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A Study of the Cutting Properties and Wear Mechanism of Ceramic Edge Tools with Nanostructure Multilayer Composite Coatings

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Abstract—The paper presents the results of studies of the cutting properties and wear mechanism of the edge cutting tool equipped with replaceable indexable inserts made of cutting ceramic with nanoscale multilayer composite coatings when cutting hardened steel. It has been shown that applying the latter allows one to tune the contact processes based on the changes in friction and lengths of dense and complete contacts between the chip and the rake face of the cutting tools, thereby reducing normal contact strains and the probability of macro- and microbrittle fracture in the contact areas of the tool.

Keywords: cutting ceramic, coating, monitoring of the contact processes, cutting properties of a tool, wear mechanism

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INTRODUCTION

Cutting tools equipped with replaceable indexable inserts (RIIs) made from cutting ceramic (CC) are increasingly being used in metalworking manufacturing. These tools do not contain rare elements and exhibit high wear resistance, in particular at high temperatures during cutting.

In the fabrication of CC edge tools, Al_2O_3 and Si_3N_4 are the most widely used compounds, since they form basis of single- and multicomponent systems. Doping oxide ceramic with zirconium oxides and titanium carbides, as well as reinforcing it with SiC whiskers, considerably improves its properties.

A main feature of CC is the lack of a binding phase that significantly decreases its degree of positional disorder upon heating during wearing out, increases its plastic strength, and predetermines the possibility of using cutting rates that are much higher than those for the solid alloy tool [1]. The lack of a binding phase also negatively affects the service properties of the CC edge tool. In particular, a decrease is observed in the brittle strength, impact viscosity, and fracture strength of CC, which has a significant influence on the tool wear, since the low fracture strength of ceramic causes the formation of a crack front that does not encounter barriers able to block or stop its development. The above factors are the reason why cutting rake faces of the ceramic tool have macro- and microchips, even at the running-in or initial stages of steady-state wear, and are the principal cause of CC complete failure is the brittle fracture of its cutting part. Another reason for the mainly brittle fracture of the ceramic tool is the concentration of thermomechanical strains relative to the face of the rake due to the decreasing length of the contact between the chipping and the front surface of tool with a slight increase in the direct force. In the case when a ceramic cutting tool is dominant, this does not depend on the cutting rate, since the temperature exerts no considerable impact on the wear transformation, but it does significantly determine the field of application of the cutting tool [1, 2, 7–11].

The most valid technological utility for the goal-seeking control of a contact during cutting with a CC tool is the formation of functional coatings with various compositions, structures, and properties at its contact areas, which considerably change the friction and thermodynamic impact on the tool and its wear.

This aim of this study was to increase the efficiency of a ceramic tool via a directional control of the contact processes and relevant change of thermomechanical strain of the tool cutting part, as well as its wearing out.

MATERIALS AND METHODS

Experimental and theoretical investigations have been performed in order to establish laws for controlling the contact processes and thermodynamic strain of a cutting part of the CC tool via the coating.

The contact between two bodies is implemented by a set of points and areas transmitting the load that results into the deflected mode of the contacting surfaces. The chip pressure on the cutting tool is unevenly distributed due to the stochastic behavior of the roughness formation of the surfaces in the contact, which are related to the intensive thermomechanical impact of high temperatures, as well as to the formation of various types of adsorbed and oxide films at the contacting surfaces. The relative length of the k segment of the plastic contact is of great importance when analyzing phenomena at the front surface of tool [4, 7, 9, 13, 15] and is strongly dependent on the zone length C_1 of the plastic contact; the resistance to chip material shift τ_c; the resistance to treated material shift τ_t and the hardening coefficient of adhesive bonds $\beta(B)$ at the point of the chip separation from the treated material.

The increase in k is obvious for improving the working conditions for the cutting wedge of a tool, since a significant part of the load on the front surface is distributed over a larger area of a contact. On the other hand, the decrease in k impairs the performance of the cutting edge, since a smaller area that is adjacent to the front surface of tool is expected to take almost the entire loading that impacts the front surface. The above is the cause of chips and macro- and microchippings of the cutting edge, which reduces the performance of the ceramic tool [2, 7–9]. The hardening coefficient of adhesive bonds β exerts the maximum influence on the intensity of adhesive contact between the materials of the tool and chip and on the plastic contact length k, respectively. Thus, it can be affirmed that any procedures that reduce the adhesive interaction between instrumental and treated materials (IM and TM, respectively) lead to an increase in the strain of the area adjacent to the cutting edge of a CC tool. Therefore, the strength of the plastic contact area between the instrument and TM must be increased in order to obtain a positive effect [1, 4, 15].

The influence of the coating on key parameters of the contact process during cutting, such as the full length of the contact between the chip and the front surface of CC tool C_γ, the coefficient of chip shrinkage ξ, and the components of the cutting forces P_z and P_y was estimated, as well as the contact normals σ and the tangential strains τ at the front surface of tool.

The objects of our investigations were the replaceable indexable inserts of a ductile layer ceramic (DLC), which contain the carbide substrate (92% WC, 8% Co) and both coated and coating-free Al_2O_3 layers. All RIIs were SNUN (03114-0370) square-shaped with a radius $r = 0.8$ mm. In accordance with GOST 8–82 and GOST 18097, incisors with mechanical fastening of DLC RIIs were used for the experiment, and their cutting parts had the following geometrical parameters: $\gamma_{ph} = -8°$; $\alpha = 8°$; $\varphi = 45°$; $\varphi_1 = 45°$; and $\lambda = 0$.

Hardened CrWoMo steel (*HRC* 58–60, GOST 5950) was used as the treated material.

The exposure was implemented on a 16K20 machine tool equipped with a thyristor drive, which allows the cutting rate to be maintained over a fixed range with decreasing blank diameter.

A multipurpose tensometric UDM-600 dynamometer equipped with an interface and software to process the obtained experimental data were used to extract information on the cutting force components P_z and P_y.

The contact processes that occur when cutting various structural materials with a standard CC tool have been taken into account with the development of coatings for a ceramic tool. These processes include the following:

—a high level of contact (in particularly, normal) between strains that arise at the rake surface of CC tool due to the intensive decrease in the contact length (area) and significantly less intensive decreases in the normal loads that impact the front surface;

—the concentration of temperature strains at the contact areas of the front and rear tool surfaces, which are caused by the low thermal conductivity of the ceramic and decreasing contact lengths (especially on the anterior surface);

—the almost complete absence of TM dead space and build-up (here, the latter occurs with the presence of the former and prevents wear in the contact area).

Based on this concept of coatings for cutting ceramic substrates, we have chosen the following compositions of nanostructure multilayer composite coatings (NSMLCCs):

Ti–(Ti,Al)N–TiN; Ti–(Ti,Al)N;

(Ti,Al,Zr,Nb,Cr)N;

(Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N.

The coatings were deposited onto the HQC substrates using the STANKIN-EKOTEK VIT-2 installation. This system is equipped with the special ion sources that allow a simultaneous implementation of several principally important processes. In particular, a complementary module screens the vapor–ionic flow and separates the neutral particles (microcondensed phase) by deviating the charged particles of the ionic flow (ions and electrons) via an intense magnetic field. Furthermore, this module can play a part of the ion accelerator, as well as be an electron source for the thermoactivation of the tool and high-charged gas ions, e.g., nitrogen, for the stimulated chemicothermal exposure of the tool [3, 6, 7, 14, 15].

A special process for synthesizing coatings based on the use of sources of low- and mid-energetic (gas and gas–metal) plasma and the separation of thermoactivation and the purification of the substrate surface, as well as the cancellation of the microarc and separation of the drop components, especially using elements

Table 1. Contact characteristics with cutting hardened CrWoMo steel

Tool material	C_γ, mm	Φ, °	μ_γ	ξ	P_z, N	P_y, N
HQC	0.114	21.6	0.294	1.906	21.018	60.409
HQC: Ti–(Ti,Al)N–TiN	0.120	21.3	0.310	1.933	22.124	62.135
HQC: Ti–(Ti,Al)N	0.174	20.9	0.366	1.988	33.186	65.587
HQC: (Ti,Al,Zr,Nb,Cr)N	0.120	21.6	0.294	1.906	22.124	60.409
HQC: (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N	0.141	21.1	0.334	1.961	26.549	63.861

C_γ is length of the chip full contact; Φ is angle of shear; μ_γ is coefficient of friction on the front surface; ξ is chip shrinkage; P_z and P_y are tangential and radial components of the cutting force, respectively; HQC—high strength layered ceramic.

with relatively low atomic masses (Al, Ti, etc.), has been developed that takes into account the low electroconductivity of ceramic substrates.

The fabrication of coatings for HQC RIIs included the preliminary purification and ablution of inserts, their charging into a vacuum camera of the installation, the preliminary (deep) pumpdown of the camera, ionic purification of the surfaces of inserts and their thermal activation, condensation of the adhesive–hardening layer and synthesis of the wear-resisting layer of coating.

The developed filtered cathode–vacuum–arc deposition enabled us to form the multilayer composite multielement coatings onto the working surfaces.

RESULTS AND DISCUSSIONS

Study of Contact Processes during Cutting

The cutting force components P_z and P_y were determined from the experiment, while other characteristics of the contact processes were theoretically calculated via the following technique. The relative length of the contact between the chip and the cutter have been determined using the dependence in [6], the cutting efforts have been calculated from the formulae in [10], and the full length of the contact between the chip and the front surface C_γ has been calculated using the formula

$$C_\gamma = a\left(P_z\frac{\cos\gamma}{2\tau_y ab} + \sin\gamma\right)^{0.1} \times\left(P_z\frac{\sqrt{2}\cos(\gamma+\frac{\pi}{4})}{2\tau_y ab} + \sqrt{2}\sin(\gamma+\frac{\pi}{4})\right). \quad (1)$$

The coefficient of friction on the front surface is determined as follows:

$$\mu_\gamma = \tan(\arctan\frac{P_y}{P_z} + \gamma). \quad (2)$$

The experiments enabled us to obtain data and calculate the contact characteristics of a tool equipped with the coating-free and coated HQC RIIs during the dry turning of hardened CrWoMo steel with t = 0.1 mm, S = 0.1 mm/rev, and v = 250 m/min. The results are shown in Table 1.

The normal and tangential contact strains over a front surface σ_N and τ_N were determined taking into account the assumption that the tangential strains in the conditional shear plane τ_Φ under the turning conditions of CrWoMo steel can be assumed to be almost unchangeable. Thus, the average tangential strains on the front surface of the tool q_F were determined using the dependence [15], and the average normal contact strains q_N on the front surface of the tool were calculated using in the context the method proposed in [16]. In accordance with the experimental data given in [17], for each material, the values τ_Φ and q_F are constant. Thus, the principal parameters that define q_N are the ratio of the cut thickness a_c to the total length of the contact between the tool and the chip C_γ, the chip shrinkage ξ (through the action angle Φ), and the front angle value γ.

The distribution of the contact strains on the front surface of a tool for the coating-free HQC RIIs and those with the coatings of various compositions under a dry turning of the CrWoMo *HRC* 58–60 hardened steel with t = 0.1 mm, S = 0.1 mm/rev, v = 250 m/min, and $\gamma = -24°$, a_{eq} = 0.025 mm are presented in Fig. 1 and in Table 2.

The data collected allowed making the following statements. The deposition of multifunctional coatings with various compositions and structures onto the working surfaces of a ceramic tool enables us to tune the contact interaction between the instrumental and the treated materials. This is due to the increase in the length of a full contact between the chip and the front surface of the tool at the cost of some friction growth and the increase in the adhesion with the treated material at only a slight increase in the normal pressure, which favors the thermomechanical strain of a cutting wedge of the tool. Thus, the results can be used

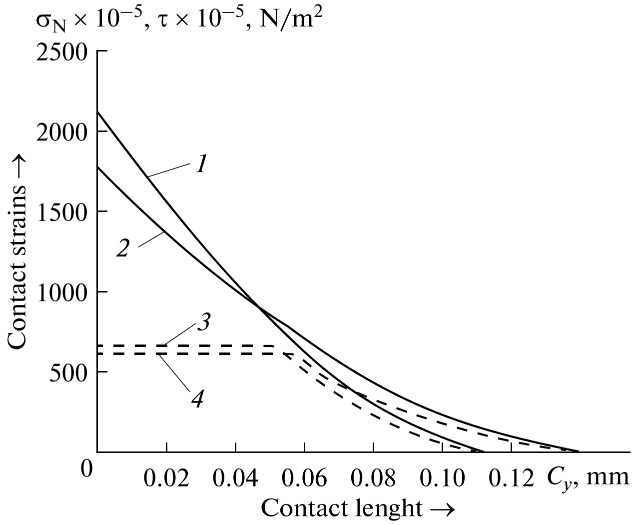

Fig. 1. Distribution of normal σ_N and tangential τ_γ contact strains on the front surface of the cutting tool during dry turning of steel: (*1*, *3*) normal and tangential strains on the front surface of a coating-free HQC RII; (*2*, *4*) normal and tangential strains on the front surface of a (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N-coated HQC RII.

to predict more auspicious conditions of the ceramic tool performance and the decrease in probability of sudden fault of a tool caused by the brittle fracture of its cutting wedge.

Study of Cutting Properties and Wear of a Cutting-Ceramic Tool

In order to highlight the effect of coatings on the CC RII stability, we have studied the cutting properties and wearing out of the cutting ceramic tool using the above technique. The results of these studied are displayed in Fig. 2.

The obtained h_3–τ dependences for HQC RIIs with various coatings exhibit typical behavior. A coating reduces the wear rate of the ceramic tool in the normal area of wear. A comparison of the cutting models for the case of the longitudinal turning of the coating-free and coated HQC RIIs reveals the wear rate of the coated tool to be lower than that for a coating-free tool under similar conditions. Coated HQC tools wear out less intensively and, in some cases, change their behavior from fatigue spalling to abrasion with some adhesive grip.

To determine the dependence of the resistance of an HQC cutting tool (the cutting time of the tool before its replacement) on the cutting mode, an experimental method that uses the the power function has been applied in the present work as follows:

$$R = C\prod_{i=1}^{n} z_i^{a_i}. \quad (3)$$

The advantage of this model is the ability of its transformation into a linear form by taking the logarithm

$$\ln R = \ln C + \sum_{i=1}^{n} a_i \ln z_i. \quad (4)$$

As the method for the experiment plan, the least-squares method was used with a rational plan of multifactor experiment, which can be represented as *p* combinations of *n* factors varied at *s* levels. The number of levels of variations is defined by the order of the model, and the number of experiments required and sufficient for the unique estimate of unknown parameters of the model (C, a_1, ..., a_n) is equal to the number of unknown model parameters. The levels of the variations in factors (cutting mode elements) were taken as equal to those recommended at the finishing turn of hardened structural steels carried out a ceramic tool.

The values of C coefficients, which are exponents of the a_i mathematical model, were determined via the least-squares method from the cutting factors *t*, *S*, and *v* and parameters (T_1, ..., T_5) implemented in the experiments.

Table 2. Parameters of dependence of distribution of contact strain over the front surface when cutting steel for HQC inserts

Tool material	C_γ, mm	$C_{\gamma n}$, mm	$\tau_\Phi \times 10^{-5}$, N/m^2	$q_F \times 10^{-5}$, N/m^2	$q_N \times 10^{-5}$, N/m^2	$\sigma_{N\max} \times 10^{-5}$, N/m^2	*n*
HQC	0.114	0.0533	603	248.999	761.751	2103.165	1.639
HQC: Ti–(Ti,Al)N–TiN	0.120	0.0542	603	243.622	739.220	2055.745	1.668
HQC: Ti–(Ti,Al)N	0.174	0.0549	603	172.612	515.704	1454.214	1.725
HQC: (Ti,Al,Zr,Nb,Cr)N	0.120	0.0538	603	240.130	734.616	2028.249	1.639
HQC: (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N	0.141	0.0538	603	207.285	624.020	1747.627	1.697

C_γ is length of full contact over the front surface; $C_{\gamma n}$ is length of the plastic (hard) contact over the front surface; τ_Φ is strain tangents in the conditional share plane; q_F is average strain tangents on the front surface of tool; q_N is average normal contact strain on the front surface of tool; $\sigma_{N\max}$ is maxima normal contact strain on the front surface; *n* is exponent.

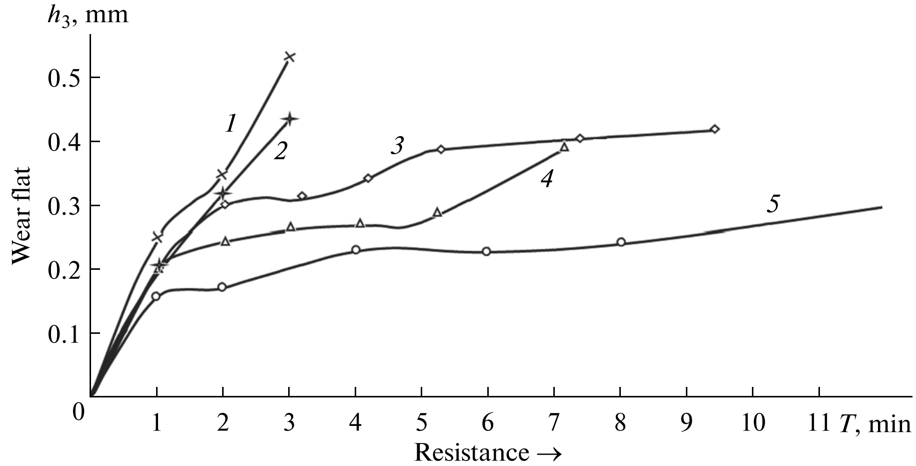

Fig. 2. Dependence of back-edge cutting of inserts on cutting time during treatment of CrWoMo HRC 58–60 steel ($t = 0.1$ mm; $S = 0.1$ mm/rev; v = 250 m/min): (*1*) control HQC tool; (*2*) Ti–(Ti,Al)N-coated HQC; (*3*) (Ti,Al)N–TiN-coated HQC; (*4*) (Ti,Al,Zr,Nb,Cr)N-coated HQC; (*5*) (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N-coated HQC.

The experimental data were processed via a special routine developed at Moscow State Technological University and the results are shown in Table 3.

Based on the carried out experiments, as well as on the verification of the obtained model validity and the estimate of significance of the regression coefficients, we obtained the following dependences of the tool resistance on the cutting mode at the CrWoMo steel turning:

1. using cutters with coating-free HQC RIIs,

$$T = \frac{957.630}{t^{1.850} S^{0.081} V^{1.866}}, \text{ min}; \quad (5)$$

2. using cutters with Ti–(Ti,Al)N–TiN-coated HQC RIIs,

$$T = \frac{0.147}{t^{1.069} S^{2.903} V^{1.007}}, \text{ min}; \quad (6)$$

3. using cutters with Ti–(Ti,Al)N-coated HQC RIIs,

$$T = \frac{1.850 \times 10^{5}}{t^{2.344} S^{2.168} V^{3.706}}, \text{ min}; \quad (7)$$

4. using cutters with (Ti,Al,Zr,Nb,Cr)N-coated HQC RIIs,

$$T = \frac{2.742 \times 10^{14}}{t^{2.135} S^{2.215} V^{7.473}}, \text{ min}; \quad (8)$$

5. using cutters with (Ti, Al)N–(Ti, Cr)N–(Ti, Cr, Al)N-coated HQC RIIs,

$$T = \frac{2.112 \times 10^{7}}{t^{0.063} S^{1.754} V^{3.209}}, \text{ min}. \quad (9)$$

Therefore, the best resistance result were obtained for (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N-coated HQC RIIs.

It is observed from the obtained resistance dependences, that the resistance abruptly decreases with an increase in the cutting rate. Here, (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N-coated RIIs provide for a higher resistance (by three to five times) at the same rate and allow one to use a higher cutting rate (by 20–30%) compared to the coating-free sample at equal resistance.

The conducted resistance tests of a tool equipped with HQC RIIs enable us mention the considerable

Table 3. Parameters of mathematical cutting model

		C_i	a_{i1}	a_{i2}	a_{i3}
HQC	T_1	957.630	–1.850	–0.081	–1.866
HQC: Ti–(Ti,Al)N–TiN	T_2	0.147	–1.069	–2.903	–1.007
HQC: Ti–(Ti,Al)N	T_3	1.850×10^5	–2.344	–2.168	–3.706
HQC: (Ti,Al,Zr,Nb,Cr)N	T_4	2.742×10^{14}	–2.135	–2.215	–7.473
HQC: (Ti,Al)N–(Ti,Cr)N–(Ti,Cr,Al)N	T_5	2.112×10^7	–0.063	–1.754	–3.209

influence of the coating on tool being worn out and the decrease in its intensity.

CONCLUSIONS

A new technique was developed, that allows for an increase in the cutting characteristics of a tool equipped with a cutting-ceramic replaceable indexable insert with nanostructure multilayer composite coatings during the treatment of hardened steel. This has been found found to increase the resistance of a ceramic tool by three to five times compared to the resistance of a coating-free tool.

The role of cutting on the contact areas of the ceramic tool has been determined as an intermediate technological medium, which allows the contact processes to be adjusted by varying the length of the contact between the chip and the front surface, as by decreasing the specific thermomechanical strains, and by stabilizing the heat sink from the cutting area.

Dynamic mathematical models have been developed that describe the cutting of hardened steel and establish the resistance dependences for a tool equipped with coating-free HQC RII and coated RIIs.

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