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NANOSTRUCTURED MULTILAYER COMPOSITE COATINGS ON CERAMIC CUTTING TOOLS FOR FINISHING TREATMENT OF HIGH-HARDNESS QUENCHED STEELS

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The functional role of nanostructured multilayer composite coatings (NMCC) deposited on the operating surfaces of replaceable faceted cutting inserts (CI) from cutting ceramics based on aluminum oxides with additives of titanium carbides is studied. It is shown that the developed NMCC not only raise substantially the endurance of the ceramic tools under high-speed dry treatment of quenched steels but also improve the quality and accuracy of processing of the parts and the ecological parameters of the cutting process.

Key words: cutting ceramic tools, nanostructured multilayer composite coatings, high-hardness steels, contact processes, endurance of tools.

INTRODUCTION

Recent strategies of advancement of processes of mechanical treatment are chiefly connected with improving the efficiency by resorting to high and superhigh cutting speeds and total abandon of cutting fluids (CF) due to their negative action on the environment and health of the personnel. In this connection, the metal-working industry often employs tools equipped with replaceable faceted cutting inserts (CI) from cutting ceramics [1, 2] possessing a unique combination of physical, mechanical, and thermophysical properties in the absence of scarce and expensive components in the composition.

The main feature of a cutting ceramics is the absence of a binding phase, which lowers considerably the degree of its softening upon heating in the wear process and raises the plastic strength of ceramic tools. This makes it possible to use high cutting speeds exceeding the cutting speed for hard-alloy tools. Thus, the limiting level of cutting speeds in finishing turning of steels with hard-alloy tools is 500 – 600 m/min, whereas the cutting speed of the tools equipped with CI from cutting ceramics increases to 900 – 1000 m/min [2].

Cutting ceramics possess a high hardness, heat resistance and wear resistance and have an exceptionally low susceptibility to physicochemical interaction with the treated materials (various steels), which predetermines their dominant use for dry treatment without CF. Such treatment is safer for the environment and for the health of the personnel. At the same time, most grades of cutting ceramics possess relatively low values of brittle strength and thermal conductivity at relatively high coefficients of thermal expansion, which increases substantially the probability of sudden failures of ceramic tools due to brittle cleavage of the cutting edges and limits their use in the metal-working industry [2 – 4]. This mechanism of failure of ceramic tools is prevalent and virtually independent of the cutting speed, because the temperature does not affect much the transformation of the properties of the ceramics, and determines to a great degree the relatively narrow range of application of ceramic tools [2, 3].

Today producers of ceramic tools mostly work with Al_2O_3 alumina ceramics and Si_3N_4 silicon nitride ceramics. With allowance for the mentioned physical and mechanical properties of cutting ceramics restricting the range of their application, wide research is performed with the aim of advancing the ceramics based on Al_2O_3 and Si_3N_4. Specifically, alloying of Al_2O_3 ceramics with zirconium oxides and titanium carbides and reinforcing them with “whisker” SiC crystals improves substantially their physical, mechanical and thermophysical properties (Table 1).

CHOICE OF PROCESSES OF DEPOSITION OF COATINGS ON SUBSTRATES FROM CUTTING CERAMICS

The most effective means for complex improvement of physical and mechanical properties of tools from cutting ce-

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TABLE 1. Properties of Oxide Ceramics after Addition of Different Compounds into the Composition

Ceramics	HV_{30}, MPa	E, GPa	σ_r, MPa	K_{1c}, $\text{MPa} \cdot \text{m}^{-1/2}$	$a_c \times 10^{-5}$, 1/K	λ, $\text{W}/(\text{m} \cdot \text{K})$
Al_2O_3	2000	390	350	4.5	7.5	30
$Al_2O_3 - ZrO_2$	2000	380	600	5.8	7.4	28
$Al_2O_3 - TiC$	2200	400	600	5.4	7.0	35
Al_2O_3 reinforced with whisker SiC crystals	2400	390	600 – 800	6 – 8	–	35

ramics is deposition of modifying functional coatings on their working surfaces [2, 6 – 9, 13 – 17]. This is connected with the phenomenological role of coatings having a double nature manifesting itself in simultaneous improvement of the surface properties of the ceramic material and lowering of the level the thermomechanical impact on the tool in the cutting process [8]. Much effort is aimed today at advancing the properties of cutting ceramics by deposition of functional coatings, which find wide use in the processes of dry forming treatment thus lowering the negative ecological effect on the environment and health of the personnel [2 – 6, 8, 9, 15, 16].

Analyzing the methods of formation of functional coatings on working surfaces of ceramic cutting tools we established that the preferred variants are chemical vapor deposition (CVD) and physical vapor deposition (PVD) [2, 5, 6, 9]. The use of standard CVD processes implemented at a high temperature (1050 – 1100°C) for quite a long time (up to 4 – 6 h) for deposition of coatings on ceramic substrates causes some softening of the surface structures of the ceramic material, which is very undesirable. For this reason we resorted to the innovation arc-PVD processes known as filtered cathode-vacuum-arc deposition (FCVAD) [8].

FCVAD does not cause structural changes in the ceramic material and provides

– high adhesive strength of the coating with respect to the ceramic substrate;

– control of the level of the “curing” energy action on the surface flaws of the ceramics in the form of microcracks and micropores and formation of favorable residual compressive stresses in the surface layers of the ceramic material;

– formation of nanosize structure in the deposited coating layers (grain size, thickness of sublayers) with high density due to the energy supplied by the precipitating condensate and transformation of the kinetic energy of the bombarding ions into thermal energy in local deposited volumes of the coating and their subsequent cooling at an exceptionally high rate (on the order of 10^{14} K/sec).

Directed modification of the properties of cutting ceramics by deposition of innovative coatings should improve its properties substantially and transform favorably the contact processes under cutting, which will widen the range of industrial application of ceramic tools and create serious competition to hard-alloy tools.

The aim of the present study was to develop nanostructured multilayer composite coatings meeting the concept of an intermediate process medium between the tool and the treated material. The coatings should simultaneously raise the surface properties of the ceramic tool and lower the thermomechanical impact causing its wear.

TECHNOLOGICAL PREREQUISITES

The high cutting capacity of tools equipped with replaceable cutting inserts (CI) from various grades of cutting ceramics (CC) makes it possible to treat preforms from high-hardness steels in rigid CNC machines at enhanced cutting speeds without CF. The size and geometry accuracy of the treated parts is high. Commercial use of ceramic tools gives a considerable economic effect. Replacement of coated hard-alloy tools by tools equipped with CI from cutting ceramics reduces the cost of mechanical treatment to 70 – 75% [2]. For example, replacement of CI from hard alloy T30K4 by CI from VOK-60 ceramics for large-scale boring of holes $\varnothing\, 50^{+0.025}$ mm in web-type parts from steel 35KhGSL with a hardness of 217 *HB* has reduced the treatment time by a factor of 1.75. Turning of spindle necks from steel 45 with a hardness of 207 – 220 *HB* with cutting inserts from VOK-60 ceramics has doubled the cutting speed as compared to cutting with inserts from hard alloy T15K6. Turning of such necks heat treated for a hardness of 42 – 46 HRC_e has increased the efficiency of the treatment with ceramic tools by a factor of 4 [2]. The use of tools equipped with CI from cutting ceramics makes it possible to increase the speed of cutting of steel and iron preforms by a factor of 1.5 – 5 as compared to hard-alloy tools.

High-speed finishing treatment of quenched steels with a hardness of 58 – 62 *HRC* by cutting tools equipped with CI from cutting ceramics may replace effectively the operation of finishing grinding in piece and large-scale productions, and the efficiency of such treatment increases with growth of the thickness of the removed tolerance. Specifically, replacement of grinding of quenched steels by turning with cutting ceramic tools not only raises the efficiency of the treatment but also provides higher quality of the treated surface (lowers of the roughness, produces more favorable residual compressive stresses, decreases the elastic aftereffect, etc.) and improves the accuracy of the treatment (deviation from the round shape by 0.004 mm [11], Fig. 1) and compensates the expenses on CF with simultaneous solution of the ecological problem.

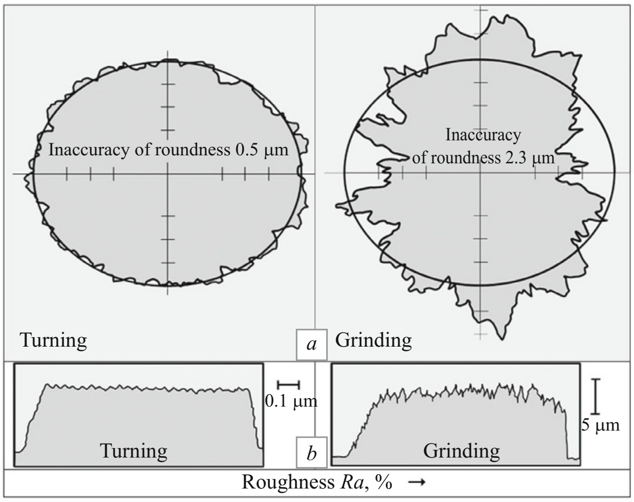

Fig. 1. Comparison of parameters characterizing the accuracy of shape (*a*) and the roughness of the treated surface (*b*) under grinding and dry treatment with ceramic tools.

It should be noted that the expenditures on cutting tools may exceed those on grinding wheels (Fig. 2*a*) by a factor of 2 or more [10]. However, the substantial shortening of the machining time (by a factor of 5 and more, Fig. 2*b*) as well as the reduction of the general cost of the treatment and of the level of negative impact on the environment in the case of the use of ceramic cutting tools is an incentive for wider application of treatment of preforms from hardened steels with ceramic cutting tools instead of grinding [10, 11].

The high cutting speed provided by ceramic cutting tools makes it possible to

- reduce the time of machining of parts by a factor of 1.5 – 5;
- replace the hard alloys with scarce and expensive elements (W, Ta, Ti, Co) by cutting ceramics with a coating containing no scarce elements;
- lower the roughness of the surface of the treated steels;
- raise the quality of treatment of the surface layer of not heat treated, heat hardened and quenched steels as compared to the roughness provided by grinding.

METHODS OF STUDY

Method of Forming of Coating

To deposit the coatings we used a VIT-2 device developed for synthesis of coatings on substrates from different tool materials [8]. We prepared CI from cutting ceramics, fixed them in special holders and then placed on the working table of the VIT-2 device. The CI performed a planetary motion about their axes and about the central axle of the table at frequency $n = 5$ rpm. This provided uniform deposition of coatings on all the surfaces of the CI and formation of a sublayer structure in three-component coatings. To deposit the coatings we used cathode systems of types Ti, Cr, Nb – Zr, and Al – Si. Then we chose two types of multilayer composite coatings for the further study, i.e., (TiAl)N – (TiCrAlSi)N and Ti – (TiAl)N – (TiZrAlSi)N. After arranging hard-alloy CI in the chamber of the device we evacuated the chamber to a pressure of 0.01 Pa. Plasma cleaning of the surfaces of the CI was performed with Ar anions at a pressure raised from 1.5 to 2.5 Pa. Then the CI were subjected to final cleaning and thermal activation in a gas discharge (GD) at a pressure of 0.5 Pa and a maximum bias potential of 1 kV.

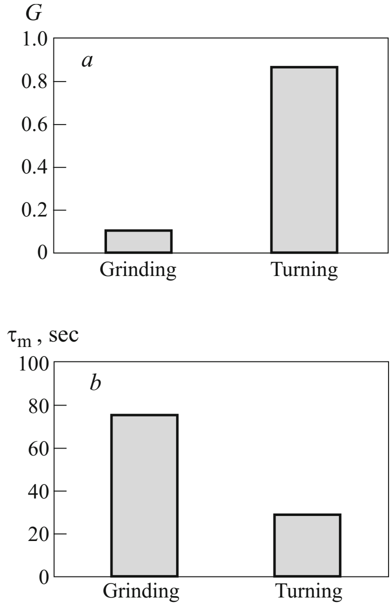

Fig. 2. Expenditures (*G* is the tool cost) (*a*) and machining time (τ_m) (*b*) in grinding and dry treatment with ceramic tools.

The modes of the deposition were as follows: $I_{Ti} = 80$ A, $I_{Cr} = 70$ A, $I_{Al} = 160$ A, $U_C = 160$ V, $p_N = 0.5$ Pa.

We studied the following characteristics of the coatings: the thickness ("Calotest" method, Fischer Sindelfingen device), adhesion strength with respect to the substrate material ("Scratchtest" method, Scem Revetest device), nanohardness and modulus E_1 ("NanoTest" method, Micromaterials Ltd. Wrexam device). Nanoindentation was performed with the help of a Berkovich indenter by the standard method. The nanohardenss of each hard-alloy specimen with deposited coating was measured 25 times on an area of 100 × 100 μm^2.

Method of Study of the Parameters of Contact Processes and of the Cutting Properties of Tools

The object of the study was a cutting tool with mechanically fixed replaceable faceted cutting inserts (CI) from cutting ceramics VOK-71. The inserts had a square shape and a size of 12.7 × 12.7 × 4.75 mm (SNUN — ISO 03111 0363; GOST 19042–80). The tool had the following geometry of the cutting part: $\gamma = -8°$; $\alpha = 6°$; $\varphi = \varphi_1 = 45°$; $\lambda = 0$; $r = 0.8$ mm.

The treated material was quenched steel KhVG with a hardness of 58 – 60 *HRC* (GOST 5950).

TABLE 2. Contact Characteristics of Ceramic Tools with Coating

Tool material	Functional parameters of cutting						
	C_γ, mm	Φ, rad	μ_v	ξ	P_z, N	P_y, N	P_x, N
VOK-71	0.114	21.6	0.294	1.906	21.018	60.409	9.194
VOK-71 – Ti – (TiAl)N – (TiCrAl)N	0.120	21.3	0.310	1.933	22.124	62.135	9.194
VOK-71 – Ti – (TiAl)N – (Ti, AlZrNbCr)N	0.120	21.6	0.294	1.906	22.124	60.409	6.129
VOK-71 – TiN – (TiAl)N – (TiCrAlSi)N	0.141	21.1	0.334	1.961	26.549	63.861	6.129

Notations: C_γ) length of full contact over the front surface; Φ) shear angle; μ_v) friction factor over the front surface; ξ) shrinkage of chips; P_z, P_y, P_x) tangential, radial, and axial components of the cutting force.

TABLE 3. Contact Characteristics of Cutting

Tool material	C_γ, mm	$C_{\gamma p}$, 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
VOK-71	0.114	0.0533	603	248.999	761.751	2103.165	1.639
VOK-71 – Ti – (TiAl)N – (TiCrAl)N	0.120	0.0542	603	243.622	739.220	2055.745	1.668
VOK-71 – Ti – (TiAl)N – (TiAlZrNbCr)N	0.120	0.0538	603	240.130	734.616	2028.249	1.639
VOK-71 – Ti – (TiAl)N – (TiCrAlSi)N	0.141	0.0538	603	207.285	624.020	1747.627	1.697

Notations: $C_{\gamma p}$) length of plastic (dense) contact over the front surface; τ_Φ) tangential stresses in conventional shear plane; q_F) mean tangential stresses on the front surface of the tool; q_N) mean normal contact stresses over the front surface of the tool; $\sigma_{N\max}$) maximum normal contact stresses over the front surface; n) parameter.

The cutting properties of the tool were studied with the help of a 16K20 universal turning lathe with a thyristor drive providing smooth regulation of the rotation speed of the spindle and maintenance of the specified cutting speed for preforms of different diameters. The cutting was performed at cutting speed $v = 200 – 400$ m/min, $t = 1.0$ mm, $S = 0.15$ mm/rev. The criterion of failure of the tool was a wear bevel on the back surface at $h_b = 0.3 – 0.35$ mm. The wear hb was measured using a MBS-10 toolmaker’s microscope.

The preliminary benchmark tests of the tool with CI from VOK-71 and several variants of nanostructured multilayer composite coatings gave the best stability results for the Ti – (TiAl)N – (TiCrAlSi)N coatings. Therefore, the subsequent study of the functional cutting parameters was performed for the tools with such coating.

RESULTS AND DISCUSSION

With allowance for the high susceptibility of ceramic tools to brittle fracture due to the relatively low strength and toughness of the ceramics, we studied the possibility of lowering of the level of normal contact stresses acting on the front surface of the ceramic tools by deposition of complex composite coatings lowering the level of the thermomechanical impact on the contact areas of the tools, which causes brittle cleavage of the cutting edge [1, 13, 14].

The preliminary comparative studies of the cutting properties of tools equipped with coated ceramic CI showed that the results were the best for CI from VOK-71 with a Ti – (TiAl)N – (TiCrAlSi)N coating deposited by the FCVAD method. This coating had the following parameters: microhardness $HV_{0.05} = 3.2$ GPa, strength of adhesion to the substrate $P_a = 140$ N, total thickness of the coating 3.9 μm, grain sizes of all the coating components 10 – 12 nm, thickness of sublayers (external and intermediate layers) 20 – 25 nm. Further research was concentrated only on the ceramic CI with the NMCC formed by the FCVAD process.

The results of the study of the functional parameters of cutting and of the contact characteristics of the process of dry (free) turning of quenched steel KhVG (58 – 60 *HRC*) with tools equipped with CI from mixed ceramics VOK-71 without coating and with NMCC of different compositions are presented in Tables 2 and 3 and in Fig. 3.

Analyzing the results obtained we established that the developed NMCC deposited onto contact areas of ceramic tools intensify somewhat the friction on the “coating – treated material” contact boundaries, which in its turn increases the length of full contact between the chips and the front surface of the tool C_γ. This lowers the contact stresses σ_n and τ_γ (see Fig. 3) and in combination with the improvement of the removal of heat reduces the specific thermomechanical loads on the cutting edge of the tool, which allows us to predict growth of its wear resistance.

The results of the comparative tests of the cutting properties of tools equipped with CI from mixed cutting ceramics with different NMCC are presented in Fig. 4.

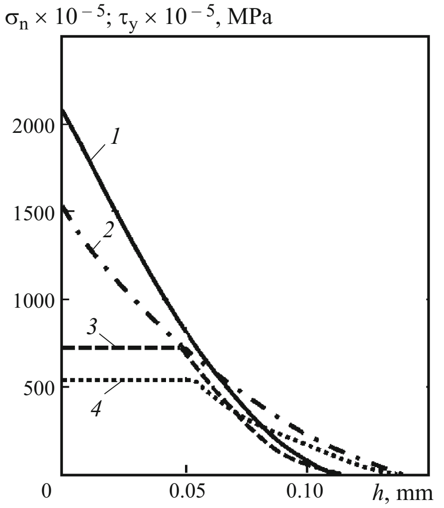

Fig. 3. Distribution of contact normal σ_n (*1*, *2*) and tangential τ_y (*3*, *4*) stresses over the front surface of CI from VOK-71 under dry treatment of steel KhVG (58 – 60 *HRC*) with $t = 0.1$ mm, $S = 0.15$ mm, $v = 250$ m/min (*h* is the distance from the cutting edge): *1*, *3*) CI from uncoated VOK-71; *2*, *4*) CI from VOK-71 with a Ti – (TiAl)N – (TiCrAlSi)N coating.

Analyzing the behavior of the wear curves of the tools as a function of the cutting time ("wear – time") we can note a standard form of the functions obtained for uncoated and coated tools (Fig. 4). The tools equipped with CI from VOK-71 ceramics with the developed NMCC of optimum composition (curve *4* in Fig. 4) demonstrate substantial decrease in the wear intensity as compared to the control tools with and without coating and to the tools with NMCC of nonoptimal composition (compare curves *1* – *3* and curve *4* in Fig. 4). We should also note the balanced wear behavior of the back surface of the CI from VOK-71 with a Ti – (TiAl)N – (TiCrAlSi)N coating without visible macro- and micro-chips of the cutting edge. The endurance of such CI is 2 – 2.5 times higher than that of the tools not coated with VOK-71.

CONCLUSIONS

1. The studies performed have confirmed the hypothesis of the possibility of raising the cutting properties of ceramic tools by controlling the contact processes due to the use of nanostructured multilayer composite coatings with optimum composition and properties.

2. Longitudinal turning of steel KhVG with a hardness of 58 – 60 *HRC* has shown that the use of cutting tools equipped with the developed Ti – (TiAl)N – (TiCrAlSi)N optimum-composition NMCC raises the efficiency of the cutting (increases the area of removal of metal from the surface of the preform) by a factor of 2 – 2.5 as compared to similar tools without coating.

3. The tools with the developed NMCC can be used for effective finishing dry treatment of quenched steels instead of the traditional grinding; they provide high accuracy of the shape and low roughness of the treated parts at simultaneous improvement of the ecological parameters of the treatment process.

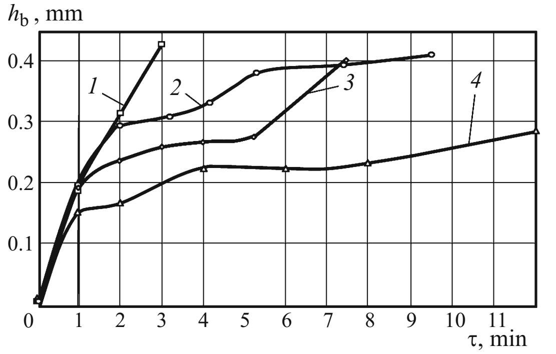

Fig. 4. Dependence of the wear of the back surface hb on the time of cutting h_b for CI from VOK-71 with different NMCC: *1*) control CI with VOK-71; *2*) VOK-71 – Ti – (TiAl)N – (TiCrAl)N; *3*) VOK-71 – Ti – (TiAl)N – (TiAlZrNbCr)N; *4*) VOK-71 – Ti – (TiAl)N – (TiCrAlSi)N.

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