Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2022 vol. 24 no. 3 pp. 53–65
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2022-24.3-53-65

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Features of ultrasound application in plasma-mechanical processing of parts made of hard-to-process materials

Vagif Abbasov [a], *Rasim Bashirov* [b, *]

Department of Machine Building, Azerbaijan Technical University, 25 H. Cavid avenue, Baku, AZ 1073, Azerbaijan

[a] https://orcid.org/0000-0002-4633-6728, abbasov49@aztu.edu.az, [b] https://orcid.org/0000-0001-6907-2502, rasim_agma@aztu.edu.az

ARTICLE INFO

Article history:
Received: 06 April 2022
Revised: 19 April 2022
Accepted: 27 June 2022
Available online: 15 September 2022

Keywords:
Hard-to-process materials
Plasmatron holder
Machinability coefficient
Ultrasonic Cutter
Ultrasonic turning device
Plasma-mechanical processing
Plasma-ultrasonic treatment
Cutter wear
Vibrational deformation of the chip.

ABSTRACT

Introduction. Structural materials, including materials made of heat-resistant and hard-to-work steels, are widely used in various branches of mechanical engineering. To increase the efficiency of manufacturing parts of thermal equipment from heat-resistant and hard-to-work steels, the technological method of cutting with preliminary plasma heating of the workpiece is used. There is also a technological method of cutting metals, including hard-to-process materials by ultrasonic turning. Proceeding from this, in order to increase the efficiency of plasma machining of hard-to-process materials, it is necessary to investigate the technological possibilities of using ultrasonic turning of hard-to-process materials during plasma machining. **The purpose of the work**: to investigate the wear of cutting tools when using ultrasound in the conditions of plasma-mechanical processing of parts made of hard-to-process materials. **The paper investigates** the features of the plasma-mechanical processing under ultrasonic cutting conditions and **determines** the wear values of carbide cutters *VK8*, *T5K10* and *T15K6* when processing steels of grades *20Cr13Ni18* and *20Cr25Ni20Si2(cast)*. And also the wear of these cutters was determined under the conditions of conventional turning of the same materials to compare the results of wear of the cutters in different processing conditions. **The research method** is to determine the linear wear of carbide cutters along the back surface with conventional, plasma-mechanical and plasma-mechanical cutting assisted with ultrasonic cutting using an instrumental microscope and visual estimation with a 10x magnifying glass. **Results and discussion**. The paper presents the results of experimental studies to determine the wear of cutting tools when processing heat-resistant steels of the *20Cr13Ni18* and *20Cr25Ni20Si2(cast)* grades with carbide cutters of the *VK8*, *T5K10* and *T15K6* grades. Studies were carried out to determine the wear of carbide cutters as with conventional mechanical cutting, plasma-mechanical cutting, as well as plasma-mechanical cutting using ultrasound. The experiments were carried out when turning these materials on a modernized lathe *mod.1A64*. A rectifier with a controlled choke and a plasma torch *mod.APR-403* are connected to the lathe; a plasma holder is placed on the lathe carriage. A semiconductor rectifier serves as a power source with a compressed electric arc of current. The arcing takes place between the cathode (plasma torch) and the anode (blank) at the point of the plasma-forming gas; compressed air passes through the nozzle channel of the plasma torch. During the experiments, the position of the plasma torch was adjusted relative to the part rotation axis. When conducting experiments on studying the wear of cutters under conditions of ultrasonic plasma-mechanical cutting, ultrasound was applied to the cutting edge using a device developed by the authors. When processing heat-resistant steels under the usual turning condition, processing modes were adopted: cutting speed $V = 10$ m/min, cutting depth $t = 3...4$ mm, longitudinal feed $S_l = 0.31$ mm/rev. It is found that when processing steel grade *20Cr13Ni18* by conventional cutting, the back surface of the carbide cutter made of *T5K10* wears out to 1 mm in size within 10 minutes, and for the cutter made of *VK8* – within 15 minutes. During plasma machining, the cutting speed and the feed rate were increased 2 times; the results of the wear of the cutters show that at the same time *T5K10* wears out to 1 mm within 20 minutes, *VK8* – within 25 minutes. Plasma-mechanical processing using ultrasound show that the carbide cutter *T5K10* wears out by 0.50 mm in less than 50 minutes of cutting, and *VK8* wears out by 0.35 mm. The same results are obtained when processing heat-resistant steel *20Cr25Ni20Si2(cast)*. Thus, the study of wear of carbide cutters in the processing of heat-resistant steels shows that the use of ultrasonic cutting in plasma-mechanical processing of steels can significantly reduce the amount of tool wear. The presented results confirm the prospects of using ultrasonic plasma-mechanical cutting of heat-resistant steels with blade tools.

For citation: Abbasov V.A., Bashirov R.J. Features of ultrasound application in plasma-mechanical processing of parts made of hard-to-process materials. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2022, vol. 24, no. 3, pp. 53–65. DOI: 10.17212/1994-6309-2022-24.3-53-65. (In Russian).

*** Corresponding author**
Bashirov Rasim J., D.Sc. (Engineering), Professor
Department of Machine Building,
Azerbaijan Technical University,
AZ 1073, 25 H. Cavid avenue, Baku, Azerbaijan
Tel: +994 (50) 212 22 73,**e-mail:** rasim_agma@aztu.edu.az

Introduction

In mechanical engineering, various hard-to-process materials are widely used for the manufacture of parts and structural elements of equipment for electrochemical, chemical and other industries. The use of hard-to-process and heat-resistant steels for the manufacture of thermal equipment is hampered by the fact that these materials are poorly subjected to machining with edge tools. In this regard, in the production of electrothermal equipment, attempts are being made to increase the efficiency of processing heat-resistant and hard-to-process materials by using various combined methods of chip removal, one of which is machining with plasma heating of the workpiece before processing. Plasma-heated high-temperature steel machining is a combined process in which mechanical energy, together with low-temperature plasma energy, is used to increase performance and reduce cutting tool consumption when machining these materials.

There are various methods for plasma heating of a workpiece during machining [1–6]. These and other works provide data on the performance of plasma-mechanical turning, milling, etc. It has been established that plasma heating improves the machinability of materials in cutting cases when the increase in tool life due to a decrease in the specific cutting work is greater than the negative effect of elevated temperatures on the increase in the intensity of adhesion and tool wear phenomena. As is known, the wear of a cutting tool is an integrated process accompanied with complex and mutually influencing phenomena at the points of contact between the tool with the chip and the workpiece, occurring under conditions of high temperatures and pressures. Therefore, it is recommended to use cutting tools with internal cooling during plasma-assisted machining.

The analysis of research works [7–20] showed that insufficient attention has been paid to the issue of determining the relationship between the wear of the cutting tool and the parameters of plasma-machining of hard-to-process materials. Also, among the available research papers, there are no works devoted to the use of ultrasonic vibrations in combinations of plasma-assisted machining of hard-to-process materials. Therefore, the task was set to investigate the process of plasma-ultrasonic-assisted machining of hard-to-process materials and the wear of the cutting tool that accompanies it.

Hard-to-process materials have a number of such specific physical, chemical and mechanical properties as high strength, high temperature strength, heat resistance, toughness, corrosion resistance, refractoriness, etc. Hard-to-process materials have a complex carbide-forming structure.

High-temperature steels and alloys belong to hard-to-process materials, which, according to their basic composition, are divided into high-temperature steels based on iron, nickel, cobalt and titanium. These steels and alloys are often used in the manufacture of parts for electrothermal equipment.

High-temperature steels based on iron, nickel, cobalt and titanium are difficult to machine with an edge tool, that is, turning and milling due to a number of specific features, in particular:

– dependence of the increase in hardening of high-temperature steels in the process of deformation during cutting on the structure of the crystal lattice of these materials, which determines the number of possible sliding directions during plastic strain in the process of machining. For example, crystals of steels of the ferritic-pearlitic group have a lattice of a body-centered cube with eight possible slip directions; crystals of steels of the austenitic class have the shape of a face-centered cube with nineteen possible slip directions [1];

– high ductility of high-temperature steels, which leads to an increase in microhardness in the chip formation zone during turning, which, in turn, complicates the process of separating materials along the front surface of the cutting edge;

– low thermal conductivity of high-temperature steels, which leads to an increase in temperature on the contact surfaces during machining, causing an increase in the intensity adhesion and diffusion phenomena and, as a result, the destruction of the cutting part of the tool;

– the ability of these materials to maintain its original strength and hardness at elevated temperatures that occur in the zone of deformation and chip flow during cutting, which leads to a very high specific pressure at the point of contact of the material with the tool during the machining;

– the increased abrasive capacity of these steels is due to the presence in it, in addition to the solid solution phase, the so-called "second phase", which forms intermetallic or carbide inclusions leading to increased tool wear during processing;

– low vibration resistance during cutting motion, due to the high hardenability of these materials with uneven flow of the process of its plastic deformation.

The above and other problems associated with the specific characteristics of high-temperature steels require the creation of new technological solutions to improve the machinability of these materials.

Research methodology

One of the methods to improve the machinability of high-temperature steels and alloys is plasma-assisted machining. During plasma-assisted machining of high-temperature steels with an edge tool, the workpiece is heated by a plasma arc. Heating a workpiece made of high-temperature steels improves the machinability of these materials with an edge tool. The use of preheating in the cutting process makes it possible to increase the difference between the contact hardness of the tool and the hardness of the material being processed, which leads to an increase in the durability of the edge tool. That is, during preheating of workpieces made of high-temperature materials during machining with edge tools, a greater softening of the material being processed occurs than the softening of the working surfaces of the cutting tool.

The experiments have shown that during plasma-assisted machining, a high concentration of heat in a small volume makes it possible to control the heating process well, achieving sufficient stability; it is most advisable to use plasma heating when machining hard-to-process materials with a low machinability coefficient. It has been established that the performance of the plasma heating process is higher, the lower the machinability coefficient of high-temperature materials; it should be noted that during plasma-assisted machining, for effective metal cutting, it is necessary to heat the workpiece layer to the cutting depth and the feed rate to the optimum cutting temperature, which is the sum of the temperature preheating and temperature resulting from chip formation. That is, the plasma heating mode should be determined depending on the composition, physical and mechanical parameters of the high-temperature material being processed [3, 4, 6–8].

During plasma-assisted machining, an increase in the heating temperature of the workpiece changes the physical, chemical and mechanical properties of not only the material being processed, but also the material of the tool. It has been established [1-5] that with an increase in the heating temperature of the wear surface, on the one hand, the plasticity of the material being processed increases, and on the other hand, the degree of the chip plastic strain increases. The local heating of the surface layers of the material being processed, which occurs upon contact with the plasma arc, causes a temperature field of a high degree of nonuniformity in the workpiece, which leads to the appearance of extremely nonuniform stress fields in the metal being processed. The nonuniformity of the stress fields is enhanced by structural transformations that occur in part of the volume of the heated metal and the melting of its individual sections. Such a mechanism of action of the plasma arc can lead to microfracture and other discontinuances in the surface layer of the workpiece and help to facilitate the deformation of chip formation during turning and milling.

The decisive influence on the nature and intensity of tool wear is exerted by the ratio between the hardness of the workpiece and tool materials under plasma heating conditions. This ratio is called coefficient of the shape stability. The experiments carried out showed that during the plasma-assisted machining of high-temperature materials the shape stability of hard alloy tools is much higher than that of other tool materials. Therefore, the experiments were carried out with turning tools equipped with inserts made of hard alloys *T15K6*, *T5K10*, *VK8*.

To carry out turning experiments, an installation was created on the basis of a *1A64* type screw-cutting lathe, on which the dimensions of the workpiece being machined make it possible to study the machinability of all types of cylindrical parts used in the production of electrothermal equipment.

The installation consists of a screw-cutting lathe, a power source *APR-403 UKhLCh-2*, a plasma torch holder, a plasma torch, an air duct for supplying to the plasma torch. The plasma torch holder is mounted on the tool holder and is closed by a casing. From the power source by an electric wire, the current is brought to the part through the current collector of the machine spindle. The workpiece is placed in a four-jaw chuck and fixed by the rear center. A tool for ultrasonic turning and cutting of metals is installed on the tool holder. The tool for ultrasonic cutting, fixed on the tool holder of the machine, forms the first stage of the ultrasonic stepped concentrator of mechanical vibrations with a piezoelectric sensor installed on the end section of its free end [5, 6, 9, 10].

The ultrasonic cutter 1 (Fig. 1) contains a cylindrical and conical concentrator – 2 and a piezoelectric emitter 3, rigidly clamped by a reflector 4 through a through-hole 5 and a clamping bolt 6 to the free end of the section of the cutting tool, and forms the second stage of the ultrasonic stepped concentrator of mechanical vibrations. The positive electrodes 7 of the piezoelectric sensor are connected to the input of the voltage amplifier 8 and the indicator, the electrodes 10 of the piezoelectric emitter are connected to the output of the variable frequency generator 12 and the indicator 11, the output of the voltage amplifier is connected to the control input of the variable frequency generator.

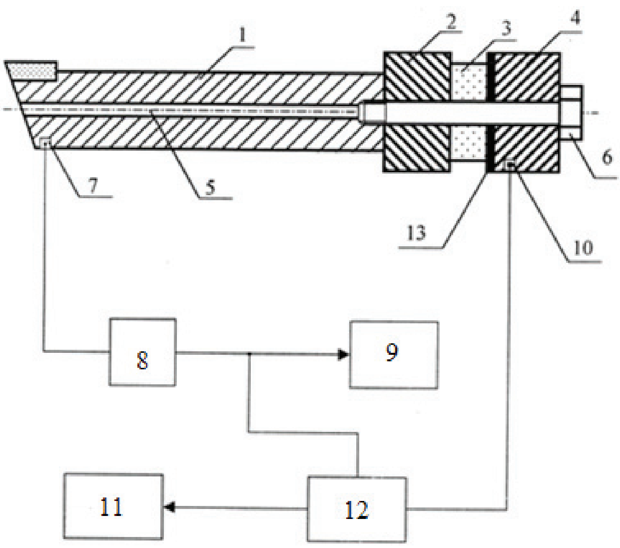

Fig. 1. Device for ultrasonic turning and cutting of metals

One of the electrodes of the piezoelectric emitter is electrically isolated from the contact surface of the reflectors by a gasket 13 made of a dielectric material. Thus, the device for ultrasonic treatment of materials contains a stepped concentrator of ultrasonic vibrations with a variable profile, the working end of which acts as a cutter and a piezoelectric emitter in the form of a washer, sandwiched between the concentrator and the reflector.

The operation of the ultrasonic cutting device is carried out as follows. In the process of plasma-assisted machining of high-temperature steels and alloys, at first, an alternating voltage from the generator output 12 with a frequency equal to the natural frequency of the piezoelectric emitter 3 is supplied to its positive electrodes 10. This leads to the appearance of ultrasonic mechanical vibrations on the surface of the piezoelectric emitter.

Mechanical vibrations are transmitted to the second stage 2 of the concentrator, then, intensifying, the mechanical vibrations of ultrasonic frequency are transmitted to the first stage, concentrated directly on the cutting tool 1 of the device. The workpiece is fixed on the spindle and treatment is carried out, while the operating parameters (speed and cutting force) are measured using a piezoelectric sensor 7, which generates an electrical signal on the surface of its electrodes. This signal is fed to the input of the voltage amplifier 8, from the output of which it is fed to the input of the indicator of the device that converts the analog signal into a digital code.

The features of the plasma-mechanical processing process were studied under ultrasonic cutting conditions during the turning of steel grades *20Cr13Ni18* and *20Cr25Ni20Si2(cast)* (Table).

The outer diameter of the workpieces was 170–196 mm, length – 1500–1800 mm. The workpieces were chunked with an emphasis on the butt end of the chuck and pressed by the rear center. Processing was carried out on the slag and on already machined surface. At the beginning, the pilot arc was turned on and after its automatic transition to the main arc, the longitudinal feed was turned on and a cylindrical section 20-30 mm long was turned to a depth of 7–10 mm. The plasma torch was installed so that the minimum distance from the cutting surface to the plasma torch nozzle at maximum jumping was 5-10 mm. The maximum distance from the plasma torch to the workpiece was taken within L = 30–40 mm. The angular position of the plasma torch was adjusted during the cutting process in order to heat optimally the cutting surface on the workpiece.

Chemical composition of work materials (according to GOST 5632–72)

	C	Si	Mn	Cr	Ni
20Cr13Ni18	≤ 0.20	≤ 1.0	≤ 2.0	22–25	17–20
20Cr25Ni20Si2	≤ 0.20	2–3	≤ 1.5	24–27	18–21

The operating voltage of the power source of the plasma heating device during the experiment varied in the range U = 150–200 V, the operating current varied in the range I = 250–300 A.

The above studies have shown that the rational range of heating the cut layer of the workpiece surface made of high-temperature steel *20Cr23Ni8* under conditions of plasma-assisted machining should be within 700–750 ^{o}C, and when processing steel *20Cr25Ni20Si2(cast)* it should be heated within 800–820 ^{o}C.

The compressed air pressure supplied by the power source to the plasma torch was regulated within 0.15–0.20 MPa. The plasma torch was cooled by tap industrial water with subsequent drain into the sewer.

Ultrasonic vibrations are applied to the cutting edge of the tool, the frequency of which varied within 18–22 kHz, the oscillation amplitude varied within 2–15 µm.

During the experiments, it was found that the selecting the diameter of the plasma torch nozzle opening for heating the surface of the workpiece during the chips formation is one of the important parameters of the plasma heating process.

Technological parameters such as power supply voltage, current, distance from the nozzle to the cutting zone, compressed air pressure, etc. are calculated in order to determine the modes of the process of stable plasma heating of the workpiece under processing conditions.

Therefore, nozzles with hole diameters of 4, 5, 6, 7, 8, and 9 mm were tested. Experiments have shown that when using a nozzle hole with a diameter of 7 mm, the conditions for heating the workpiece are significantly improved, providing a stable flame and better removal of combustion products from the working area.

The experiments were carried out using turning tools with brazed-tip and disposable inserts. The geometric parameters of the cutting part of the tools were: $\gamma = 5–10^{o}$; $\alpha = 8–12^{o}$; $\lambda = 10–15^{o}$; $\varphi = 15–20^{o}$; and the radius of the top of the cutting edge r = 1.5 mm.

To compare the results of the research, the turning of high-temperature steels was carried out both by plasma-assisted machining and with the use of ultrasonic plasma machining.

To compare the results of plasma and plasma ultrasonic cutting, experiments were also carried out without the use of plasma heating and ultrasonic cutting, which showed that when selecting the geometric shape of the inset, it is necessary to provide a chamfer on the front surface of the insert equal to the value of the length feed, as a result of which the tool wedge is hardened [9–11]. At the same time, in order to achieve the appropriate strength of the cutting edge, the value of the clearance angle α was taken a little bit less.

Turning without the use of plasma heating was carried out according to the factory technological processing modes, for example: at a cutting speed V = 10 m/min (n = 160 rev/min), depth of cut t = 3–4 mm, length feed S_l = 0.8 mm/rev.

When conducting experiments to determine the wear of the cutting tool under normal cutting conditions, moderate modes were used, where the depth of cut was within t = 3 mm, length feed S_l = 0.31 mm/rev. When cutting steels *20Cr23Ni18* and *20Cr25Ni20Si2(cast)* at speeds up to 10 m/min, the wear of carbide inserts remains within the permissible. Therefore, in the usual cutting of high-temperature steels, the indicated modes are used. The conducted experiments established that during plasma-assisted machining in order to increase the heating performance, processing should be carried out with an increase in the depth of cut to t = 6 mm [12–16].

The work also studied the wear of inserts made of hard alloy *T15K6* when turning high-temperature steels of the *20Cr23Ni18* and *20Cr25Ni20Si2(cast)* grades under various processing conditions. It was found that the wear of *T15K6* inserts compared to the wear of *T5K10* inserts, when turning these materials, is much greater, therefore, in further studies, tools equipped with inserts made of *T15K6* alloy were not used.

Fig. 2 shows the results of a study of the wear of carbide inserts *T5K10* and *VK8*, where curve reflects the dynamics of wear under normal cutting conditions (V = 10 m/min, t = 3 mm; S_l = 0.31 mm/rev); 2-2′ – during plasma-assisted machining (V = 20 m/min, t = 6 mm; S_l = 0.31 mm/rev; $\dot{I}$ = 250 A; U = 150 V); 3-3′ – when cutting with plasma-ultrasonic-assisted machining (V = 20 m/min, t = 6 mm; S_l = 0.31 mm/rev; $\dot{I}$ = 250 A; U = 150 V; f = 18 kHz; A = 4 μm): 1, 2, 3 – when machining with *T5K10* grade hard alloy inserts: 1′, 2′, 3′ – when machining with *VK8* grade hard alloy inserts.

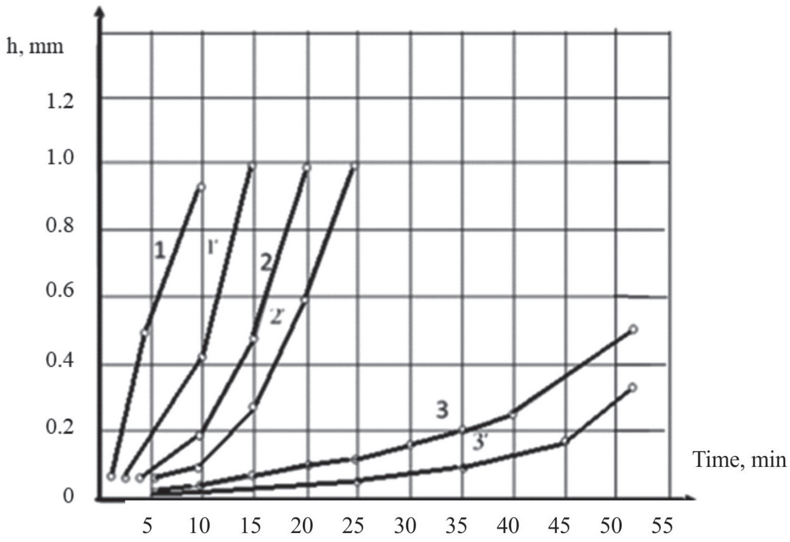

Fig. 2. Wear on the back surface of the cutter under various processing conditions when turning steel *20Cr13Ni18* slag

The wear of the inserts in the normal mode of machining was studied at V = 10 m/min, S_l = 0.31 mm/rev. When the cutting modes increase from the specified value, the cutting tool loses its cutting ability within 2-3 minutes. Plasma-machining and plasma-machining with the use of ultrasound were carried out in the same mode of mechanical cutting.

When processing high-temperature steel grade *20Cr13Ni18* under various cutting conditions, it was found that *T5K10* carbide inserts compared to *VK8* wear faster on the back surface in all types of processing. It was revealed that when turning steel *20Cr13Ni18*, both single-carbide carbide inserts and double-carbide ones wear out significantly more with the usual turning method than with other processing methods [16–23].

Results and discussion

Analysis of the results obtained made it possible to find out that during plasma-assisted turning of steel *20Cr13Ni18*, despite the fact that the depth of cut is 2 times greater (curves 2, 2′, Fig. 2) than during the conventional turning, (curves 1, 1′, Fig. 2), wear of the end flank of the straight turning tool is 1.5–2 times less, subjected to the cutting speed. And during plasma-assisted machining with the use of ultrasound, the wear of inserts (curves 3, 3′, Fig. 2) is 5–10 times less than the wear of inserts during conventional turning (curves 1, 1′). For example, during conventional turning of high-temperature steel *20Cr13Ni18* with a *T5K10* carbide insert for 5 minutes of cutting, wear of the insert is achieved within 0.5–0.6 mm (curves 1 in Fig. 2), and when turning the same steel by plasma-assisted machining using ultrasound, wear of the *T5K10* cutter up to 0.4 mm is achieved within 52 minutes, which indicates a decrease in insert wear by 10 times.

In the current study, five experiments were performed to plot each point.

Experiments have shown that, both with the conventional method and with plasma-assisted machining along the slag, turning tools equipped with *VK8* single-carbide carbide inserts have a number of advantages compared to turning tools equipped with two-carbide carbide inserts. In particular, studies have shown that the nature of the wear of the end flank of the cutting edge of the *VK8* hard alloy inserts is more uniform, the intensity and rate of wear are slowed down, no catastrophic damage is observed, which favorably affects the process of turning steels. And when turning high-temperature steels with *T5K10* carbide inserts, the wear of the end flank of the cutting edge of the insert is uneven, there are traces of microchipping and a wear groove, which leads to a rapid loss of its cutting ability.

Studies have established that the most favorable condition arises when turning high-temperature steels by plasma-ultrasonic machining, both when turning with single-carbide and two-carbide inserts (curves 3, 3′, Fig. 2).

The results of the experiments showed that with the conventional method of turning steel *20Cr13Ni18*, the maximum wear of the inserts is observed after machining during 10–15 minutes. And with plasma-assisted machining, the maximum wear of the inserts is observed after machining during 25 minutes.

It has been established that in the process of plasma-ultrasonic machining, the maximum wear of inserts (h = 1.0 mm) is achieved after 90 minutes. This is due to the fact that when using ultrasound for plasma-assisted machining of high-temperature steels, the formation of microchips in the contact zone occurs under the influence of ultrasonic vibrations by the cutting edge of the inserts. The cutting edge of the cutter receives both in the longitudinal and in the radial ultrasonic vibrations with a frequency of 18 kHz and an amplitude of the order of A = 4 μm, leading to additional deformation of the chip during its descent, which actually eliminates the contact of the chip with the cutting edge.

At the same time, the presence of ultrasonic vibrations improves the conditions for sliding and chip flow in the zone of its formation, which makes it possible to reduce significantly the friction of chips on the contact surfaces of the insert.

Fig. 3 shows the wear curves obtained during the machining of high-temperature steel grade *20Cr25Ni20Si2(cast)*, where 1, 1′ – wear during conventional cutting t = 3 mm, S_l = 0.31 mm/rev: 2, 2′ – wear during plasma-assisted machining t = 6 mm, S_l = 0.31 mm/rev, I = 250 A, U = 150 V: 3, 3′ – wear during plasma-ultrasonic-assisted machining t = 6 mm, S_l = 0.31 mm/rev, I = 250 A, U = 150 V, f = 18 kHz, A = 4 μm: 1, 2, 3 – when machining with *T5K10* grade hard alloy inserts: 1′, 2′, 3′ – when machining with *VK8* grade hard alloy inserts.

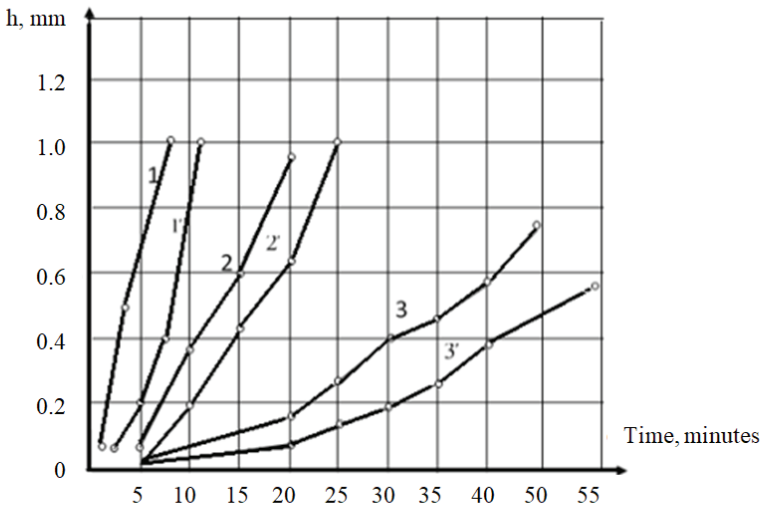

Fig. 3. Wear on the end flank of the cutter under various processing conditions when turning steel *20Cr25Ni20Si2(cast)* slag

Depending on the cutting time, the wear of the insert along the end flank changes similarly to Fig. 2. In other words, when machining the above material with conventional turning, the wear of the insert is much greater during plasma-assisted and plasma-ultrasonic-assisted machining. An analysis of graphs 1, 1′ in Fig. 2 and 3 shows that, as in the turning of high-temperature steels with *T5K10* and *VK8* carbide inserts, the greatest wear of the inserts is observed when turning steel *20Cr25Ni20Si2(cast)*. Studies have established that when machining *20Cr25Ni20Si2(cast)* high-temperature steel in all processing modes, the linear wear of the tool and its intensity are much higher than when machining steel *20Cr13Ni18*. The obtained results are explained by the fact that high-temperature steel *20Cr25Ni20Si2(cast)*, compared with steel *20Cr13Ni18*, contains more alloying elements such as chromium (2 % more), nickel (2 % more), and silicon, which leads to the formation of a large amount of carbides.

A large amount of carbides in steels causes an increase in the intensity of wear of the cutting tool during machining, including plasma-assisted and plasma-ultrasonic-assisted machining.

From the given curves presented in Fig. 2 and 3, it was possible to find out that during plasma-assisted machining of high-temperature steels, the wear rate of tool material is reduced compared to the conventional cutting method. At the same time, tool life increases by about 1.8–2.5 times compared to the conventional machining method.

Studies have shown that with the conventional method of high-temperature steels turning, high specific loads and temperatures are observed on the contact surfaces of the cutting insert, which are continuously formed during the cutting process, which creates unfavorable conditions for the operation of the cutting tool. At the same time, high-temperature steels tend to adhere to the tool material and have high strength, which leads to significant inclinations during plastic deformation of the contact zone when cutting, and to an increase in the wear rate of the cutting blade during conventional cutting.

When processing high-temperature steels with plasma heating, the loads acting on the cutting face of the tool are reduced due to preheating. Also, the contact pressures on the back surface of the cutting blade are significantly reduced compared to the pressure when cutting with the conventional method, i.e. without preheating. Therefore, when processing materials by cutting with plasma heating, the working conditions of the tool are improved, and the probability of plastic deformation of the cutting edge of the insert is reduced.

The experiments performed (Fig. 2 and 3)showed that when processing heat-resistant steels by plasma-ultrasonic-assisted machining, the durability of the cutting tool, both hard alloy grade *VK8* and hard alloy grade *T5K10*, is 4-5 times higher compared to the plasma method of processing, and is 10–12 times higher compared to compared to conventional machining (without plasma heating). This is due to the kinematic feature of the ultrasonic cutting process and the source of ultrasonic vibrations.

Cutting tools, in the designs of which a concentrator of mechanical vibrations made of a titanium alloy of grade VT-1 is used, are used in the processing of high-temperature steels. The use of a titanium alloy as a concentrator of ultrasonic vibrations can significantly reduce the frequency loss in the process of transmitting vibrations to the cutting edge and reduces the heating temperature of the insert body. This is due to the fact that titanium alloys have a sufficiently high mechanical strength and low wave resistance, as well as a low sound absorption coefficient.

Experiments have shown that when using ultrasonic vibrations in the process of turning high-temperature steels under plasma heating, the durability of the cutting tool increases due to the vibration of the cutting edge of the tool. This phenomenon makes it possible to improve chip formation in the contact zone of machining. When turning, ultrasonic waves vibrate the cutting edge of the insert 18,000 times for one minute about (18 kHz), which creates additional chip deformation, and the presence of ultrasonic vibrations moves the tip of the cutting edge of the tool both in the radial and longitudinal directions. Therefore, under these conditions, the formation of chips is fundamentally different from the conventional method of metal cutting. Namely, during ultrasonic turning, the transmission of ultrasonic vibrations to the tool significantly reduces shear deformations in the cutting zone; also, in the chip shear zone, many microcracks form in its metal separation plane. In addition, the presence of high-frequency vibrations in the cutting edge of the tool does not allow the accumulation of build-up on its surface, the sharpness of the wedge in the contact zone is maintained, which reduces the friction conditions of the chips on the cutting face, thus reducing the cutting force and heating of the cutting tool.

It should be noted that with the varying the parameters of ultrasonic vibrations, it is possible to control the process of chip formation in such a way that the cutting edge of the tool can retain its geometric shape due to which the point of contact of the chip changes when it leaves the cutting zone.

For example, with an increase in the amplitude of ultrasonic vibrations in the contact zone, the cyclic effect of ultrasonic vibrations on the working surface increases, leading to an increase in the fatigue strength of the surface. In addition, during ultrasonic cutting of metals, due to ultrasonic vibrations, the kinematic rake angle of the tool increases, which leads to an improvement in the conditions for the insert wedge feeding-in into the material being machined and, therefore, the dynamics of material machinability decreases.

Thus, on the basis of a comprehensive study, the following conclusions are made:

1. The use of ultrasound in the plasma-assisted machining of high-temperature steels makes it possible to reduce (up to 10 times) the wear of hard-alloy inserts.

2. It has been established that with conventional machining of steel *20Cr13Ni18*, the wear of *T5K10* carbide inserts is 1.5...2 times greater than that of *VK8* inserts.

3. When turning high-temperature steels *20Cr13Ni18* and *20Cr25Ni20Si2(cast)* both with the conventional method and with the plasma-assisted method using ultrasound, the wear of single-carbide hard alloy *VK8* is much less than when machining with two-carbide hard alloy *T5K10*.

References

1. Poduraev V.N. *Rezanie trudnoobrabatyvaemykh materialov* [Cutting hard-to-cut materials]. Moscow, Vysshaya shkola Publ., 1974. 587 p.

2. Poduraev V.N., Sokolov N.M. Plazmenno-frezernaya obrabotka krupnykh svarnykh uzlov iz vysokoprochnykh stalei [Plasma-milling processing of large welded assemblies from high-strength steels]. *Stanki i instrument = Machines and Tooling*, 1989, no. 7, pp. 23–28. (In Russian).

3. Reznikov A.N., Chertorizhskii Yu.N., Murin I.A. Opredelenie rezhima plazmenno-mekhanicheskoi obrabotki [Determination of the mode of plasma-mechanical treatment]. *Stanki i instrument = Machines and Tooling*, 1990, no. 1, pp. 30–31. (In Russian).

4. Mikhal'kova S.A. Plazmenno-mekhanicheskaya obrabotka detalei metallurgicheskogo oborudovaniya [Plasma-mechanical processing of parts of metallurgical equipment]. *Vestnik mashinostroeniya = Russian Engineering Research*, 1989, no. 5, pp. 53–56. (In Russian).

5. Maslov A.R., Skhirtladze A.G. *Obrabotka trudnoobrabatyvaemykh materialov rezaniem* [Processing of hard-to-cut materials by cutting]. Moscow, Innovatsionnoe mashinostroenie Publ., 2018. 208 p. ISBN 978-5-6040281-0-0.

6. Abbasov V.A., Bashirov R.D. *Ustroistva dlya ul'trazvukovogo rezaniya i rastachivaniya metallov* [Devices for ultrasonic cutting and boring of metals]. Patent AZ, no. I 2003.0014, 2003.

7. Bashirov R.D., Abbasov V.A. Vybor parametrov p'ezoelementov i raschetov tokarnogo reztsa-kontsentratora dlya ul'trazvukovogo tocheniya [Choice of parameters of piezoelectric elements and calculations of a turning tool-concentrator for ultrasonic turning]. *Mekhanika – mashinostroenie = Mechanics – Machine Building*, 2001, no. 1, pp. 42–45. (In Russian).

8. Bashirov R.D., Abbasov V.A. [Devices for ultrasonic turning and cutting of metals]. *48-ya uchebno-metodicheskaya nauchno-tekhnicheskaya konferentsiya professorsko-prepodavatel'skogo sostava i aspirantov AzTU* [Proceedings of the 48th educational and methodological scientific and technical conference of the faculty and postgraduate students of AzTU]. Baku, 2001, pt. 2, pp. 79–81.

9. Shchitsyn Yu.D., Fomin I.B., Strukov N.N., Belinin D.S., Kuchev P.S. Regulirovanie gazodinamicheskikh parametrov szhatoi dugi na vykhode dvukhkamernogo plazmotrona [Regulation of the gas-dynamic parameters of the compressed arc at the output of a two-chamber plasma torch]. *Svarka i diagnostika = Welding and Diagnostics*, 2011, no. 6, pp. 14–16.

10. Ablyaz T.R., Belinin D.S. Wire electrical discharge machining of items after plasmatic surface hardening. *Middle-East Journal of Scientific Research*, 2014, vol. 19, no. 8, pp. 1096–1098. DOI: 10.5829/idosi.mejsr.2014.19.8.21041.

11. Churyumov A.Yu., Pozdnyakov A.V. [Hot deformation behavior and microstructure of the stainless heatresistant steel AISI 310]. *Aktual'nye problemy fizicheskogo metallovedeniya stalei i splavov: sbornik tezisov dokladov XXV Ural'skoi shkoly metallovedov-termistov* [Proceedings of the XXV Ural School of Thermal Metallurgists "Actual Problems of Physical Metallurgy of Steels and Alloys"], Ekaterinburg, 2020, pp. 185–187. (In Russian).

12. Tarasov S.S., Koryazhkin A.A. Povyshenie effektivnosti tokarnoi obrabotki detalei GTD iz zharoprochnykh nikelevykh splavov keramicheskim instrumentom [Improving the efficiency of turning of the gte heat-resistant nickel alloys, ceramic tool]. *Spravochnik. Inzhenernyi zhurnal = Handbook. An Engineering Journal*, 2012, no. 11, pp. 14–19.

13. Volkov D.I., Proskuryakov S.L., Tarasov S.S. Primenenie vysokoskorostnoi tokarnoi obrabotki dlya izgotovleniya detalei iz zharoprochnykh nikelevykh splavov keramicheskim instrumentom [Application of high-speed turning for high-temperature alloys details manufacturing by instruments with cutting ceramics in conditions of high pressured lubricant coolant feeding]. *Vestnik Rybinskogo gosudarstvennogo aviatsionnogo tekhnicheskogo universiteta im. P.A. Solov'eva*, 2012, no. 2, pp. 134–137. (In Russian).

14. Volkov D.I., Tarasov S.S. Raschetnoe opredelenie parametrov secheniya sreza pri vysokoskorostnoi tokarnoi obrabotke krivolineinykh poverkhnostei detalei GTD iz zharoprochnykh nikelevykh splavov [Estimated calculation of cut section parameters at high-speed turning processing of curvilinear surfaces of gte details made of heat resisting nickel alloys]. *Vestnik Rybinskogo gosudarstvennogo aviatsionnogo tekhnicheskogo universiteta im. P.A. Solov'eva*, 2013, no. 1, pp. 61–68. (In Russian).

15. Koryazhkin A.A., Tarasov S.S. Povyshenie effektivnosti protsessa tokarnoi obrabotki krivolineinykh poverkhnostei detalei iz zharoprochnykh splavov keramicheskim instrumentom [Improving the efficiency of the process of turning curvilinear surfaces of parts from heat-resistant alloys with ceramic tools]. *STIN = Machines and Tooling*, 2013, no. 8, pp. 23–27.

16. Leppert T. Surface layer properties of AISI 316L steel when turning under dry and with minimum quantity lubrication conditions. *Proceedings of the Institution of Mechanical Engineers. Pt. B: Journal of Engineering Manufacture*, 2012, vol. 226, iss. 4, pp. 617–631. DOI: 10.1177/0954405411429894.

17. Bushlya V., Zhou J., Ståhl J.E. Effect of cutting conditions on machinability of superalloy Inconel 718 during high speed turning with coated and uncoated PCBN tools. *Procedia CIRP*, 2012, vol. 3, pp. 370–375. DOI: 10.1016/j.procir.2012.07.064.

18. Attia H., Tavakoli S., Vargas R., Thomson V. Laser-assisted high-speed finish turning of superalloy Inconel 718 under dry conditions. *Procedia CIRP*, 2010, vol. 59, pp. 83–88. DOI: 10.1016/j.cirp.2010.03.093.

19. Prihandana G.S., Mahardika M., Hamdi M., Mitsui K. Effect of low-frequency vibration on workpiece in EDM processes. *Journal of Mechanical Science and Technology*, 2011, vol. 25, no. 5, pp. 1231–1234. DOI: 10.1007/s12206-011-0307-1.

20. Kötter D. *Herstellung von Schneidkantenverrundungen und deren Einfluss auf das Einsatzverhalten von Zerspanwerkzeugen*. These. Universität Dortmund. Vulkan-Verlag, 2006. 107 S. ISBN 3802787366. ISBN 978-3802787362.

21. Takhman S.I. Razrabotka edinykh modelei protsessa iznashivaniya instrumental'nykh tverdykh splavov [Development of unified models of the instrumental hard alloys wear-out process]. *Vestnik mashinostroeniya = Russian Engineering Research*, 2008, no. 9, pp. 56–59.

22. Astakhov V.P., Davim P.J. Tools (geometry and material) and tool wear. *Machining*. Ed. by P.J. Davim. London, Springer, 2008, pp. 29–57. DOI: 10.1007/978-1-84800-213-5_2.

Conflicts of Interest

The authors declare no conflict of interest.

© 2022 The Authors. Published by Novosibirsk State Technical University. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).