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RESEARCH

The Investigation of Coated Tools Tribological Characteristics Influence on the Cutting Process and the Quality Parameters of the Parts Surface Layer

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A B S T R A C T

The influence of cutting tools nanostructured coatings on the parameters of machined parts surface layer has been researched. The interaction between friction characteristics of coated tools and shear plane angle during machining has been determined. The results of different materials cutting with coated carbide-tipped tools have been shown.

1. INTRODUCTION

The most important production properties are reliability and endurance. These properties provide product safety and competitiveness. The main cause leading to breakdown of parts is fatigue cracks. Such cracks appear and propagate in thin surface layers of parts. In order to hamper crack growing, the surface layer has to exhibit certain features. They are: roughness, residual stress and strain hardening, which depend on the characteristics of cutting operation.

The cutting force, temperature of cutting, depth of wear hardening and degree of deformation are referring to the main characteristics of cutting operation. These characteristics influence on the parts quality, reliability and endurance. Technological conditions of cutting such as tools geometry, processing conditions, work material properties and tooling material properties, including tribological feathers, determine the characteristics of cutting process. Therefore there is a need to select optimal cutting conditions to provide the requirement parts quality. In order to select optimal cutting conditions, there is necessity to have a special methodic, which takes into consideration the relationship between parts quality and technological conditions.

2. TASKS OF RESEARCH

At the Rybinsk state of aviation technical university named after P.A. Solovjev (Russia) there was developed the methodic, which permit to estimate the optimal cutting conditions. On the base of this methodic underlay a functional connection between cutting rate, tools geometry and the parameters of surface layer, accuracy of machining and the rigidity of manufacturing system, including work material and tool material properties.

But all advanced tools have wear-resistant coatings that exhibit specific properties [8]. Wear-resistant coatings have low friction coefficient in consequence of weak adhesion interaction of covering material with work material. They influence on the cutting process and quality parameters of the surface layer. Tools coverings reduce chips contact length with tools surface, cutting force, temperature of cutting and deformation of cut allowance [6]. It causes due to increasing of a chip flow angle.

Thus the main purpose of research was the creation of the methodology for calculation of technological conditions of turning, which provides required quality and accuracy levels at the stage of machining and takes into consideration the tribological properties of coated tools.

In order to provide both high parts quality and maximum tools life one should calculate so called «optimal cutting speed» v_0. Optimal cutting rates (v_0, S_0) correspond to the optimal cutting temperature. It is constant magnitude for the define combination work – tool material [1]. When machining with this temperature, maximum tools lifetime, minimal roughness of machined surface Ra, minimal amount of surfaces defects have been occurred. Therefore these cutting rates should be used, when finishing work was performed for parts, which work in corrosive medium and high temperature, because the surface layer has to contain minimal amount of defects. For estimating of the optimal cutting speed the equation is obtained by prof. Silin S. S. [1]:

$$v_O = \frac{C_O \cdot a}{a_1}\left(\frac{a_1 \cdot b_1 \cdot c\rho \cdot \theta}{Pz_{\min}}\right)^n, \quad (1)$$

where: a_1, b_1 – is the thickness and the width of cut respectively [m];

a – is the coefficient of the temperature conductivity of the work material [m^2/s];

$c\rho$ – is the specific heat capacity per unit volume [J/(m^3 · s · degree)];

θ – is the temperature in the cutting area, °C;

n, C_o – are coefficients, which depend on the properties of work material;

$Pz_{\min}$ – is a minimal stabilized cutting force [N].

But very often there is a need to select cutting conditions, which differ from the optimal ones. Therefore the opportunity to estimate the technological conditions of turning with taking into consideration the tribological properties of coated tools, will provide the required quality and service properties of parts at the stage of machining.

The analysis of the mathematical models for estimating of the parameters of cutting process and quality of the surface level has shown, that the more important variable quantities are the shear plane angle β_1 and the adhesive component of the friction coefficient f_M. Thus the main tasks of the scientific research were:

1. To investigate the influence of tribological characteristics of coated tools on cutting process and the parameters of surface layer.
2. To define optimal cutting speed for tools with different coatings.

3. EXPERIMENTAL CONDITIONS

The wide range of cutting rates, different work materials and coated tools were selected for performing of experiments (Table 1).

In the capacity of tools were used the replaceable inserts 120412, material – VK6R (chemical composition: Co – 6 %, basis – WC tungsten carbide) and TT7K12 (chemical composition: Co – 12 %, TiC – 1 %, TaC – 7 %, basis – WC). The different composite nanolaminated ion-plasmous coatings were deposited on the replaceable inserts: (Ti;Si)N, (Ti,Si,Zr)CN and (Ti;Si;Al)N. Other group replaceable inserts was modified by implanting of nanoparticle TiB_2, Al_2O_3, Ta_2O_3 and ZrB_2 in work surface of tools. All selected coatings have been characterized by the minimal adhesive of the tools surfaces with work material, and also they have been provided maximum tools lifetime. The machining was performed by the regular engine lathe NH 22. The temperature was measured by means of a dynamic thermocouple of work material – tooling material [2]. The normal component of a cutting force *Pz* was measured by using the tool dynamometer Dyna-Z, which was connected with personal computer (Fig. 1). The tool dynamometer Dyna-Z is a self-sufficient measurement system, which can use without an additional power source, a tensometric station and DAQ board. And a precision measured signal can be shown and saved in a very useful for operator form. The tool dynamometer Dyna-Z was made by Technologist LLC [3].

Fig. 1. The tool dynamometer Dyna-Z.

4. RESULTS AND DISCUSSION

The experimental data of machinability investigation has been shown, that a cover of tool can reduce a temperature θ in a cutting area on 50-70 °C, and a cutting force *Pz* can be reduced on 10-30 % (Fig. 2) [7].

Thus on the base of obtained power dependences, one can make an equation of machinability to estimate of optimal cutting speed v_0 for different combination work material – coated tool. The equations of machinability for considered examples have been given on Table 2.

The optimal cutting speed of coated tool exceeds the optimal cutting speed of uncoated tool. Then fewer the coatings friction coefficient, then bigger optimal cutting speed.

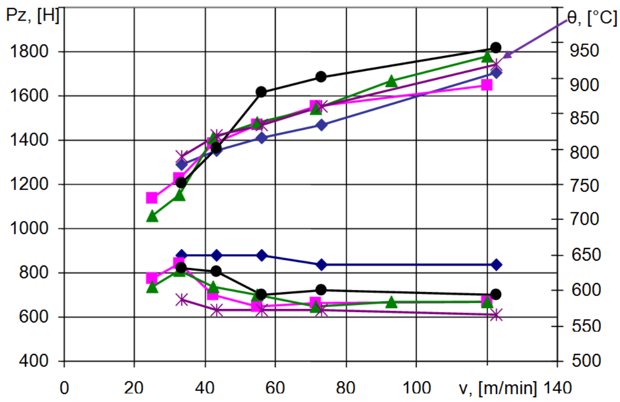

Fig. 2. The dependence of a cutting force and temperature on cutting conditions and tools cover; work material – Stainless steel EK26; Tool material – carbide material VK6R; tools geometry: $\varphi = \varphi_1 = 45$ °, $\gamma = 8$ °; $\alpha = 7$ °, r = 1,2 mm; cutting rate: t = 1 mm; S = 0,32 mm/rev; nanostructured coatings of tool: VK6R (without cover); (Ti;Si)N; (Ti;Si;Al)N; TiB2; Al_2O_3.

Table 1. Experimental conditions.

Changing parameters		Work material				
		Heat-resistant alloy (CrNi77TiAlW) EI437		Stainless steel (05Cr12Ni2Co3Mo2WV) EK26		Titanium alloy OT4
Tools geometry	Cutting angle, γ°	5		8		0
	Relief angle, α°	10		12		10
	Lead angle, φ, φ1°	45				
	Nose radius, *r* [mm]	1,2				
Cutting rate	Deph, *t* [mm]	0,25; 0,5; 0,75; 1				
	Feed, *S* [mm/rev]	0,07; 0,14; 0,2; 0,32				
	Speed, *v* [m/min]	14-170		33-190		15-130
Tool material – carbide material		VK6R	TT7K12	VK6R	TT7K12	VK6R
Nanostructured coating		(Ti,Si)N	Ta_2O_3	(Ti,Si)N	Ta_2O_3	(Ti,Si)N
		(Ti,Si,Al)N	ZrB_2	(Ti,Si,Al)N	ZrB_2	(Ti,Si,Zr)CN
		TiB_2		TiB_2		ZrB_2
		Al_2O_3		Al_2O_3		Al_2O_3

Table 2. The equations of machinability.

Materials	VK6R–EK26	VK6R–EK26–(Ti,Si)N	VK6R–EK26–Al_2O_3
Equation of machinability	$v_O = \frac{2{,}31\cdot a}{a_1}\left(\frac{a_1\cdot b_1\cdot c\rho}{t^{0,77}\cdot S^{\frac{0,72}{t^{0,083}}}}\right)^{2,47}$	$v_O = \frac{2{,}76\cdot a}{a_1}\left(\frac{a_1\cdot b_1\cdot c\rho}{t^{0,68}\cdot S^{\frac{0,766}{t^{0,106}}}}\right)^{2,48}$	$v_O = \frac{4{,}76\cdot a}{a_1}\left(\frac{a_1\cdot b_1\cdot c\rho}{t^{0,737}\cdot S^{\frac{0,695}{t^{0,044}}}}\right)^{2,53}$
Friction coefficient f_M θ = 800 °C	0,44	0,35	0,16
v_O [m/min], cutting rate t = 1 [mm]; S = 0,32 [mm/rev]	56	64	102

In order to estimate the influence of coated tools on the parameters of surface layer, one have to determine the influence of coated tools on a shear plane angle β_1 or a criterion *B*. This criterion is one of the major parameter, which used for estimating of roughness, residual stress and strain hardening in the parts surface layer.

B = tg β_1 – Is the quantity, which defines the degree of allowance plastic deformation and the deformation of parts surface layer.

The quantity β_1 was estimated by means of Tim's I. A. formula using a chip reduction coefficient k_a, which was determined experimentally [1].

$$k_a = \frac{\cos(\beta_1 - \gamma)}{\sin\beta_1}, \qquad (2)$$

where γ – is a cutting angle.

Figure 3 shows the dependence of criterion *B* on the technological conditions of operation.

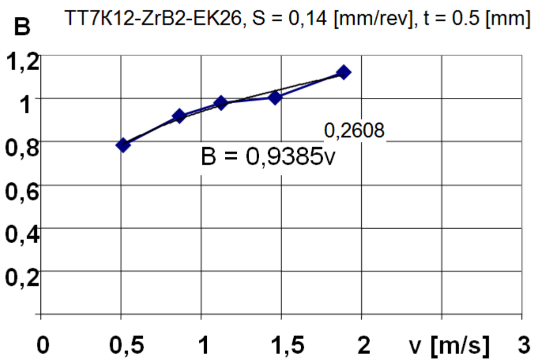

Fig. 3. The comparison the criterion B and technological conditions of operation; Work material – the stainless steel EK26, tool – TT7K12, coating – ZrB_2.

It is clearly shown, that in the time of increasing of cutting speed *v* the criterion *B* increases too. It is the reason for increasing of an angle of shear plane β_1. The angle of shear plane β_1 increases, because the materials ultimate stress σ_B reduces by reason of increasing of rate of deformation and temperature in the cutting area.

On the base of experimental research the influence of different technological conditions on the criterion *B* has been obtained. The quantity of shear plane β_1 of coated tool increases approximately on 5-10 %. But experimental equations are limited by technological conditions of experiments and couldn't be used for other conditions or other covers of tool. Therefore the methodology for estimating of a criterion B for other covers of tool has been developed. This methodology is based on the taking into consideration adhesive component of the friction coefficient f_M of coated tool.

For determination of the friction coefficient two approaches were used [4]. According to the first approach, friction coefficient μ^F was determined as a ratio of a tangential force to a normal force of cutting:

$$\mu^F = \frac{F_{\tan}}{N} = \frac{\overline{Py} + \overline{Px}}{Pz} = \frac{Py\cdot\cos\varphi + Px\cdot\cos(90-\varphi)}{Pz}, \quad (3)$$

where:
μ^F – friction coefficient;
Py, Px, Pz – components of a cutting force, [H];
F_{tan} – tangential force to a cutter face, [H];
N – normal force to the cutter face, [H];
Py – radial component of a cutting force, [H];
Px – axial component of a cutting force, [H].

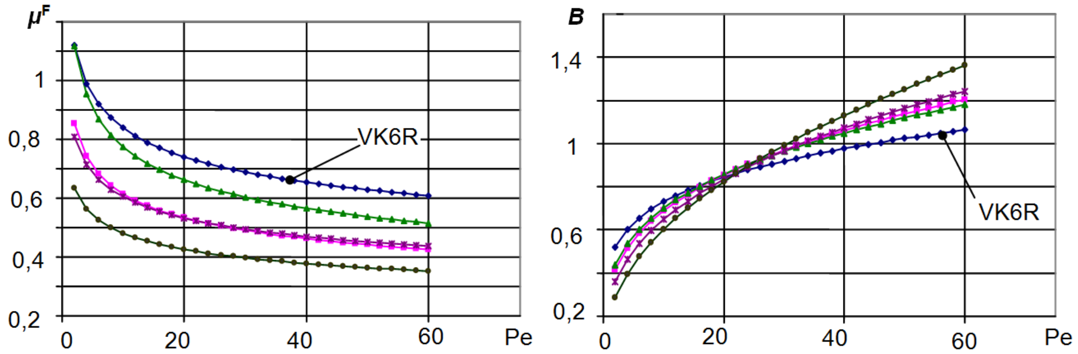

Fig. 4. The dependence of criterion *B* and friction coefficient μ^F on a dimensionless complex *Pe*; work material – Stainless steel EK26; tool material – carbide material VK6R; nanostructured coatings of tool: VK6R (without cover); (Ti;Si)N; (Ti;Si;Al)N; TiB_2; Al_2O_3.

On the Fig. 4 the dependence of criterion *B* and friction coefficient μ^F on a dimensionless complex $Pe = \frac{v \cdot a_1}{a}$, which defines the technological conditions of operation, has been shown.

The comparison of curves on the Fig. 4 permits to create the proportion:

$$B_2 = \frac{\mu_1^F \cdot B_1}{\mu_2^F} \tag{4}$$

The magnitude of unknown criterion B_2 can be approximately estimated if the magnitudes of criterion B_1 and friction coefficients μ_1^F, μ_2^F which correspond to the tools with different coatings, are known. But the determination of the friction coefficient μ^F according to the first approach doesn't take into consideration the temperature in the cutting area.

The second approach has 'not this shortcoming. According to the second approach for determination of the friction coefficient the adhesiometer was used (Fig. 5). It is known, that the friction coefficient:

$$f = f_D + f_M , \tag{5}$$

where:
f_D – deformation component of the friction coefficient;
f_M – adhesion (molecular) component of the friction coefficient:

$$f_M = \frac{3}{4} \cdot \frac{F \cdot R}{N \cdot r}, \tag{6}$$

where:
R – radius of the disc, [m];
r – radius of the impress on the sample, [m];
N – normal force, [H];
F – peripheral force on the disc, [H].

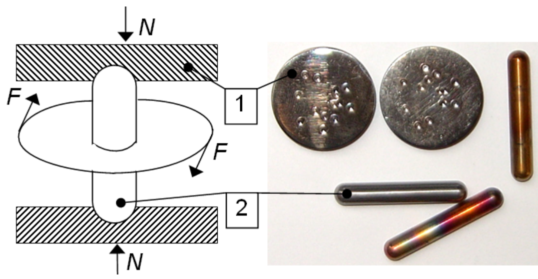

Fig. 5. The flow chart of one-ball adhesiometer; 1 – samples of the work material; 2 – indenter of the tool material; N – normal force, which impress the indenter [H]; F – peripheral force, which roll the disc, [H].

Fig. 6 shows the friction coefficient, which was determined for different temperatures and combinations of work materials – coated indenter (pin).

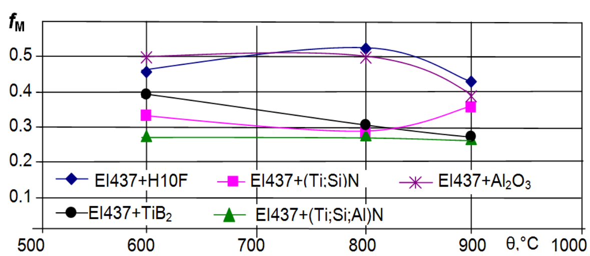

Fig. 6. The influence of the temperature on a friction coefficient; work material – heat-resistant alloy EI437; tool material – carbide material H10F; nanostructured coatings of indentor: H10F (without cover); (Ti;Si)N; (Ti;Si;Al)N; TiB_2; Al_2O_3

Thus if the magnitude of the criterion B_1 of cover 1 and the functions of friction $f_M = f(\theta)$ of cover 1 and 2 like the dependence of friction coefficient on the temperature θ are known, the magnitude of a unknown criterion B_2 of cover 2 can be approximately estimated by means of correcting coefficient:

$$k = \frac{f_M^{cover1}}{f_M^{cover2}} \tag{7}$$

where:

$f_M^{cover1}, f_M^{cover2}$ – adhesion component of the friction coefficient of work material with cover 1 and 2.

On the base of obtained results of experiments the methodology for calculation of technological conditions of turning, which provides required quality and accuracy levels at the stage of machining and takes into consideration the tribological properties of coated tools, has been developed. The methodology can estimate technological conditions of turning and solve an inverse task – it can estimate roughness, residual stress and strain hardening. The algorithm for calculation of required technological conditions of turning was implemented in the software (Fig. 7).

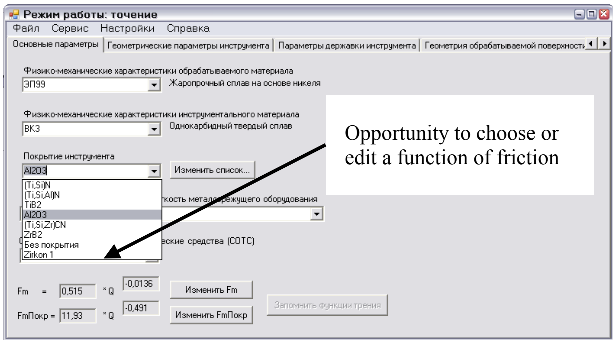

Fig. 7. The software for calculation of required technological conditions of turning.

In order to check the obtained mathematical models, the comparison of the experimental and calculated data was performed. The investigation of the parameters of surface layer has been performed on the machined parts "ring". The conditions of turning of the parts "ring": work material – stainless steel EK26; tool material – carbide material VK6R; tools geometry: $\varphi = \varphi_1 = 45$ °, $\gamma = 8$ °; $\alpha = 7$ °, r = 1,2 mm; cutting rate: t = 0,75 mm; S = 0,2 mm/rev; nanostructured coatings of tool: (Ti;Si)N; (Ti;Si;Al)N.

The results of experiments (Table 3) have been clearly shown, that coated tool reduces the magnitude of the roughness, residual stress and strain hardening in according with the magnitude of friction coefficient. The calculation of the parameters of the surface layer was performed by means of mathematical models presented in [5] and software. The parameters of the roughness *R*a and *R*z reduce on the average 5 %, therefore the main cause leading to the formation of the roughness are tools geometry, feed rate, vibration and so on, but not the cover of tool. The strain hardening reduces on 20 % as compared with uncoated tool.

In order to check our obtain data we have compared the experimental and calculated distribution diagrams of tangential residual stress. The using of coated tool leads to the considerable reduces of adverse tensile residual stresses.

The distribution diagrams of the tangential residual stress are shown on a Fig. 8.

The experimental distribution diagram of the tangential residual stress was performed by means of methodology of layer-by-layer electrochemical etching (Fig. 9). The using of coated tool leads to the considerable redaction of adverse tensile residual stress and its depth, the calculated data correlate with the experimental ones.

Table 3. Experimental and calculated value of strain hardening h_C and parameters of the roughness *R*a and *R*z.

Cover	Calcul.	Exper.	Δ, %	Calcul.	Exper.	Δ, %	Calcul.	Exper.	Δ, %	Criterion B
	Ra, mkm			Rz, мкм			h_C			
VK6R	1,84	1,42	29	8,4	6,8	23	37	50	26	0,95
(Ti;Si)N	1,53	1,35	13	7	6,3	11	34	40	15	1,02
(Ti;Si;Al)N	1,64	1,34	22	7,5	5,8	29	35	40	13	1,01

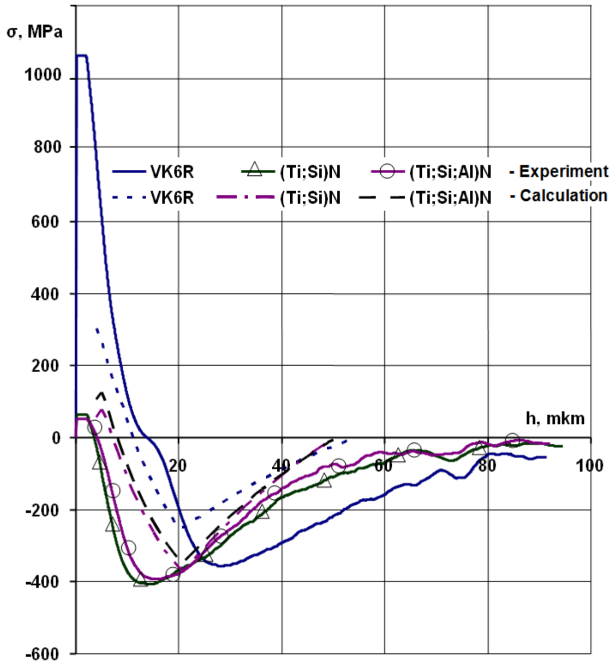

Fig. 8. The distribution diagrams of the tangential residual stress of machined part.

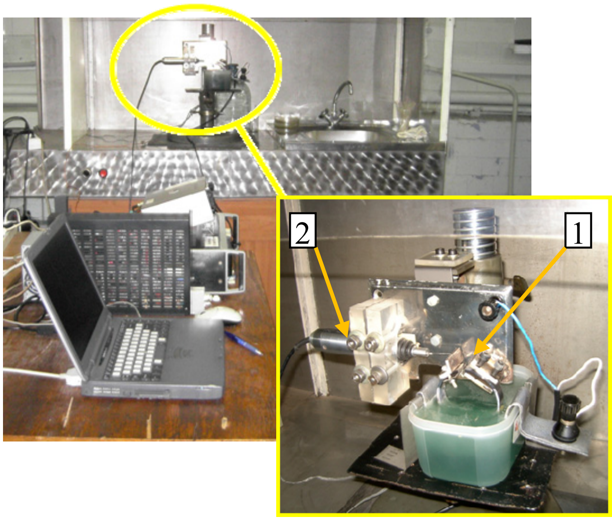

Fig. 9. The equipment for layer – by - layer electrochemical etching: 1 – operative embodiment “ring”; 2 – mechanical motion transducer.

5. CONCLUSION

The optimal cutting speed of coated tool exceeds the optimal cutting speed of uncoated tool; then less the coatings friction coefficient, then more optimal cutting speed.

The using of coated tool leads to the considerable redaction of adverse tensile residual stress and its depth.

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