance of the difference in their wear resistance is determined by the Student's criterion (with less than 20 items).

$$t_k = \frac{|\bar{v}_{u_1} - \bar{v}_{u_2}|}{\sqrt{n_1\sigma_1^2 + n_2\sigma_2^2}} \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{n_1 + n_2}}, \qquad (2.9)$$

де $\bar{v}_{u_1}$, $\bar{v}_{u_2}$ – the average values of the cutting speed at which the wear occurred for the first and second batch, respectively;

n_1, n_2 – sample sizes.

2.2.4 Method of estimating of the tool properties by the method of destructive feeding

The method establishes organizational and methodological principles of collecting and processing information about the reliability of cutting tools in operating conditions.

The minimum amount of observations N for estimating the average reliability with a relative error of $\delta < 0.15$ and a confidence level of $P \leq 0.9$ is 15.

The amount of observations is N = 18. The number of tools with indexible inserts is recommended to be equal to $N_K = 6$.

The following failure criteria were adopted during operational tests: achievement of the maximum allowable amount of wear, destruction of the cutting part of the tool. When comparing different design and technological options, tools of different types were randomly alternated. In the case of tests on several spindles and machines, the same number of tools was tested on each of them.

During the observations, the tool life (time of trouble-free operation or the number of machined parts) between regrinding or reinstallation of the indexible inserts, as well as the nature of the failure of the tool are recorded.

For tools with indexible inserts, the actual number of periods of insert tool life and its total tool life is recorded.

The main indicators of tool failure are the averagetool life T, the coefficient of variation V_T and gamma percentage of a tool life T_Y.

Average tool life:

$$T = \frac{1}{N}\sum_{i=1}^{n} T_i \,, \tag{2.10}$$

where T is the tool life of the tool in the *i*-th test;

N - the amount of observations.

Coefficient of variation of a tool life:

$$V_T = S/T, \tag{2.11}$$

where S is the standard deviation

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{n}\left(T_i - T\right)^2} \,. \tag{2.12}$$

Upper T_b and lower T_n confidence limits:

$$Tb = \sqrt[b]{r_1}T,\ Tn = \sqrt[b]{r_3}T, \tag{2.13}$$

where β is the Weibull distribution parameter due to V_T.

Gamma percentage of a tool life $T\gamma$ – is the tool life that has and exceeds the specified percentage of cutting tools γ:

$$T_\gamma = a\left(-\ln\left(\gamma/100\right)\right)^{\frac{1}{\beta}}, \tag{2.14}$$

where α is the Weibul distribution parameter, $\alpha = T/Kb$.

Average number of tool life periods for the tool being regrinded:

$$K = \frac{1}{N}\sum_{i=1}^{n} K_i, \qquad (2.15)$$

where N is the amount of observations;

K_i is the actual number of grindings of the *i*-th tool.

The average number of periods tool life of the inserts for the prefabricated tool:

$$K_{pl} = \frac{1}{N}\sum_{i=1}^{n} K_{pl\,i}, \qquad (2.16)$$

where N is the amount of observations;

K_{pl} - the number of tool life periods of the inserts;

$$K_{pl1} = \frac{1}{N}\sum_{i=1}^{n} K_{pl1\,i}, \qquad (2.17)$$

where K_{pl1} - the average consumption of inserts per 1 tool holder, due to consumption standards or estimated statistically.

$$K_K = M_{pl} / K_K, \qquad (2.18)$$

where K_K - average monthly or average annual consumption of inserts;

Mk – consumption of the toolholders for the same time period.

The main indicator of the maintainability of the tools with indexible inserts is the average recovery time:

$$t_b = \frac{1}{N} \sum_{y=1}^{l} t_{bi} r_y , \qquad (2.19)$$

where l is the number of structural elements of the cutting tool: indexible insert, support insert, mounting, tool holder;

t_{bi} - time to eliminate the failure of the *i*-th element;

r_y - the number of failures of the j-th element during the test

$$\sum_{y=1}^{l} r_y = N , \qquad (2.20)$$

where N is the amount of observations.

The purpose of experimental research was to establish the dependences of the destructive feed rate and the probability of destruction of the tool on the cutting conditions.

As the feed increases, the probability of breakage of the cutting tool grows, which is quantified as the ratio of the number of breakages to the observed quantity of a tool life periods. With a certain value of feed rate, the probability of failure will be equal to 1.0; that is, all cutting tools will collapse in the first period of tool life. This feed is called destructive and its value is established by the step-increasing feed cutting test according to the test methodology developed at the Donbas State Machine-Building Academy [54].

At each feed, the cutter works for a certain time, after which the feed is increased to the next step and so on, until there is a breakdown of a cutting tool. Before testing in accordance with the method of selection and diagnosis of the cutting tools.

Studies have shown that the destructive feed depends on both the time of machining on each feed and the number of feed stages that precede the destructive action. For most trials, a run time of 2 minutes was adopted, which provided both sufficient reliability and experimental performance. Operational tests were performed on heavy lathes on machines tools models KZh.16274F3, 1A670F3 and in laboratory conditions on the machine mod. 1A64.

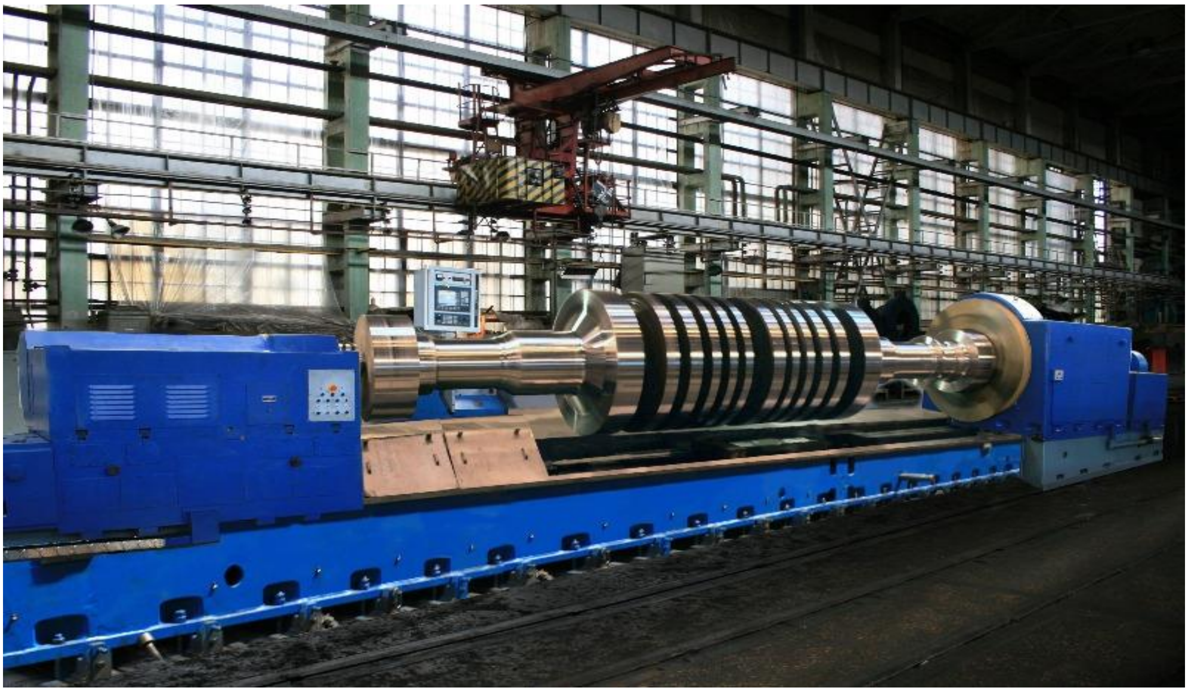


Figure 2.3 - General view of a heavy machine tool

Characteristics of metals in the processing of which the study was conducted, are given in table 2.3.

The tests were performed on machines with D_{max} = 1250–2500 mm with a tool holder height from 40 to 80 mm.

Table 2.3 - Characteristics of materials in the processing of which were studied the strength of the cutting part of the cutting tools

Processed material	Chemical composition, %								
	C	Mn	Si	Cr	Ni	V	Mo	S	P
								No more than	
40X	0.35-0.45	0.5-0.8	0.17-0.37	0.8-1.1	0.4			0.045	0.04
55X	0.5-0.6	0.5-0.2	0.17-0.37	1.0-1.3	0.5			0.04	0.04
50XH	0.45-0.55	0.5-0.8	0.17-0.37	0.45-0.75	1.0-1.5			0.04	0.04
45XHM	0.3-0.4	0.5-0.8	0.17-0.37	1.3-1.7	1.3-1.7		0.2-0.3	0.35	0.03
90XΦ	0.85-0.95	0.2-0.35	0.25-0.45	1.4-1.7	0.3	0.1-0.2		0.04	0.04
3X13	0.25-0.34	0.6	0.6	12-14	0.6			0.03	0.035

The geometric parameters of the cutting tools for all tests were taken in accordance with plant standards. The tests were performed at a cutting depth of 5–30 mm with a cutting speed in a range 0.25–2.0 of the optimal speed for these conditions.

Each experiment to determine the destructive feed was repeated at least three times. In addition to establishing the destructive feed during short-term tests, its connection with the processing time and the effect of the feed on the probability of failure were tested.

Table 2.4 - Mechanical properties of parts materials

Mark of the processed material	Mechabical properties				
	Yield strength, N/mm^2	Ultimate tensile strength, N/mm^2	Relative elongation, δ_s%	R ψ% l	Impact strength, $N{\cdot}m/cm^2$
40X	400	600	17	35	60
55X	350	650	10	30	–
40XH	300–350	650–700	18–20	45–50	–
90XΦ	690	950	1,2	1,0	6

Indexible inserts of one batch were tested, their main characteristics are given in table 2.5.

Table 2.5 - Mechanical properties of cemented carbide grades

Grade	Mechanical properies		
	Bending strength, MPa	Specific weight, g/cm^3	Hardness, HRA
T5C10	1469	12,72	90
TT7C12	1550	13,0	87
WC8	1650	14,8	88

2.2.5 Comparative method of operational evaluation of the effectiveness of modification of cutting inserts to determine the resistance to failure and wear under contact load

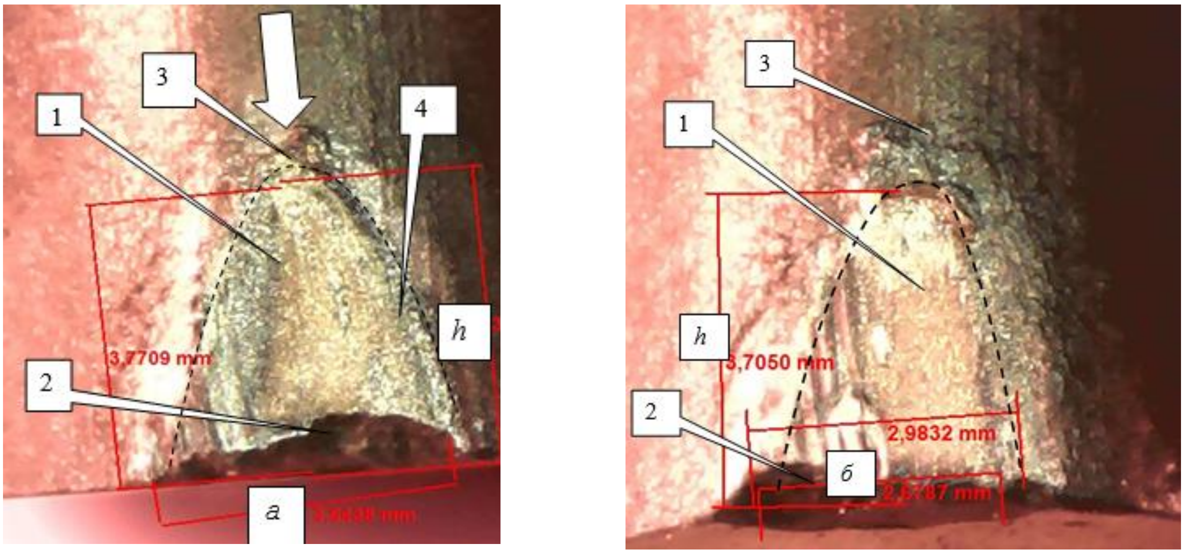
The specifics of tool failures on heavy machines and the use of modification methods that can be quickly implemented and optimized in production conditions, requires the development of comparative methods that allow one to quickly obtain a set of parameters that characterize wear resistance and resistance to destruction under heavy load.

The proposed approach involves testing cutting inserts under conditions of high contact pressure with friction at elevated temperatures using equipment used in machining. A massive cylindrical workpiece mounted on a lathe is used as a counterbody. The tested insert is fixed in the tool holder in such a way to minimize chip formation (Fig. 2.4). The design of the tool holder allows the installation of a dinamometr, which controls the force *P* of pressing the insert to the counter body. Due to the high level of contact load, the formation of a chamfer on the clearance face of the cutting insert is ensured. The wear parameter is defined as the area of the wear land *S* formed during a certain test time. Specific pressure (ratio of compression force to the area - *P/S*) and ratio of force to wear land width *P/b* are taken as characteristics of resistance to failure. The parameter *P/S* characterizes the resistance to scattered contact damage, and the value of *P/b* - resistance to chipping.

Figure 2.4 - The position of the insert relative to the processed part in determining the resistance to failure and wear under contact load on lathes

When assessing the damage and wear resistance of the inserts, the presence of microcracks on the wear surface, changes in the geometry of the counterbody in the contact zone are also taken into account.

The technique was used to assess the effect of PMFP on the resistance to destruction of the inserts from WC8 cementet carbide. Indexible square inserts in the initial state and after PMFP in two different modes were tested on the 1K62 lathe. The counter-body was a shaft with a diameter of 47.8 mm made of 40XH steel, which rotated with a frequency of 800 rpm. Modes: feed rate 0.07 mm/rev, speed 120 m/min, force P = 150 N, test time was 6 minutes. The dimensions of chips and chamfers formed as a result of tests were analyzed (Fig. 2.5).



A) B)

1 - semi-elliptical chamfer, 2 - chip at the exit of the contact.
3, 4 - sticking of the metal of the counterbody on the contour of the chamfer
(dimensions are given with the calibration factor k = 3.175)

Figure 2.5 - Semi-elliptical chamfers (wear lands) formed during tests of cemented carbide inserts WC8 in the initial state (a) and after PMFP (b)

3. AN INFLUENCE OF PMFP ON PHYSICO-MECHANICAL FACTORS, WHAT DETERMINES THE TOOL LIFE OF CEMENTED CARBIDES

3.1 Theoretical basement of the PMFP impact on the exploitation properties of the cutting tools.

P

M

F

$$dW = TdS - IdH - pdV$$

P

p

h

$$dG = -SdT - IdH + Vdp$$

e

n

It is known that the strength of hard alloys is largely determined by the binder phase. Observations of the propagation of the destructive crack have shown that in WC/Co and TiCTaC/Co alloys the destructive crack propagates mainly in the cobalt phase, and in TiC/Co alloys where the destructive crack propagates mainly in the (Ti,W)C phase, the cobalt component can inhibit the destruction.

n

$$C(x) = C_0 + C_m \cos(\pi x/l)$$

$$C(x,t) = C_0 + C_m \cos(\pi x/l)\exp\left(-\pi^2 Dt/l^2\right)$$

$$C - C_0 \approx \exp(-t/\tau)$$

τ – is the relaxation time.

τ

$$D = 1/6\,\Gamma\alpha^2$$

Γ is the frequency of atomic jumps;

α is the lattice period.

$$\Gamma = z\nu\exp(-\Delta G/RT)$$

where z is the number of neighboring atoms;

ν is the fraction of oscillations in a certain direction, which will lead to atomic jumps;

ΔG - change of free lattice energy.

3.2 Investigation of changes in strength during cantilever bending of hard alloys

Modeling methods were used to study the influence of PMFP on the physical and mechanical properties that determine the cutting ability of hard alloys. As is known [52], models are simplified systems that reflect certain limited in the right direction sides of the phenomena of a particular process.

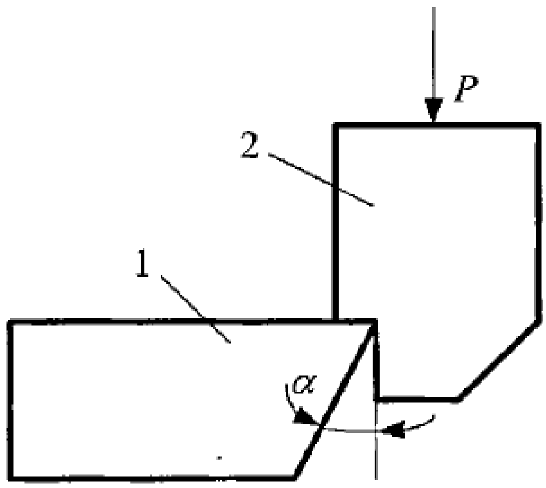
Since the preliminary turning (roughing), on the one hand, is associated with the action of large stresses, which due to insufficient strength of the hard alloy lead to the destruction of the cutting edge of the tool [21], on the other hand, the surfaces of the tool are exposed to various abrasive inclusions of the workpiece, and therefore subject to abrasive wear. These two sides of the cutting process were adopted for modeling.

Tests of samples at cantilever bending are carried out for the purpose of estimation of strength of material of a working part.

The scheme of loading of the sample during tests of samples at cantilever bending is given in figure 3.1.

The samples were made in a shape close to the geometric shape of the working part of the tool.

The sample was loaded on a UME-10M test machine in the direction of action of the main component of the cutting force *P*. According to the accepted test model, the limit value of the destructive load P_P was recorded during tests.



а)

б)

a - the scheme of loading of a sample at cantilever bending:

1 - sample; 2 - punch;

b – experimental setup for testing samples during cantilever bending

Figure 3.1 - Tests of samples during cantilever bending

For a more uniform distribution of the load on the contact area we used gaskets, made from steel with a thickness of 0.1 mm. As is known, during roughing the probability of brittle failure of the tool directly depends on the thickness of the chip, so the criterion of strength was the ratio of the destructive load P_P to the contact area F at a constant punch load speed (up to 0.01 m/min).

The selected test method allows:

- identify the influence of structural factors (structural defects, surface micromechanical defects, etc.) on the strength of the sample;

- to create a stress state that leads to destruction in conditions close to those that occur during the machining process, when there is a fragile destruction of the cutting tool.

In a number of works the feasibility of the application of the statistical theory of brittle strength under different types of stress state was experimentally proved.

The statistical theory of brittle strength allows to explain quite reliably the influence of body volume on mechanical characteristics, based on the position of the predominant influence on the strength of the most dangerous defect in the material. Fragile materials are very sensitive to changes in size, because they are characterized by the presence of defects. The theory is based on the assumption of the existence of defects in the material, regardless of the nature and causes of their appearance.

The most well-founded theory of brittle strength should be considered a theory based on the asymptotic distribution of experimental values of sufficiently large sets. Weibull distribution is more often used for engineering practice. Weibull's formula determines the probability of brittle fracture of the material $P(\delta)$ at stresses which are equal or greater than δ:

$$P\ (\delta) = \left\{1 - \exp\left[-\int\left(\frac{\delta-\delta_n}{\delta_0}\right)^m dV\right]\right\} \text{ when } \delta \geq \delta_n\ , \qquad (3.1)$$

where δ_n is the stress below which the probability of failure of the sample is zero, regardless of body size;

δ_0 - a parameter that for a unit volume gives a probability of failure equal to 0.632;

m - parameter that characterizes the homogeneity of the material, the degree of uniform distribution of defects in body volume;

V - working volume.

The parameters *δn, δ0, m* cannot be considered as physical constants of the material, because they characterize only a certain selection of samples made by a certain technology and with a certain geometry. Depending on the condition of the surface and heat treatment, the distribution varies widely.

When $V = 1$ and $\delta - \delta_n = \delta_0$: $P(\delta) = 0.632$.

Therefore, δ_0 is the stress that for a unit volume gives the probability of failure $P(\delta) = 0.632$. The size δ depends on the working volume.

After transforming equation (3.1) we have:

$$\lg ln\frac{1}{1-P(\delta)} = \ln n(\delta^{/}) + \lg V. \tag{3.2}$$

It is seen that in a rectangular coordinate system with axes lg $n\ (\delta^{/})$ and $\lg ln\frac{1}{1-P(\delta)}$ a change in the volume of the test specimens only leads to a parallel movement, but not to a change in the distribution function.

If the distribution functions are given by the equation:

$$n\left(\delta^{/}\right) = \left(\frac{\delta-\delta_n}{\delta_0}\right)^m, \tag{3.3}$$

and the abscissa axis is lg $(\delta\text{-}\delta_0)$, then in these coordinates the distribution function will be linear:

$$\lg ln\frac{1}{1-P(\delta)} = m \cdot \lg\ (\delta - \delta_n) - m \cdot \lg \delta_n + \lg V\ \ . \tag{3.4}$$

Analysis of equation (3.4) allows us to conclude that the homogeneity index *m* does not change under the same conditions of sample manufacturing, at the same time its numerical value changes when the working volume changes.

With known values of the strength of two batches of samples tested in different working volumes, the value of *m* can be determined from the equation:

$$\frac{\overline{\delta_1}}{\overline{\delta_2}} = \left(\frac{V_2}{V_1}\right)^m, \quad (3.5)$$

where $\overline{\delta_1}$, V_1 – average strength and working volume of one series of samples;

$\overline{\delta_2}$, V_2 – the average strength and working volume of another series of samples.

After transforming equation (3.5.) We obtain:

$$m = \frac{\lg V_2 - \lg V_1}{\lg \delta_1 - \lg \delta_2}. \quad (3.6)$$

In the general case, when increasing the values δ_0, δ_n, $m_\circ$ it should be assumed that the average strength of the material increases, and the scatter of strength values decreases.

It is more convenient to determine the value of the indicator *m* by the formula derived when decomposing the j-function into a static series, based on the assumption about the negligible small value of the second term of equation (3.3):

$$m = \frac{127.5}{K_\delta} - 0{,}5, \quad (3.7)$$

where $K_\delta = \frac{S}{\delta_{av}}$ – coefficient of strength variation;

$S = \sqrt{\frac{\sum \varepsilon^2}{n}}$, $\varepsilon = \delta_1 - \bar{\delta}$ standard deviation;

δ_{av} – arithmetic mean value of strength.

Formula (3.7) gives the most satisfactory results in comparison with the results obtained by formula (3.6) in the range of values of *m* from 3 to 20 and the number of experiments more than 30. When *n* <30 we need to use the estimate *S*:

$$S = \sqrt{\frac{\sum \boldsymbol{\varepsilon}^2}{\boldsymbol{n-1}}} \quad . \tag{3.8}$$

Thus, the indicator *m*, which characterizes the homogeneity of the cutting tool material, can be estimated using the coefficient of variation calculated by mathematical processing of a sufficient number of test results of one series of samples, the number of experiments with 95.4%.

The test results showed (Fig. 3.2, Table 3.1, confidence interval: $\Delta\sigma\_{bend}$ = ± 4.056 MPa) that the pulsed magnetic field processing can increase the strength characteristics of the material in the conditions of brittle failure. As can be seen from Table 3.1, there is an increase in the strength of the material after PMFP in 1.12 times, and when processed on the inductor № 2 (with increased power) - 1.14-1.22 times. Magnetic pulse processing helps to increase the homogeneity and the degree of uniform distribution of defects in body volume, as evidenced by a decrease in the coefficient of variation of strength by 1.2 times, as well as an increase in homogeneity by 1.3 times. The best results were obtained using mode B2.

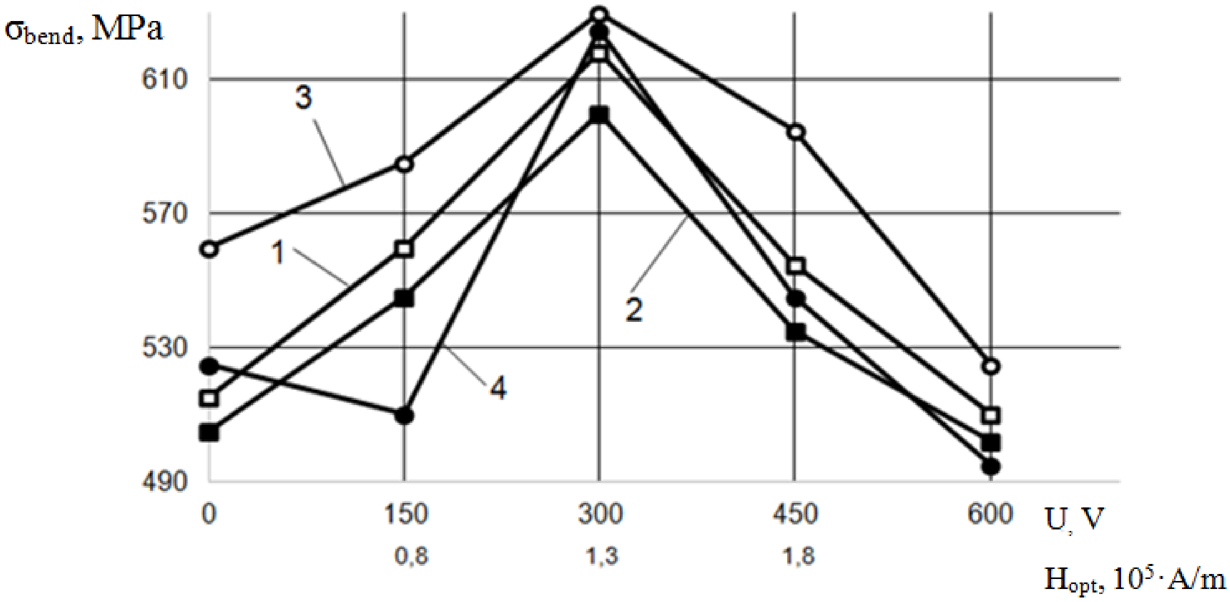


Figure 3.2 - Dependence of strength on cantilever bending after PMFP on the inductor №2: 1 – TiC5/Co10; 2 – TiC15/Co6; 3 – WC/Co8; 4 – WC/Co6

Table 3.1 – Impact of PMFP on the cemented carbide strength in cantilever bending conditions

Cemented carbide grades	Strengthening		Critical Stress, MPa (stress of fracture)	Stress ratio coefficient $\frac{\delta_{PMFP}}{\delta_{initial}}$	Strength variation coefficient K_δ	Показник однорідності Equality characteristic m
TiC5Co10	without strengthening		515	--	0,68	1,375
	PMFP		618	1,2	0,52	1,95
TiC15Co6	without strengthening		495	-	0,72	1,27
	PMFP		604,5	1,22	0,6	1,625
WC/Co8	without strengthening		558,4	-	0,68	1,375
	PMFP		625,3	1,14	0,56	1,78
WC/Co6	without strengthening		522,25	-	0,71	1,3
	PMFP inductor №2)	B 1	501,3	0,96	0,87	0,97
		B 2	624	1,2	0,58	1,7
		B 3	548	1,05	0,6	1,625
		B 4	491,1	0,92	0,87	0,97

	PMFP (inductor №1)	B 2	588	1,12	0,66	1,43

3.3 Investigation of changes in the strength of hard alloys under the action of concentrated load on a sample lying on two supporting points.

For comparison, tests of concentrated load were performed on a sample lying on two supports (Fig. 3.3)

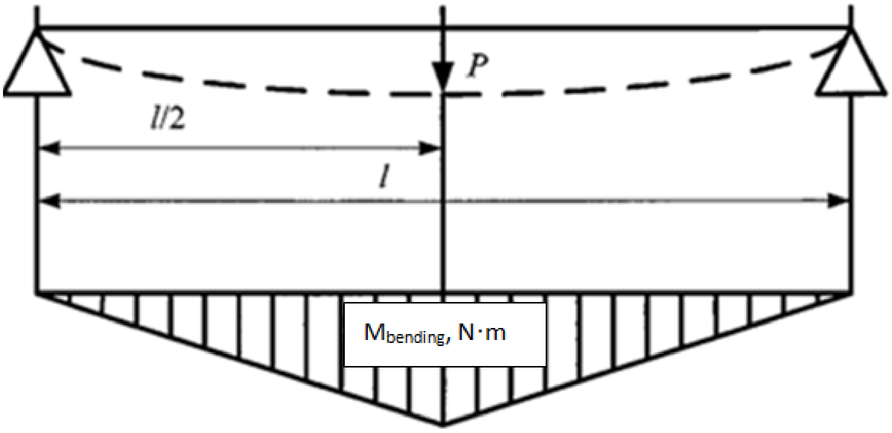


Figure 3.3 - Scheme of bending test specimens concentrated load

Loads in the bearings and in places of forces application are created through roller bearings to reduce friction forces during bending deformation.

Tests of the samples were performed on a test machine P-10. In this experiment, the total effect of *Pz* (cutting force) and *Py* (thrust force) was simulated. The bending strength was calculated by the formula:

$$\delta_{bend} = \frac{M}{W}, \qquad (3.9)$$

where *M* is the bending moment;

W is the section modulus.

In case of loading by concentrated force:

$$M = \frac{P \cdot l}{4}, \qquad (3.10)$$

where l is the length of the span between the supports.

For a rectangular sample:

$$W = \frac{b \cdot h^2}{6}, \tag{3.11}$$

where b – is the height of the sample;

h – is the width of the sample.

Therefore, the working formula for calculating the elastic stresses in bending samples of rectangular cross section is

$$\delta_{bend} = \frac{3 \cdot P \cdot I}{2 \cdot b \cdot h}, \tag{3.12}$$

where P – is the load recorded by the device of the test machine. Estimation of the value of δ_{bend} was carried out on indexible inserts.

Table 3.2 and Figure 3.4 (confidence interval: $\Delta\delta_{bend} = \pm$ 1,114 MPa) show the test results of the samples under concentrated load on a sample lying on two supports. The test results showed that PMFP can improve the strength characteristics of the material operating under conditions of brittle fracture.

As can be seen from Table 3.2 and Figure 3.4, there is an increase in the strength of the material 1.2-1.22 times (mode B2). PMFP helps to increase the homogeneity and the degree of uniform distribution of defects in body volume, as evidenced by a decrease in the coefficient of variation of strength in 1.8-2.3 times.

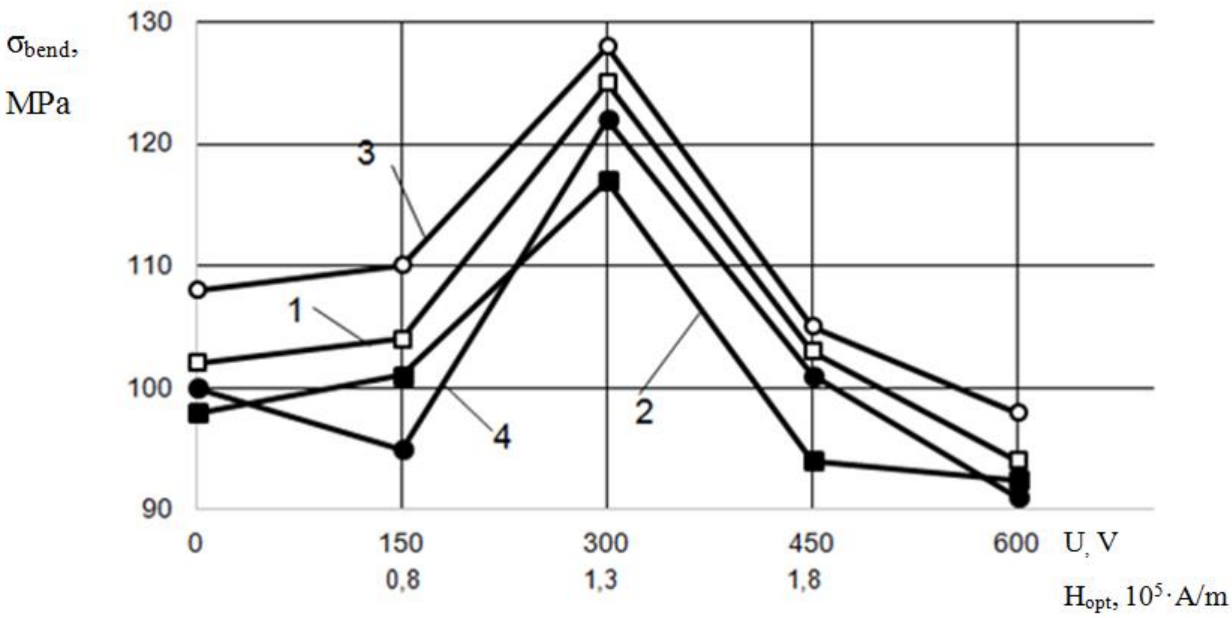


Figure 3.4 - Dependence of bending strength under the action of concentrated load: 1 – TiC5Co10; 2 – TiC15Co6; 3 – WC/Co8; 4 – WC/Co6

The best results were obtained on the inductor № 2 at mode B2, when the strength increased by 1.2 times, and the homogeneity of the material properties by 4.3 times. Thus, if the cutting tool works in the conditions of fragile destruction, (rough turning of processing of a casting skin, interrupted machining with impacts) it is expedient to carry out strengthening of PMFP on the inductor № 2 with the B2 mode.

It should also be noted that two different types of tests, described above, showed that after strengthening by PMFP the strength of the material changes to the same extent. Therefore, when conducting this type of experiment, we can use only second type of testing (under the action of a concentrated load). Because this is a simpler and cheaper way.

Table 3.2 - The effect of PMFP on the strength of the hard alloy under concentrated load

Cemented carbide grades	Strengthening		Bending stress, MPa	Stress ratio coefficient $\frac{\delta_{PMFP}}{\delta_{init}}$	Strength variation coefficient K_δ	$\frac{K_{\delta_{init}}}{K_{\delta_{PMFP}}}$
TiC5Co10	without strengthening		101,3		0,2	
	PMFP		124	1,22	0,1	2
TiC15Ko6	without strengthening		98,7		0,16	
	PMFP		118	1,2	0,17	2,3
WC/Co8	without strengthening		107		0,22	
	PMFP		131	1,22	0,12	1,9
WC/Co6	without strengthening		99,6		0,18	
	PMFP	B 1	95,4	0,96	0,15	1,2
		B 2	121	1,21	0,1	1,8
		B 3	102,7	1,03	0,1	1,8
		B 4	89,8	0,9	0,15	1,2

3.4 Investigation of changes in the structural strength of cutting inserts for three-point bending

The effective use of PMFP in industrial practice is hampered by the lack of data on the impact of this type of processing, as well as different modes of PMFP on changes in the set of properties that determine the performance of the carbide inserts. According to [30] in cutting conditions on heavy machines, when, as noted above, a significant area of the rake face of the cutting tool is under tensile stresses, an important indicator of performance is tensile or bending strength.

Standard methods of testing hard alloys for bending and other types of testing using special samples do not reflect the real properties of the tool due to large differences in manufacturing technology, design, actual stress and geometry of the indexable insers. But they identify important trends in mechanical behavior, which can be the basis for a rough assessment of the performance of new tool materials and tool quality control in the absence of appropriate complex experiments. The importance of developing methods to control or predict strength and durability is growing due to the development of new technologies to strengthen hard alloys through volume and surface modification.

Table 3.2 shows the results of structural strength tests for bending of square indexable made of hard alloy TiC5Co10 with dimensions of 15,875x15,875x4,76 mm, used for turning and boring cutters, as well as end mills. PVD coatings with a thickness of 5 μm were applied to the cutting surfaces of the inserts. The inserts were processed with a pulsed magnetic field.

The plates were tested for three-point bending. The surface with the cutting edge and the coating was placed in the area of tensile stresses. Testing was performed on a ZD-40 hydraulic machine with a loading speed of 6.5–10 MPa/s (Fig. 3.5). Three batches of insers (5 pcs in the each batch) were tested. To compare the bending strength of standard samples $\sigma_{bend\ sampl}$ of this alloy with the real level of strength in cutting inserts $\sigma_{bend\ insert}$, the ratio $\sigma_{bend\ sampl}$ / $\sigma_{bend\ insert}$ is shown in table 3.3.

Tests for strength in three-point bending were also carried out with indexable insers in the form of hexagon made of hard alloy TiC15Co6 without coating (thickness of the inserts is 4.76 mm). Two batches of the inserts (6 pcs. each batch) tested on a ZD-40 hydraulic machine with a loading speed of 20–22 MPa/s.

Figure 3.5 - Testing on a ZD-40 hydraulic machine

Table 3.3 - Structural strength of transverse bending of cutting plates made of alloy TiC5Co10

State of inserts	Bending strength σ_{bend} , MPa	Range $\sigma_{bend\ min}$ ...$\sigma_{bend\ max}$, MPa	Ratio $\sigma_{bend\ insert}/\sigma_{bend\ sampl}$	Strengthening, %
Initial state	892	711/ 1046	0,5…0,75	-
Strengthened by PMFP (processing mode - B1)	1037	762/ 1280	0,6…0,9	16
Strengthened by PMFP (processing mode - B2)	1130	884/1295	0,66…0,98	27

Inserts in the initial state and strengthened by pulsed magnetic field processing according to B2 mode were studied. The test results are shown in table 3.4.

Analysis of the obtained test results of cutting inserts made of TiC5Co10 and TiC15Co6 alloys (Fig. 3.6–3.7), which are reinforced by PMFP, shows that due to the influence of a set of technological and structural factors the structural bending strength of carbide cutting inserts is much lower than traditional standard prismatic samples. Depending on the processing technology and test conditions, the measurment of the strength of real cutting inserts can demonstrate values, which are lower by 10-50% relative to the results of traditional mechanical tests of hard alloys for bending, which directly affects the performance of the tool, the reliability of its durability and efficiency in hard cutting conditions.

For TiC15Co6 samples in the initial state and for inserts from the same material, it was also obtained that the value of $\sigma_{bend\ insert}$ largely depends on which surface is in the stretching zone: when the flat surface is in the stretching zone, the average value of $\sigma_{bend\ insert}$ is 799 MPa (when the surface with a cutting edge is located in the zone of stretching $\sigma_{bend\ insert}$ is equal to only 642 MPa).

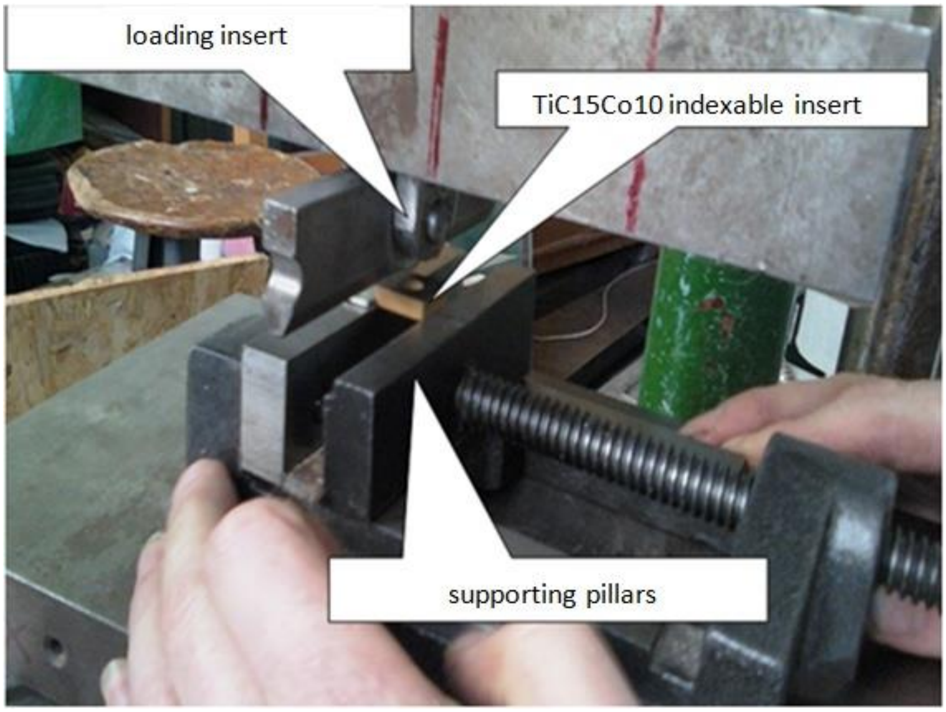


Figure 3.6 - Testing for bending of a indexable insert TiC5Co10

on ZD-4 equipment

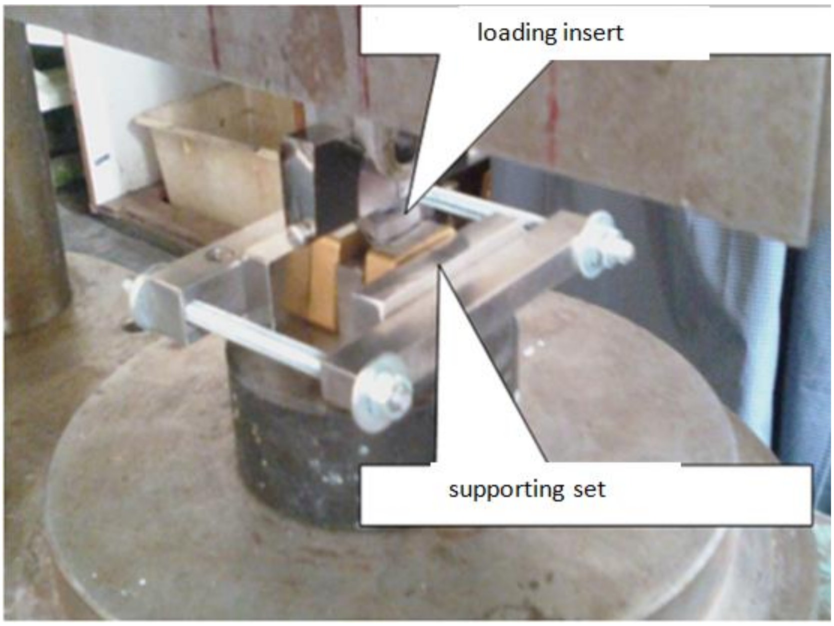


Fig. 3.7 - Testing for bending of a indexable cutting insert from TiC15Co6 on ZD-40 equipment

Table 3.4 - Structural strength for transverse bending of cutting inserts made from alloy TiC15Co6

State of inserts	Maximal loading *P*, kg	Bending strength σ_{bend}, MPa	range $\sigma_{bend\ min} \ldots \sigma_{bend\ max}$, MPa	Ratio σ_{bend} … nd sampl	Strengthening, %
Initial state	655	642	549/804	0,61…0,80	-
Strengthened by PMFP (processing mode - B2)	750	735	608/804	0,67…0,80	14%

It was also found that the applied method of modification of hard alloy TiC5Co10 allows to increase its bending strength by 16-27% depending on the processing mode. And PMFP processing in the second mode increased the bending strength of the insert from TiC15Co6 by 14%. It is also established that after PMFP the scatter of bending strength values decreases. It can be assumed that the increase in the strength of the hard alloy as a result of PMFP is associated with a decrease in tensile stresses in the cobalt phase, which prevents the development of cracks.

4 EXPERIMENTAL STUDY OF THE PMFP EFFECTIVENESS

4.1 Methodology of production tests.

An important means of increasing the efficiency of tests and expanding the amount of information obtained is to conduct tests of cutting tools in production conditions at a specific technological operation. Production tests have the following advantages: they do not require additional material costs for equipment, material to be processed, tools; the technological criteria of wear of the tool allow for a more complete and correct assessment of its quality; obtain dependencies in real operating conditions by appropriate mathematical processing of test results.

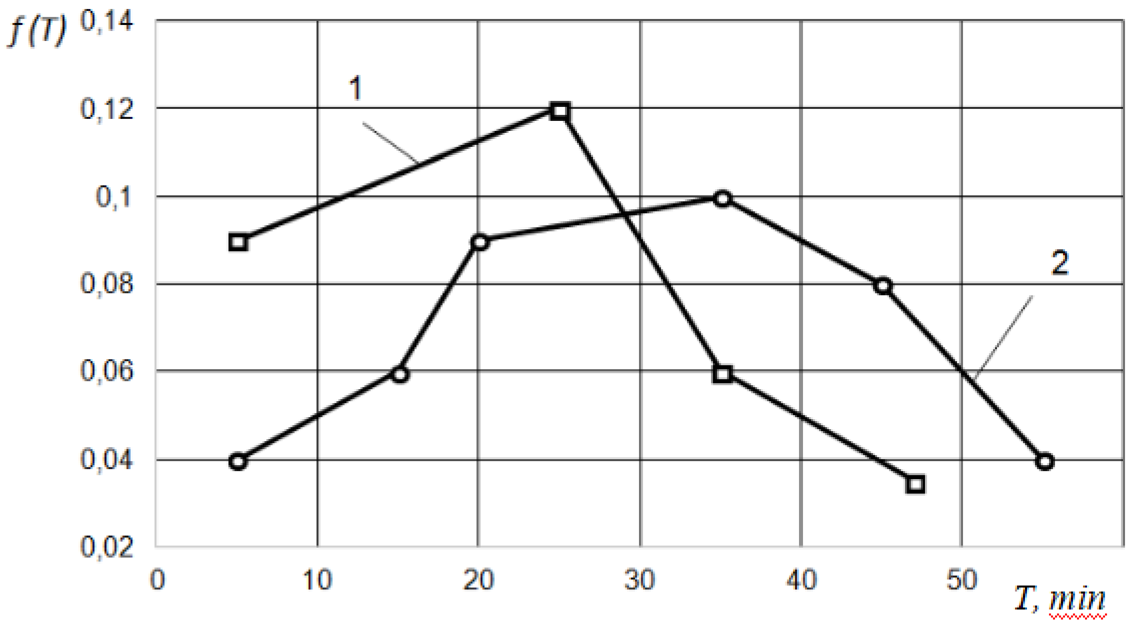
Table 4.1 – Conditions for conducti ng tests of hard alloy cutting tools, which are strengthened by treatment with a pulsed magnetic field.

Number of batch	Company	Type of cutting tool	Grade	Machine Tool	Processed material	Machined surface	Cutting conditions		
							Cutting depth *t*, mm	Feed *S*, mm/rev	Cutting speed *V*, m/min
1	2	3	4	5	6	7	8	9	10
1	KRAMATORSK HEAVY DUTY MACHINE TOOL BUILDING PLANT	Turning cutting tool (φ = 60°)	WC-Co8	KZh16274F3	Grey cast iron-20 HB 170–241	Mould crust	5	3	78,7
2		Triangle indexable insert	TiCTaC10-Co8	KZh16274F3	Steel 45 HB 190–240	Prelimenary machined surface	1	0,25	70
3		Quadratic indexable insert	TiC-Co6				1,4	0,05	68
4		Quadratic indexable insert	TiC5-Co6				2	0,1	100
5	NOVOKRAMATORSK MACHINE BUILDING PLANT	Turning cutting tool (φ = 60°)	TiC5-Co10	1A665	Steel 9Cr2M HB 201–321	Machined surface	4	1,6	36
6		Turning cutting tool (φ = 60°)	TiC15-Co6	164	Steel 38CrNi3MA HB 340–360	Prelimenary machined surface	0,4	0,8	125
7		Brazed cutting insert (turning) (φ = 75°)	TiC5-Co10	1A670F3	Steel 35CrNi HB 240–260	Mould crust	2,0	1,0	80
8		Brazed cutting tool (turning) (φ = 60°)	WC-Co6	1A670F3	Grey casrt iron HB 240–260	Mould crust	1,0	0,15	42

4.2 Influence of PMFP on indicators of operational stability of the tool

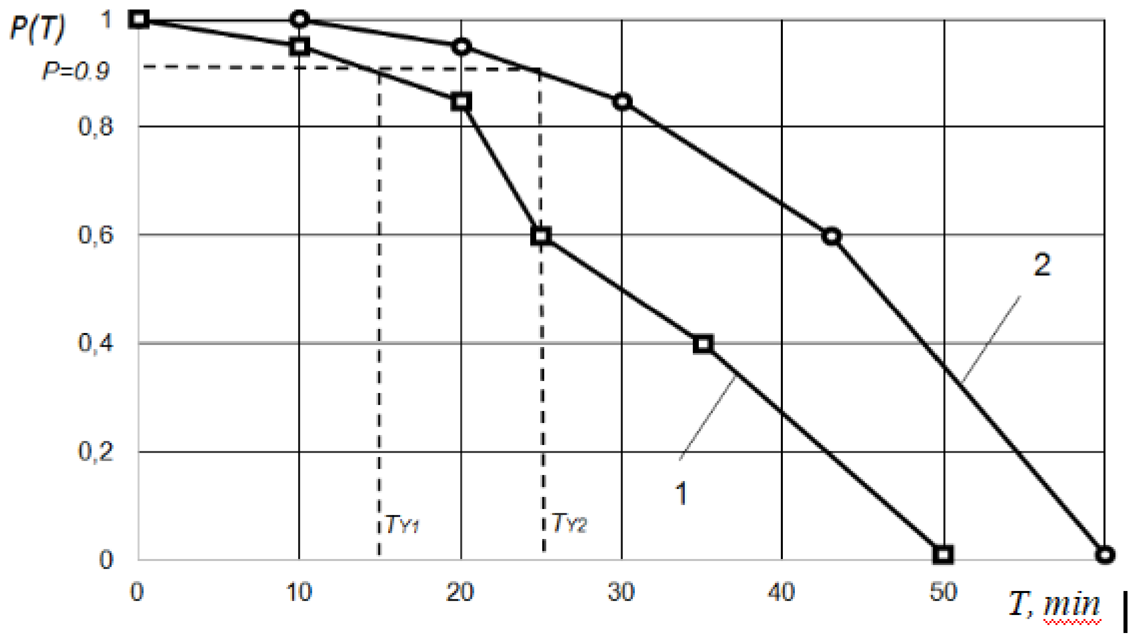
Figures 4.1–4.6 present the results of tests of various types of cemented carbide cutting tools. All data indicate an increase in the wear resistance of tools strengthened by PMFP by 1.2–2 times.

In all cases (Figs. 4.1–4.6), there is also a 1.3–3.1 times decrease in the variation coefficient. More significant efficiency takes place in increasing the gamma-percentage resistance. So, with a probability of 0.9, this increase occurs 1.7–2.8 times, which indicates the feasibility of using cutting tools that are strengthened by PMFP on heavy machine tools.



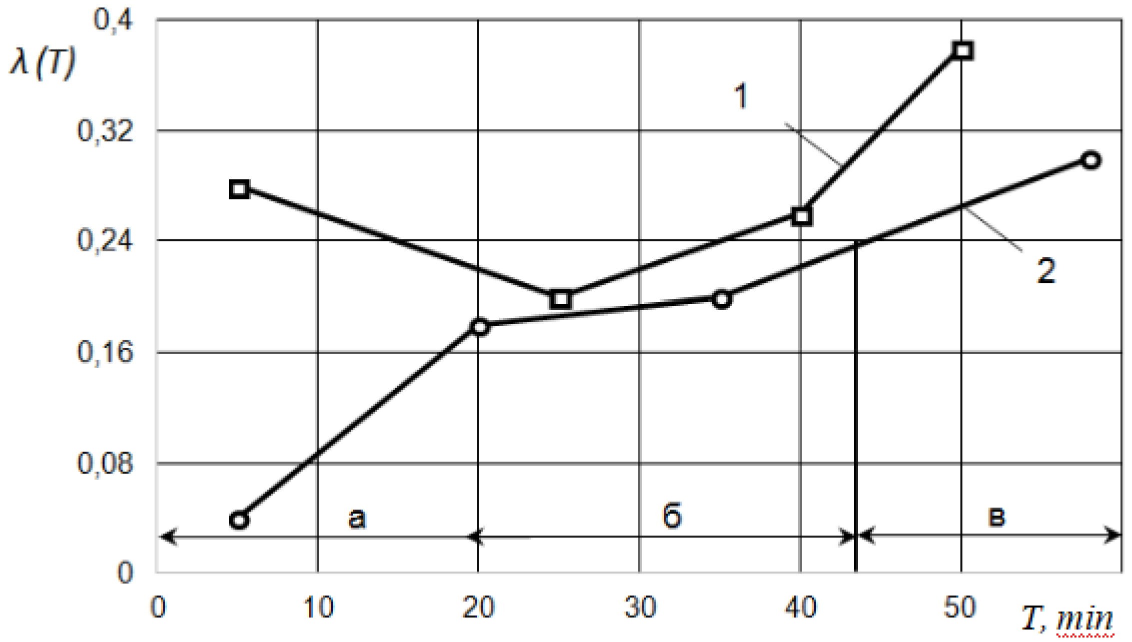
1 – tools without strengthening, 2 – strengthened tools

Figure 4.1 – Density of failure distribution.



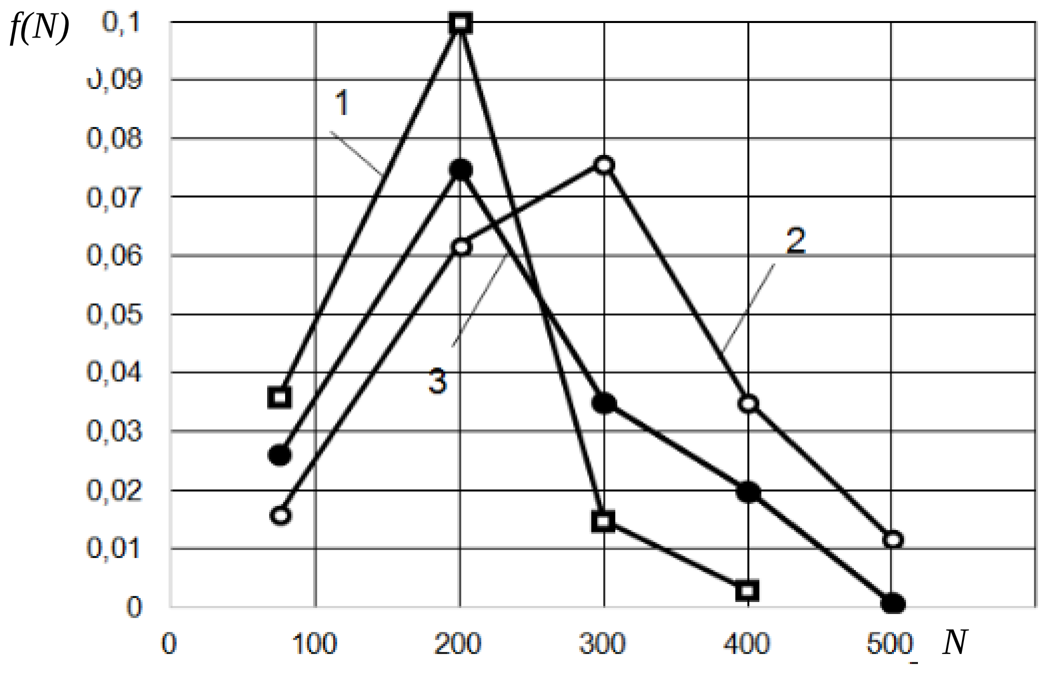
1 – tools without strengthening, 2 – strengthened tools

Figure 4.2 – Probability of failure-free machining



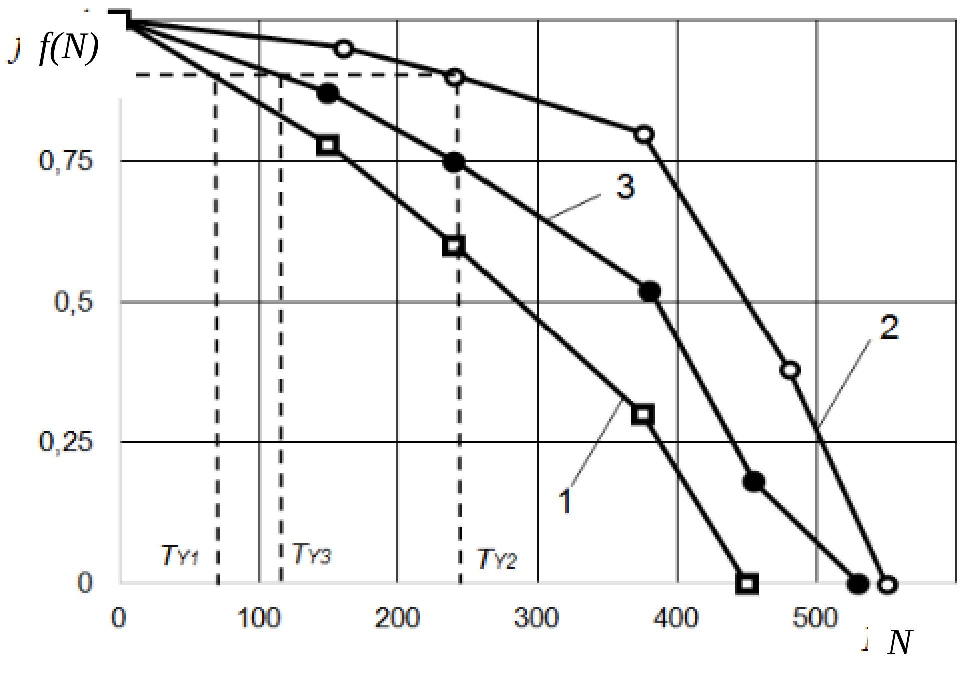
1 – tools without strengthening, 2 – strengthened tools

Figure 4.3 – Intensity of failures



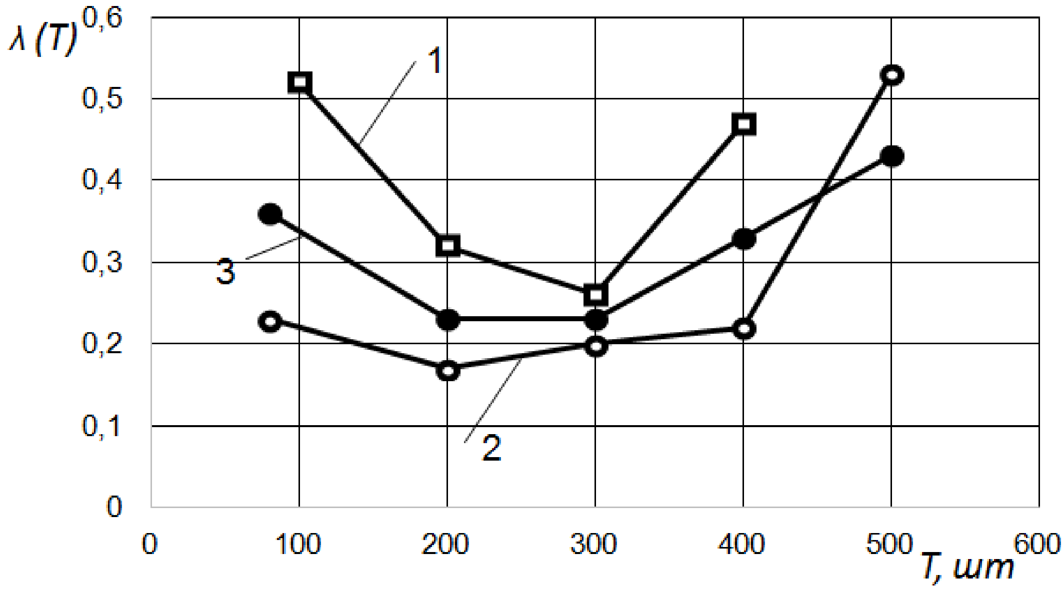
1 – tools without strengthening, 2 – strengthened tools after the first period of tool life; 3 – strengthened tools after the fifth period of tool life

Figure 4.4 – Density of failure distribution



1 – tools without strengthening, 2 – strengthened tools after the first period of tool life; 3 – strengthened tools after the fifth period of tool life

Figure 4.5 – Probability of failure-free operation



1 – tools without strengthening, 2 – strengthened tools after the first period of tool life; 3 – strengthened tools after the fifth period of tool life

Figure 4.6 – Intensity of failures

Analysis of the graphs of the probability of failure-free operation, the density of the distribution of failures and the intensity of failures (Fig. 4.1–4.6) shows:

– increase in the wear resistance of tools that are strengthened by PMFP, corresponding to the highest density of the *f (T)* distribution;

– increase in the probability of failure-free operation *P(T)* of tools that are strengthened by PMFP, with a given wear resistance (confidence interval: $\Delta P\ (T) = \pm\ 0.124$)

The most significant increase in the wear resistance of tools occurs for the seventh batch (Figs. 4.4–4.6). This batch is characterized by the presence of difficult working conditions: the presence of a mould crust, a large cutting depth, a relatively high feed, significant hardness of the material and a low cutting speed. All this causes up to 68% fatal failure of unreinforced tools.

The most interesting picture is observed on the graph of changes in failure intensity λ(T) (Fig. 4.3). For non-reinforced tools, at the initial stage of operation, a period of running-in (zone a) is characteristic, when a high intensity of failures will occur. There is no running-in period for strengthened tools. At the beginning of operation, the intensity of failures is 2.4 times less, and it is constant (zone b) until the beginning of the zone of catastrophic wear (zone c) (on the graph up to N = 400 pieces).

It should also be noted that the test results of the tools of the sixth batch did not show a significant increase in wear resistance. The wear resistance of strengthened tools increased by only 1.08 times. The coefficient of variation of stability did not change either. Such results can be explained by relatively easy working conditions (small cutting depths and feed) and relatively high cutting speed. In addition, the cutting process takes place on a pre-treated surface. Apparently, the proportion of abrasive and brittle wear in this operation is small. Therefore, the effectiveness of PMFP in this operation is weak. Thus, the use of PMFP contributes to increasing the stability of carbide tools and reducing its dispersion during preliminary processing.

CONCLUSIONS

1. The effect of volumetric strengthening of a carbide cutting tool by processing with a pulsed magnetic field has been established.

2. Tests of hard alloy samples during cantilever bending showed that tools strengthened by PMFP have a 1.2–1.22 times increase in strength, as well as higher homogeneity and uniformity of the distribution of defects by body volume. Studies on abrasive wear showed that after processing with a pulsed magnetic field, the abrasive wear resistance of carbide tools increases by 1.3–1.4 times and the coefficient of variation of wear decreases by 1.5 times.

3. It was found that the modification of the TiC5-Co10 hard alloy by processing with a pulsed magnetic field, depending on the applied modes, leads to an increase in the bending strength limit under static load by 16–27%, which allows predicting an increase in the endurance limit.

4. Defects in the structure of the surface layer have a significant effect on the strength and destruction of the studied hard alloy indexable inserts. It was established that the modification of hard alloys by processing with a pulsed magnetic field leads to an increase in their homogeneity, a decrease in the thickness of the cracked layer, stabilization of mechanical characteristics, and an increase in the bending strength limit.

5. The use of modeling methods made it possible to establish optimal regimes and conditions of strengthening depending on the brand of hard alloy and geometric parameters of the tool. The optimal values of the magnetic field strength and pulse frequency depending on the geometrical parameters of the tool were determined.

6. On the basis of production tests of carbide cutting tools, it was established that the use of processing with a pulsed magnetic field contributes to:

– increasing the wear resistance of cutting tools by 1.2–2 times;

– a decrease in the coefficient of variation of stability by 1.3–3.1 times;

– increase of gamma-percentage resistance by 1.7–2.8 times;

- 2.7 times reduction in the number of chippings and breakages in the area of tool fitting;

– the strengthening effect after resharpening the tool is preserved.

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Наукове видання

Затверджено до друку Вченою радою
Донбаської державної машинобудівної академії (ДДМА)
(протокол № 4 від 26.11.2024)

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(англійською мовою)

Монографія

Редагування, комп'ютерне верстання М. В. Шаповалов

125/2020. Формат 60 × 84/16. Ум. друк. арк. 6,90.
Обл.-вид. арк. 14,17. Тираж 300 пр. Зам. № 18

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ДК №1633 від 24.12.2003