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Cutting ceramics for turning of specialised stainless hard-to-machine steel

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Abstract: This study shows the possibility of using cutting ceramics as a turning tool. Replaceable standard cutting plates made of VOK-60 and VOK-71 cutting ceramics are used. In the work, based on simulation modelling in the DEFORM software environment, the possibility of high-speed processing with the specified cutting ceramics is substantiated and then experimentally confirmed. Additionally, the authors propose to apply hardening coatings by condensation with ion bombardment, which ensures an increase in the cutting speed to 100 m/min and more with an increase in the service life of the cutting ceramics from 3 to 3.8 times. The maximum stresses in the tool material and the deformation rate of the process material are studied. To select rational solutions in simulation modelling, the authors used the "temperature in the cutting zone", "stresses in the tool material", and "tool wear" parameters, which characterise the combined tension of the tool material. The transition from these parameters to the predictive design of cutting ceramics was performed by measuring the cutting force during natural cutting. The measured values of the cutting force components were used to calculate the stresses in the tool material. The study confirmed the hypothesis that the cutting ceramics is capable of operating under the conditions of processing viscous hard-to-machine corrosion-resistant specialised stainless steels such as 09H17N7Yu (C-0.09; Cr-17; Ni-7; Al-1) grade (EU 1.4568, X7CrNiAl17-7), which have a high content of chromium (16–17.5 %) and nickel (7–8 %). The authors propose original technological methods to improve the performance of the cutting ceramics through special heat treatment and coating deposition. In particular, heat treatment in a vacuum at a temperature of 1100–1400 °C for 20–40 min increased the bulk strength of the ceramics, and additional thermochemical treatment by ion nitriding performed at the final stage of heat treatment made it possible to alloy the bond.

Keywords: cutting ceramics; turning of stainless steel; turning process modelling; cutting speed.

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INTRODUCTION

Mechanical processing of hard-to-machine corrosion-resistant stainless steels, such as 09H17N7Yu (C-0.09; Cr-17; Ni-7; Al-1) steel, is a problem for many mechanical engineering industries. This is due to the high content of chromium (16–17.5 %) and nickel (7–8 %) in the 09H17N7Yu steel. The scope of application of this steel is growing: it is used in shipbuilding, marine structures, chemical and food industries, and space and defence industries. Accordingly, the share of tool costs in the cost of manufactured products is growing. Traditionally, such stainless steels are processed with hard-alloy metal-cutting tools. In this case, the cutting speed cannot exceed 50 m/min; extra measures can increase it to 60 m/min. This situation slows down the growth of processing productivity. Major measures are needed.

In the Russian literature, the authors did not find any publications dealing with solving this problem. Publications on the use of cutting ceramics under other conditions are available [1; 2], but they do not solve the problems of increasing the productivity of processing the specified stainless steel. Foreign publications [3–6] consider the issues of applying cutting ceramics in a general sense, i. e., to all grades of stainless steels. They do not refer to the 09H17N7Yu steel grade or similar foreign steels. In the catalogues of the world's leading tool companies – Walter (Germany), Sandvik Coromant (Sweden), Mitsubishi (Japan), ISCAR (Israel), the recommendations for processing special stainless steels are of a general nature, without specifying steel grades, i. e., all hard-to-machine stainless steels are combined into one conditional group. Testing of their recommendations on Russian 09H17N7Yu steel showed that VOK-60 and VOK-71 cutting ceramics are destroyed in the first minutes of cutting [1; 2]. This allows concluding that the recommendations are inconsistent and do not solve the issue of increasing the processing productivity in relation to turning of 09H17N7Yu steel.

The authors have their own experience in processing hard-to-machine stainless steels with hard-alloy metal-cutting tools. Thus, the works [1; 2] show that milling with monolithic hard-alloy end-milling cutters is possible, but not promising due to the limited period of their service life. The use of interlocking side mills with mechanical fastening of hard-alloy cutting plates is more promising. The indicated works present the results of using different interlocking side mills and recommendations on the parameters of their cutting mode.

The efficiency of using hard-alloy tools is limited in terms of processing productivity due to the low cutting speed. Therefore, this paper considers the experience of more highly productive processing due to the use of cutting ceramics. The work is performed on the example of turning Russian 09H17N7Yu steel and similar hard-to-machine 12H18N10T, 13H15N5 AM-3 stainless steels. The DEFORM software environment was used for simulation modelling of operational properties [7] and physical and technical characteristics of the most rational tool materials. The study was aimed at determining the necessary (input and output) variables in simulation modelling. The authors assessed the possibility of using VOK-60 and VOK-71 black cutting ceramics for high-performance turning of 09H17N7Yu steel grade and similar 12Kh18N10T, 13Kh15N5 and AM-3 steel grades. At the same time, the possibility of increasing the cutting speed to 100 m/min or more by using wear-resistant coatings on the cutting ceramics was assessed.

The aim of this work is to study the possibility of high-performance turning of blanks made of hard-to-machine 09H17N7Yu steel with a cutting speed of more than 50 m/min by applying nanostructured coatings to the VOK-60 and VOK-71 cutting ceramics and by means of preliminary heat treatment.

METHODS

Methodological approach to solving the problem and its tasks

The work uses a methodological approach to the development of turning cutting plates made of tool cutting ceramics, based on the simulation modelling of the cutting tool in the DEFORM software environment [7] equipped with a large number of applications in the form of different libraries. This allowed selecting new modelling options and designing different operating conditions for the cutting tool. The authors considered a flat orthogonal free cutting scheme representing the penetration of a prismatic cutting wedge into the material of the blank. The cutting wedge was taken as a solid body fully corresponding to the shape and geometry of a standard replaceable plate. The following restrictions were specified: preventing the coating destruction according to the brittle mechanism; preventing plastic deformation of the coating and substrate due to excess temperatures in the cutting zone. For the simulation modelling of turning with cutting ceramics, an approach known from work [7] was used, but with a significant revision of the approach.

The mathematical framework of the DEFORM software environment is based on the calculation of internal stresses in the material. The stress tensor was used to describe them. The equation and characteristics of the stress tensor are given below, they use the notations adopted in work [7] with their dimensions:

$$\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}.$$

Here, normal stresses σ and shear stresses τ are considered along the corresponding *X*, *Y* and *Z* coordinate axes. One of the main characteristics of the stress tensor is its quadratic invariant, which is usually called the effective stress:

$$\sigma_i = \sqrt{\begin{aligned}&\frac{1}{2}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right] + \\ &+ 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)\end{aligned}}.$$

The element deformation is described by the ε_x, ε_y, ε_z, γ_{xy}, γ_{yz}, and γ_{zx} components, which are determined by the displacements of the *u*, υ, ω element in the direction of the *x, y, z* coordinates, respectively:

$$\varepsilon_x = \frac{\partial u}{\partial x}; \quad \gamma_{xy} = \frac{\partial \upsilon}{\partial x} + \frac{\partial u}{\partial y};$$
$$\varepsilon_y = \frac{\partial \upsilon}{\partial y}; \quad \gamma_{yz} = \frac{\partial \omega}{\partial y} + \frac{\partial \upsilon}{\partial z};$$
$$\varepsilon_z = \frac{\partial \omega}{\partial z}; \quad \gamma_{zx} = \frac{\partial u}{\partial z} + \frac{\partial \omega}{\partial x}.$$

It is accepted that it is sufficient to introduce the following input parameters and conditions: the physical and mechanical characteristics of the materials being processed and the architecture (features of the design, composition, and application technology) of the tool coatings. It is accepted that it is sufficient to obtain the output predicted results for the "temperature in the cutting zone", "stresses in the tool material", and "tool wear" parameters. If necessary, the "tool material deformation" and "tool material deformation rate" parameters were additionally used. This allowed characterising the combined tension state of the tool. The transition from these parameters to the predictive design of the coating architecture was carried out by monitoring the cutting force during natural cutting. The values of the cutting force components were used to calculate the stresses in the tool material according to the professor S.I. Petrushin's well-known dependence [6; 7].

Predictive design of cutting ceramics was carried out by measuring the cutting force during natural cutting. All three cutting force components were measured during cutting. The transition from the values of the cutting force components to the stresses in the tool material was carried out, according to the dependencies given in works [6–9]:

$$\sigma_{\max} = 2 \cdot \frac{P_y \cdot [\cos\gamma \cdot \sin(\gamma+\Theta) - \sin\alpha \cdot \cos(\alpha-\Theta) + \beta \cdot \cos\Theta]}{r \cdot \left[\left(\sin^2\alpha - \cos^2\gamma\right) - \beta^2 + \left(\sin\alpha \cdot \cos\alpha - \sin\gamma \cdot \cos\gamma\right)\right]} +$$

$$+ \frac{P_z \cdot [\sin\alpha \cdot \sin(\alpha-\Theta) - \cos\gamma \cdot \cos(\gamma+\Theta-\beta \cdot \sin\Theta)]}{r \cdot \left[\left(\sin^2\alpha - \cos^2\gamma\right) - \beta^2 + \left(\sin\alpha \cdot \cos\alpha - \sin\gamma \cdot \cos\gamma\right)\right]},$$

where P_y is the radial component of the cutting force;
P_z is the main component of the cutting force;
α is the main back angle;
γ is the rake angle;
r and Θ are the polar coordinates in the main secant cutting plane.

Based on the results of the experimental tests, graphs showing the dependence of the wear value on the coatings used were constructed. According to the rate of wear for an equal processing time, the most rational coatings were selected, based on the fact that the lower is the rate of wear, the more rational is the coating. Metals of groups 4–8 of the Mendeleev's periodic table (Ti+TiN+(NbZrTiAl)N, Ti+Zr+ZrN+(ZrAlNb)N, and Ti+Zr+TiCN+(TiZrAl)CN) were used as coatings. A nitride or carbonitride coating layer was applied over the metal coating layer to reduce interaction with the blank.

The model shown in Fig. 1 was used to develop (virtual design in the DEFORM software environment) rational options for cutting ceramic tools, and consequently, to design the architecture of their coatings. The model took into account options in which the durability period (it is called the service life P in the model) should increase by 2–4 times, productivity N and quality K of processing should increase in comparison with the original option, and tool costs Q should decrease.

Within the specified approach, it is accepted that it is possible to apply coatings to the tool material as a measure to improve the tool performance. This method has proven itself in the processing of basic structural materials with a hard-alloy tool. The proposed approach borrows this methodology to improve the performance of cutting ceramics, developing and adapting it to specific tool operating conditions.

The authors considered it methodologically necessary to compare the manufacturing technologies of ceramic tools and hard-alloy tools with coatings. For ceramic tools, the recommendations of work [10] were used; for hard-alloy tools, the recommendations of work [11] were used.

Comparison of special aspects of technological processes for manufacturing ceramic and hard-alloy tools

The technological process (TP) for manufacturing ceramic and hard-alloy tools is generally presented in Fig. 2. Block A shows what exactly is taken into account – the base of the tool material, for example, VOK-60 cutting ceramics or VK8 tool hard alloy. This is considered the first stage of tool production. The next stage of the technological process of tool production is coating deposition (block B). This sequence of stages allowed obtaining technological processes called the TP1 group. Technological processes in the TP1 group include the use of a particular tool base material, a particular coating deposition process, etc.

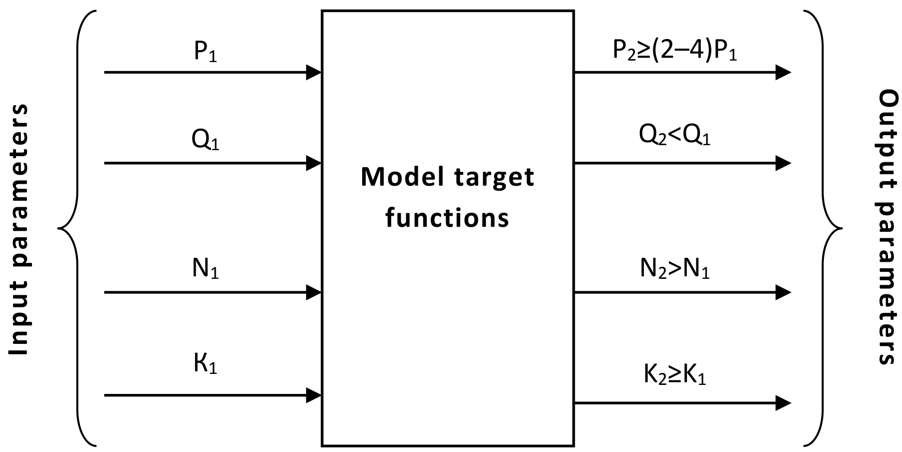

***Fig. 1.** A model for the implementation of simulation (virtual) design of tool materials:*
P – service life; Q – tool costs; N – productivity; K – quality of treatment
***Рис. 1.** Модель реализации имитационного (виртуального) проектирования инструментальных материалов:*
P – период стойкости; Q – затраты на инструмент; N – производительность; K – качество обработки

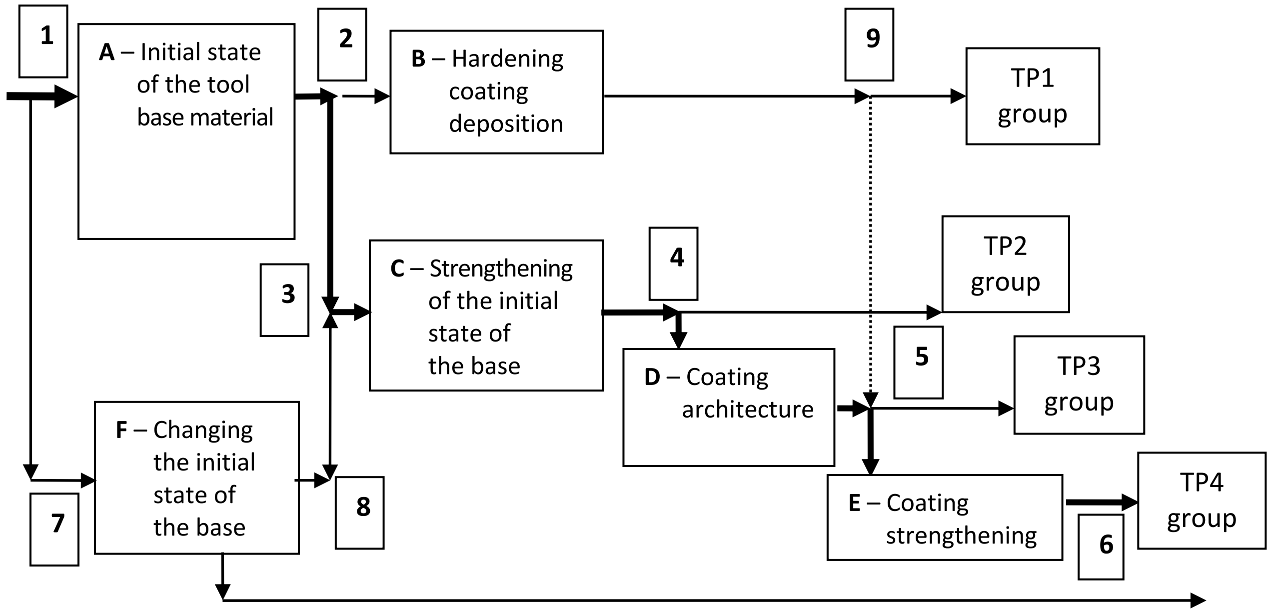

Fig. 2. *Generalized scheme of technological processes for manufacturing hard-alloy and ceramic tools: TP1, TP2, TP3, TP4 – technological processes; 1, 2…9 – nodal points of technological process branching*
Рис. 2. *Обобщенная схема технологических процессов изготовления твердосплавного и керамического инструмента: TP1, TP2, TP3, TP4 – технологические процессы; 1, 2…9 – узловые точки разветвления технологических процессов*

If it was necessary to apply strengthening effects on the tool base material (for example, ion nitriding of the base, i. e. VK8 alloy), a chain of actions by branches at points 2 and 3 is formed. This sequence of stages allowed obtaining technological processes called the TP2 group. TP2 were developed and applied in order to improve the operational performance of the cutting tool. However, TP1 are simpler to be implemented and cheaper.

If after implementing TP1 or TP2, the tool performance or processing productivity turned out to be insufficient, then there is a need for a TP3 group of technological processes. This can be achieved by coating architecture (block D). Architecture is understood as the creation of a particular coating (single-layer, multi-layer, nitride, carbide, carbonitride, with the same or different layer thicknesses, using the same or different coating deposition methods, etc.).

If this is not enough, then by the coating strengthening (block E) it is possible to implement the TP4 group of technological processes. The coating strengthening is understood as extra measures to improve the performance properties of the coating as a whole or its particular layers. For example, when applying the first coating layer with a thickness of less than 1 µm, the coating may contain discontinuities, i. e. uncovered areas of the base of the tool material. This is undesirable. Discontinuities can provoke the seizure of the base material of the tool material with the material being processed or reduce the adhesion strength of this layer to the next one. To "heal" such discontinuities, extra effects can be used, for example, ion nitriding [11] of the layer with discontinuities before applying the next layer.

Technologically, TP4 is more complex than TP3, and TP3 is more complex than TP2 and TP1. Accordingly, the cost of implementing these technological processes is different: for TP4 it is higher than for TP3, etc. However, the performance of the tool manufactured according to TP4 is higher than that of TP3, etc.

If it turns out that the performance of the tool manufactured according to TP4 is still insufficient for specific conditions of processing blanks of parts, then it is possible to influence purposefully the base of the tool material in order to improve its operational properties. We are talking about minimising or eliminating those defects on the base of the tool material that formed during its manufacture, for example, microcracks of mechanical or thermal origin formed during grinding of cutting plates or when sharpening the required edges, fillets, and radii on them. Such cracks are present both on hard-alloy plates [11] and on cutting ceramics [10]. In these cases, it is possible to change the initial state of the tool material base (block F), for example, to heal these microcracks by applying [11], one or another coating before applying the main coating or subject the tool base to "etching" by ion nitriding [11].

Thus, a group of technological processes is implemented (we will conventionally designate it as TP*i*, it is not shown in Fig. 2), which is more complex than TP4. Such a technological process is more expensive, but it can be the most effective in terms of increasing the cutting tool performance and increasing the processing productivity.

Materials and methods

In this work, VOK-60 and VOK-71 cutting ceramics (GOST 19043-80, 25003-81) were used as the material for the cutting tool.

The authors used hard-to-machine 09H17N7Yu (EI 973) stainless steel (old designation is 0H17N7Yu (analogues in the European Union – 1.4568, in the USA – 631.S17700, in England – 301 S81)). It is produced in accordance with GOST 19904-90 (cold-rolled sheet metal products) and GOST 7350-77 (Standard ST SEV6434-88).

For comparison and generalisation of the results, the authors also used less durable 12H18N10T and 13H15N AM-3 stainless steels. 13H15N AM-3 steel was accepted for analysis as the base one (ordinary steel that does not present any particular difficulties during blade processing). 12H18N10T steel was chosen as the hard-to-machine one. This steel is unique because its tensile strength is significantly affected by heat treatment conditions.

12H18N10T steel is manufactured according to GOST 5362-2014 "Stainless steels and corrosion-resistant, heat-resistant and heat-proof alloys", position 6-42. It contains 17–19 % of chromium and 9–11 % of nickel. Its Brinell hardness HB is 179 MPa. Impact toughness KCU is 285 kJ/cm^2. Information on the strength of this steel varies, for example, the ultimate strength is σ_{-1}=279 MPa, σ_B=610 MPa, $\sigma_{0.2}$=196–236 MPa. The closest substitutes are 08H18G8N2T and 12H18N9T steels. The analogues in the USA are 321, 321H, S32109 steels, in Germany – X12CrNiNi8-9.

13H15N5 AM-3 steel (other designations – EP310, VNS-5) is produced according to the industry standard OST 1 90005-91 and according to the technical specifications TU14-1-1271-75 of the manufacturer. Its closest substitutes are 07H16N6 (EP-288), 18H14N4 AM-3 steels. It has a good combination of strength, impact toughness and ductility. The difficulty of its processing is caused by the significant amount of chromium (14–16 %) and nickel (4–6 %). Its hardness depends on many parameters, primarily on the conditions of its strengthening. A small tensile strength (500–800 MPa) of this steel is noted during its heat treatment under normal conditions. During cold hardening, the tensile strength increases to 1200–1700 MPa.

Heat treatment and coating deposition were carried out in a Bulat installation (Russia) operating using the condensation method with ion bombardment. Heat treatment in a vacuum was carried out by heating to 1100–1400 °C for 20–40 min. Metals of groups 4–8 of the periodic table were used as coatings. The use of evaporable cathodes made of metals from groups 4–8 of the periodic table in the Bulat installation allowed producing various coatings. The following coatings were considered as the most rational:

a) the lower layer is made of titanium, a titanium nitride layer is deposited on it, then a Ti+TiN+(NbZrTiAl)N nitride of a combination of niobium, zirconium, titanium, and aluminium is deposited;

b) the lower layer is made of titanium, a zirconium layer is deposited on it, a zirconium nitride layer is deposited on it, and then a Ti+Zr+ZrN+(ZrAlNb)N nitride of a combination of zirconium, aluminium, and niobium is deposited;

c) the lower layer is made of titanium, a zirconium layer is deposited on it, then a titanium carbonitride layer is deposited and then a Ti+Zr+TiCN+(TiZrAl)CN carbonitride of a combination of titanium, zirconium, and aluminium is applied.

Cutting plates made of VOK-60 and VOK-71 cutting ceramics were tested in their different states, namely:

a) in the as-delivered condition supplied from the manufacturer (OOO Technical Ceramics Plant, Aprelevka, Moscow Region);

b) after additional heat treatment (in a vacuum at a temperature of 1100–1400 °C for 20–40 min), which allowed for the relaxation of internal stresses in the plate; this increased the strength of the ceramics;

c) after the plates were subjected to additional heat treatment followed by ion nitriding in a Bulat-type installation, ion bombardment allowed alloying the bond, which increased the strength of the grain boundaries of the cutting ceramics;

d) after the plates were subjected to the application of hardening coatings in a Bulat-type installation.

In each type of these tests, ten (or more if necessary) square tetrahedral plates were used, i. e. at least 40 tests (ten plates with four cutting edges). Since there were four types of tests (listed above as a, b, c, and d), the total number of tests was 160. Since the cutting plates were double-sided (i. e. they could be both rotated and turned over with the backside), 320 final tests were conducted.

The operating time of each cutting edge was monitored until 0.5 mm wear along the back face or until the cutting edge chipped.

RESULTS

When using the technological processes for manufacturing hard-alloy and ceramic tools according to the scheme shown in Fig. 2, the following was experimentally identified:

a) the tool life period before 0.5 mm wear on the rear face when turning a blank made of 09H17N7Yu steel, in the case of using VOK-60 and VOK-71 cutting ceramics, is up to 7–10 times higher for TP1 and TP4 in comparison with a tool made of VK8 hard-alloy material;

b) in this case, the processing productivity of VOK-60 cutting ceramics in comparison with VK8 hard-alloy cutting tool increases up to 1.4–1.6 times with the same cutting mode parameters, and it increases more than 2 times for VOK-71 cutting ceramics. This makes it possible to consider that an arsenal of technological processes has been developed that allows choosing the most rational technological process for the tool life period for specific processing conditions.

Table 1 shows the results of applying cutting ceramics using the VOK-71 grade as an example. The table indicates the operating time (service life) of the cutting plate for external turning of a 09H17N7Yu steel blank until the plate wears out to 0.5 mm or until the cutting edge breaks. VOK-71 ceramics in its initial state had a service life of 5 min. VOK-71 ceramics that was thermally treated had a service life of 9 min, which is 1.8 times higher than the ceramics in its initial state. The reason for such an increase in the service life is the relaxation of internal stresses in the cutting ceramics after heat treatment. VOK-71 ceramics after heat treatment and ion nitriding had a wear life of 14 min. This is 2.8 times higher in comparison with the ceramics in the initial state and 1.5 times higher than that of the ceramics after heat treatment. Such a positive result in terms of the service life of cutting ceramics is accompanied by a significant increase in processing productivity, compared to the use of a hard-alloy cutting tool due to the increased cutting speed (120–140 m/min for cutting ceramics and 50 m/min for a hard alloy, i. e. by 2.6 times).

Examples of implementing simulation modelling in the DEFORM environment are shown in Fig. 3 in the form of screenshots for VOK-71 ceramics (Fig. 3 a, 3 b), and VOK-71 ceramics with a Ti+TiN+(NbZrTiAl)N coating (Fig. 3 c, 3 d), where a and b are the maximum primary stresses, c and d are the resulting strain rates. From the comparison of screenshots using the VOK-71 example, it is clear that the maximum primary stresses and resulting strain rates are preferable in the case of using a coating, in this case the Ti+TiN+(NbZrTiAl)N coating.

The numerical values of the longitudinal, radial and vertical components of the cutting forces are given in Table 2. From the table data, it follows:

a) the highest values of the cutting force components occur when turning 09H17N7Yu steel in comparison with 12H18N10T and 13H15N AM-3 steels, i. e. this is the case when the minimum period of tool life should be expected;

b) the use of uncoated cutting ceramics leads to an increase in all cutting force components, therefore, the use of a coating is rational;

c) in all the cases considered, the vertical component of the cutting force dominates, therefore, it will limit the period of tool life.

Table 3 presents the results obtained during the simulation modelling of the architecture of different coatings. The table shows how many times the service life of cutting ceramics is predicted to increase when applying one of the three studied coatings. The effect of the Ti+TiN+(NbZrTiAl)N coating is shown for the entire range of cutting speeds. The effect of the other coatings is shown selectively for those cases where the maximum increase in the service life was predicted. It follows from Table 3 that:

a) the use of the Ti+TiN+(NbZrTiAl)N coating is preferable at a cutting speed of less than 100 m/min for VOK-60 cutting ceramics, with an increase in the cutting speed, the use of VOK-71 ceramics is preferable;

b) at high cutting speeds, the Ti+Zr+(TiCN)+(TiZrAl)CN coating is preferable for VOK-60 cutting ceramics.

Table 4 gives an example of the effect of coatings on the cutting force components. The data in Table 4 show a significant contribution of the coating to the reduction of the cutting force components, which allows predicting a reduction in the tool wear intensity and an increase in its service life. The use of the coating led to a decrease in the vertical cutting force component (it is this that limits the tool service life) by 1.2 times for VOK-60 ceramics and by 1.4 times for VOK-71 ceramics, while the use of heat treatment and ion nitriding led to its reduction by only 1.2 times.

DISCUSSION

The study confirmed the hypothesis that cutting ceramics is capable of working when processing viscous hard-to-machine corrosion-resistant specialised stainless steels such as 09H17N7Yu steel. Previously, it was believed that cutting ceramics is intended for processing hard materials. Thus, the scope of application of black cutting ceramics has been expanded. The study also confirmed the hypothesis about the possibility of processing 09H17N7Yu (EU 1.4568, X7CrNiAl17-7) steel, which has a high content of chromium (16–17.5 %) and nickel (7–8 %).

When confirming the hypothesis, unique technological methods for increasing the performance of cutting ceramics through special heat treatment and coating deposition have been proposed. In particular, the authors proposed heat treatment in a vacuum at a temperature of 1100–1400 °C for 20–40 min, which increased the bulk strength of the ceramics, and additional thermochemical treatment by ion nitriding performed at the final stage of heat treatment made it possible to alloy the bond. This set of proposed technological measures ensured an increase in the cutting speed by up to three times, which increased the processing productivity to 17 %.

The results of simulation modelling of the cutting process with cutting ceramics and experimental studies, presented in the paper, allowed discovering a number of features that were previously unknown. The effect of a significant increase in processing productivity was revealed, which makes cutting ceramics an effective competitor to hard-alloy cutting tools in turning hard-to-machine specialized stainless steels such as 09H17N7Yu. The authors associate this effect with several factors, including the use of coatings, as well as the use of heat treatment and ion nitriding.

It was found that the processing productivity in comparison with the VK8 hard alloy increased by 1.4–1.6 times for the VOK-60 cutting ceramics, and by 2.6 times for the VOK-71 cutting ceramics. The possibility of high-speed processing of hard-to-machine viscous steels with the specified cutting ceramics was substantiated and experimentally confirmed. This was achieved, among other things, by applying hardening coatings by condensation with ion bombardment, which ensured an increase in the cutting speed to 100 m/min and more with an increase in the service life of the cutting ceramics from 3 to 3.8 times.

This allows considering that the above objective of the work (to study the possibility of high-performance turning

***Table 1.** Service life of plates made of VOK-71 cutting ceramics during external turning of 09H17N7Yu steel (cutting speed is 120–140 m/min; feed is 0.21 mm/rev of a blank; cutting depth is 1 mm; without the use of lubricating and cooling process media)*

***Таблица 1.** Период стойкости пластин из режущей керамики ВОК-71 при наружном точении стали 09Х17Н7Ю (скорость резания 120 –140 м/мин, подача 0,21 мм/об. заготовки, глубина резания 1 мм, без применения смазывающе-охлаждающих технологических сред)*

Cutting plate state		
VOK-71 in the initial state	VOK-71 + heat treatment	VOK-71 + heat treatment + ion nitriding
5 min	9 min	14 min

Note. Values are given as the average of five measurements with a coefficient of variation of 0.27.
Примечание. Значения даны как среднее по 5 измерениям при коэффициенте вариации 0,27.

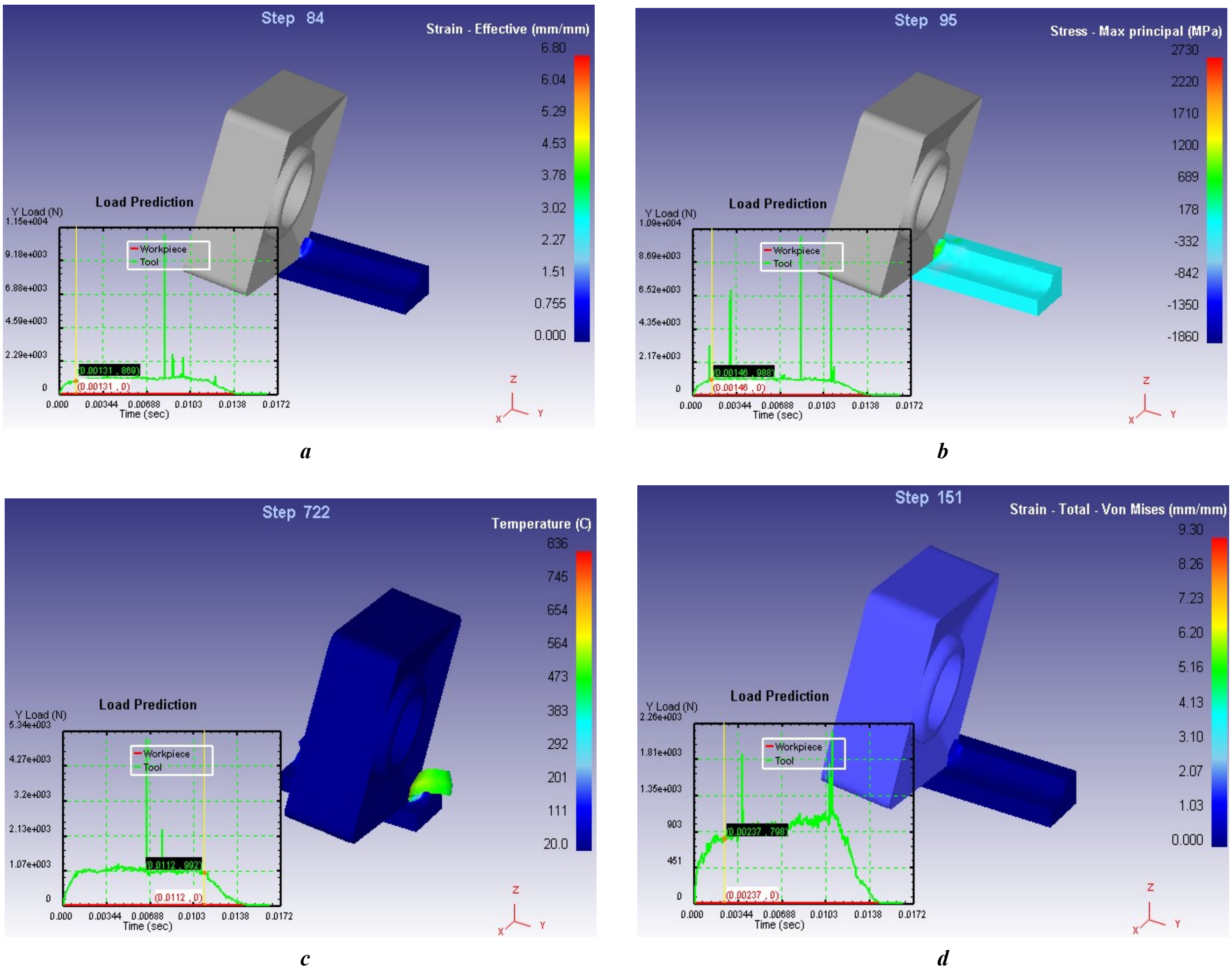

***Fig. 3.** Results of simulation modelling of the stress state of the cutting tool when turning 09H17N7Yu steel with VOK-71 cutting ceramics (**a**, **b**) and VOK-71 cutting ceramics with a Ti+TiN+(NbZrTiAl)N coating (**c**, **d**): **a**, **b** – maximum primary stresses (MPa); **c**, **d** – resulting strain rates (mm/s). The colour scheme demonstrates the range of the illustrated parameter, a graph reflecting the dynamics of this process is shown at the bottom left*

***Рис. 3.** Результаты имитационного моделирования напряженного состояния режущего инструмента при точении стали марки 09Х17Н7Ю режущей керамикой марки ВОК-71 (**a**, **b**) и режущей керамикой ВОК-71 с покрытием Ti+TiN+(NbZrTiAl)N (**c**, **d**): **a**, **b** – максимальные основные напряжения (МПа); **c**, **d** – результирующие скорости деформации (мм/с). Цветовая гамма демонстрирует диапазон иллюстрируемого параметра, слева внизу приведен график, отражающий динамику данного процесса*

***Table 2.** Numerical values of the quantities composing the cutting forces when turning with VOK-71 cutting ceramics with a Ti+TiN+(NbZrTiAl)N coating at a cutting speed of 120 m/min with a cutting depth of 0.1 mm*
***Таблица 2.** Числовые значения величин, составляющих силы резания, при точении режущей керамикой ВОК-71 с покрытием Ti+TiN+(NbZrTiAl)N при скорости резания 120 м/мин с глубиной резания 0,1 мм*

Resulting cutting force components	**Steel grade**		
	09H17N7Yu	**12H18N10T**	**13H15N AM-3**
Cutting force longitudinal component *Fx*, N	85.5/106	64.7/98	35.2/54
Cutting force radial component *Fy*, N	305.2/382	308.0/396	310.1/404
Cutting force vertical component *Fz*, N	362.5/465	284.6/320	191.4/241

Note. The denominator shows the values for the case of using VOK-71 without coating.
Примечание. В знаменателе указаны значения для случая применения ВОК-71 без покрытия.

***Table 3.** Results of simulation modelling of the coating architecture*
***Таблица 3.** Результаты имитационного моделирования архитектуры покрытия*

Grade of cutting ceramics	**Cutting speed**	**Coating**		
		Ti+TiN+(NbZrTiAl)N	**Ti+Zr+ZrN+(ZrAlNb)N**	**Ti+Zr+(TiCN)+(TiZrAl)CN**
Increase in the service life, times				
VOK-60	up to 100 m/min	3.2*		
VOK-71		3**	3.8***	
VOK-60	from 100 m/min to 130 m/min	3		3.5
VOK-71		3.6		3.3

*Note. * when increasing the cutting speed by 25 %;*
*** when increasing the cutting speed by 20 %;*
**** when increasing the cutting speed by 32 %.*
*Примечание. * при повышении скорости резания на 25 %;*
*** при повышении скорости резания на 20 %;*
**** при повышении скорости резания на 32 %.*

***Table 4.** Values of predicted cutting force components when turning 09H17N7Yu steel with cutting ceramics in different states*
***Таблица 4.** Значения прогнозируемых составляющих силы резания при точении стали 09Х17Н7Ю режущей керамикой, находящейся в разном состоянии*

Tool material	**Cutting force longitudinal component *Fx*, N**	**Cutting force radial component *Fy*, N**	**Cutting force vertical component *Fz*, N**
VOK-60	120	340	440
VOK-60 with a Ti+TiN+(NbZrTiAl)N coating	95	300	370
VOK-71	96	310	370
VOK-71 + heat treatment + ion nitriding	82	270	310
VOK-71 with a Ti+TiN+(NbZrTiAl)N coating	64	220	260

of blanks made of hard-to-machine 09H17N7Yu steel, with a cutting speed of more than 50 m/min by applying nanostructured coatings to the VOK-60 and VOK-71 cutting ceramics, and due to previous heat treatment) has been achieved. Thermochemical treatment in the form of ion nitriding was performed on a Bulat-type installation (Russia), which operates using the condensation with ion bombardment (CIB) method. This made it possible to alloy the bond, which increased the strength of the grain boundaries of the cutting ceramics.

Comparison with other existing studies [12; 13] showed a high result of using cutting ceramics. This study established the fact of an increase in the service life of cutting ceramics in comparison with the VK8 hard alloy by 7–10 times, depending on the applied technological process of hardening the cutting tool. It was identified that in comparison with cutting ceramics in the initial state, the service life for VOK-71 increased by 1.8 times due to the use of heat treatment, and by 2.8 times due to the use of heat treatment followed by ion nitriding. The obtained results supplement (update) the recommendations of the world's leading tool companies – Walter (Germany), Sandvik Coromant (Sweden), Mitsubishi (Japan), ISCAR (Israel). The results do not contradict the existing concepts formulated in the works [14–18]. It is shown that the obtained results are applicable to related hard-to-machine 12H18N10T and 13H15N AM-3 stainless steels.

The authors plan to conduct further research in the area of identifying the contribution of a particular coating to increasing the tool life, identifying the share of the contribution of heat treatment and heat treatment followed by ion nitriding.

According to the authors, the scientific novelty of the work is that the possibility of using VOK-60 and VOK-71 cutting ceramics for turning blanks of parts made of hard-to-machine 09H17N7Yu specialized stainless steel has been substantiated by using hardening coatings, as well as by heat treatment and heat treatment followed by ion nitriding. In fact, the use of the DEFORM software environment as a tool for designing coatings is also a scientific novelty of the work. The practical significance of such application of the DEFORM software environment allowed selecting the most rational coatings from all possible options at the stage of coating design. This is a significant saving of research funds and time.

As a result of the conducted research, one can conclude the following: an arsenal of technological processes for manufacturing a tool made of cutting ceramics has been developed. For specific operating conditions of the tool, it is necessary just to select from this arsenal the most rational technological process in terms of the tool performance indicator, taking into account productivity and cost.

The practical significance of the work is that the cutting mode parameters have been identified, at which the effects of increasing productivity and the tool life period are most fully realised.

CONCLUSIONS

During the simulation modelling of the cutting tool stress state, as well as the study of the process of turning hard-to-machine corrosion-resistant 09H17N7Yu stainless steel, the possibility of using VOK-60 and VOK-71 cutting ceramics was proven.

The use of coatings in comparison with cutting ceramics without a coating allowed increasing the service life of cutting ceramics from 25 to 32 % with an increase in the cutting speed to 100 m/min.

The processing productivity in comparison with the VK8 hard alloy increased by 1.4–2.6 times.

The increase in the service life in comparison with the VK8 alloy was 7–10 times.

In comparison with cutting ceramics in the initial state, the service life increased by 1.8 times due to the use of heat treatment and by 2.8 times due to the use of heat treatment followed by ion nitriding.

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Режущая керамика для точения специализированной нержавеющей труднообрабатываемой стали

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Аннотация: Показана возможность применения в качестве токарного инструмента режущей керамики. Использованы сменные типовые режущие пластины, выполненные из режущей керамики марок ВОК-60 и ВОК-71. В работе на основе имитационного моделирования в программной среде deform обоснована и затем экспериментально подтверждена возможность высокоскоростной обработки указанной режущей керамикой. Дополнительно предложено нанесение упрочняющих покрытий методом конденсации с ионной бомбардировкой, что обеспечило повышение скорости резания до 100 м/мин и более с повышением периода стойкости режущей керамики с 3 до 3,8 раз. Проведены исследования максимальных напряжений в инструментальном материале и скорости деформации обрабатываемого материала. Для выбора рациональных решений при имитационном моделировании использовали параметры «температура в зоне резания», «напряжения в инструментальном материале», «износ инструмента», что характеризует сложно-напряженное состояние материала инструмента. Переход от этих параметров к прогнозному проектированию режущей керамики выполняли путем измерения силы резания при натуральном резании. Измеренные значения составляющих силы резания использовали для расчета напряжений в инструментальном материале. В результате выполненного исследования подтверждена гипотеза о том, что режущая керамика способна работать в условиях обработки вязких труднообрабатываемых коррозионностойких специализированных нержавеющих сталей типа марки 09Х17Н7Ю (EU 1.4568, X7CrNiAl17-7), имеющих высокое содержание хрома (16–17,5 %) и никеля (7–8 %). Предложены оригинальные технологические приемы повышения работоспособности режущей керамики за счет специальной термообработки и нанесения покрытий. В частности, термообработка в вакууме при температуре 1100–1400 °С в течение 20–40 мин повысила объемную прочность керамики, а дополнительная химико-термическая обработка путем ионного азотирования, выполненная на заключительном этапе термообработки, позволила легировать связку.

Ключевые слова: режущая керамика; точение нержавеющей стали; моделирование процесса точения; скорость резания.

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