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THE INFLUENCE OF TRIBOLOGICAL CHARACTERISTICS OF COATED TOOLS ON THE CUTTING PROCESS AND THE QUALITY PARAMETERS OF THE PARTS' SURFACE LAYER

WPŁYW CHARAKTERYSTYK TRIBOLOGICZNYCH NARZĘDZI POKRYTYCH POWŁOKAMI NA PROCES SKRAWANIA I PARAMETRY JAKOŚCIOWE WARSTWY WIERZCHNIEJ

Key words:

nanostructured coatings, quality parameters of the surface layer, tools friction coefficient, turning, optimal cutting speed

Słowa kluczowe:

powłoki nanostrukturalne, parametry jakościowe warstwy wierzchniej, współczynnik tarcia dla narzędzi, optymalna prędkość skrawania

Summary:

The influence of cutting tools nanostructured coatings on the cutting parameters and the surface layer parameters of machined parts was researched. The wide

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range of cutting rates, different work materials, and coated tools were selected for the experiments. The results cutting different materials with coated carbide-tipped tools are presented. Based on obtained power dependences, an equation of machinability to estimate optimal cutting speed for different combination work material–coated tool was performed. The interaction between friction characteristics of coated tools and the shear plane angle during machining has been determined.

On the basis of the obtained results of experiments, the methodology for the calculation of technological conditions of turning, which provides the required quality and accuracy levels at the stage of machining and takes into consideration the tribological properties of coated tools, has been developed. In order to check the obtained mathematical models, a comparison of the experimental and calculated data was performed. The results of experiments show that coated tool reduces the magnitude of the roughness, residual stress, and strain hardening in correlation with the magnitude of the friction coefficient.

INTRODUCTION

The main cause leading to the breakdown of parts is fatigue cracks. Such cracks appear and propagate in thin surface layers of parts. In order to hamper crack growth, 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, the temperature of cutting, the depth of wear hardening, and the degree of deformation are the main characteristics to consider in a cutting operation. These characteristics influence the quality, reliability, and endurance of parts. Technological conditions of cutting such as tools geometry, processing conditions, work material properties, and tooling material properties, including tribological features, determine the characteristics of the cutting process. Therefore, there is a need to select optimal cutting conditions to provide the required parts' quality. In order to select optimal cutting conditions, there is a special method, which takes into consideration the relationship between parts' quality and technological conditions.

TASKS OF RESEARCH

Research at the Rybinsk State Aviation Technical University named after P.A. Solovjev (Russia) was developed a method to estimate the optimal cutting conditions. This method is based on the functional connection between cutting rate, tools geometry, and the parameters of surface layer, the accuracy of machining, the rigidity of manufacturing system, the work material, and tool material properties.

All advanced tools have wear-resistant coatings that exhibit specific properties. Wear-resistant coatings have a low friction coefficient due to the weak adhesion interaction of covering material with work material. They influence the cutting process and quality parameters of the surface layer. The coatings reduce the chip flow angle, contact length with tools surface, cutting force, the temperature of cutting, and the deformation of the cut. Thus, the main purpose of research was the creation of the methodology for calculation of technological conditions of turning, which provides the 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 quality parts and maximum tools life, one should calculate "the optimal cutting speed" - v_O. Optimal cutting rates (v_O, S_O) correspond to the optimal cutting temperature. It is a constant magnitude for the define combination work – tool material **[L. 1]**. When machining at this temperature, maximum tool life, minimal roughness of machined surface Ra, and minimal amount of surfaces defects have occurred. Therefore, these cutting rates should be used for finishing work for parts, which work in a corrosive mediums and high temperatures, because the surface layer has to have minimal defects. For estimating of the optimal cutting speed, the equation was obtained by Prof. Silin S.S. **[L. 1]** as follows:

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

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]; cρ – is the specific heat capacity per unit volume [$J/(m^3 \cdot s \cdot degree)$]; 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].

There is often a need to select cutting conditions, which differ from the optimal ones. Therefore, the opportunity to estimate the technological conditions of turning, while 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 the cutting process and the 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 this scientific research were the following:

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.

EXPERIMENTAL CONDITIONS

The wide range of cutting rates, work materials, and coated tools were selected for the experiments.

In the tools used replaceable inserts 120412, material – VK6R (chemical composition: Co – 6%, basis – WC) and TT7K12 (chemical composition: Co – 12%, TiC – 1%, TaC – 7%, basis – WC). The different composite nano-laminated ion-plasma coatings were deposited on the replaceable inserts – (Ti;Si)N, (Ti,Si,Zr)CN, and (Ti;Si;Al)N. Another group of replaceable inserts were modified by implanting nanoparticles of TiB_2, Al_2O_3, Ta_2O_3, and ZrB_2 in the work surface of tools. All selected coatings have been characterized by minimal adhesion of the tools surfaces with work material, and they have maximum tool life. The machining was performed by a regular NH22 lathe. Temperature was measured by means of a dynamic thermocouple of the work material – tooling material. The normal component of the cutting force Pz was measured by using Dyna-Z tool dynamometer, which was connected to a personal computer **(Fig. 1)**. The Dyna-Z tool dynamometer is a self-sufficient measurement system, which can be used without an additional power source, a tensometric station, or DAQ board, and a precisely measured signal can be shown and saved in a very useful form **[L. 2]**.

Fig. 1 The dynamometer Dyna-Z
Rys. 1. Dynamometr Dyna-Z

RESULTS AND DISCUSSION

The experimental data of the machinability investigation indicates that a tool coating can reduce temperature θ in the cutting area by 50–70°C, and the cutting force Pz can be reduced by 10–30% **(Fig. 2)**.

Thus, based on the obtained power dependences, one can make an equation of machinability to estimate optimal cutting speed v_O for different combinations the work material and coated tool. The comparison of optimal cutting speed and friction coefficient for the considered examples are given in **Table 1**.

The optimal cutting speed of coated tools exceeds the optimal cutting speed of uncoated tools. The lower the friction coefficient of the coatings, the higher the optimal cutting speeds.

In order to estimate the influence of coated tools on the parameters of the surface layer, one determines the influence of coated tools on a shear plane angle β_1 or on criterion B. This criterion is one of the major parameters, which is used for estimating roughness, residual stress, and strain hardening in the surface layer of the part being machined **[L. 3, 4]**.

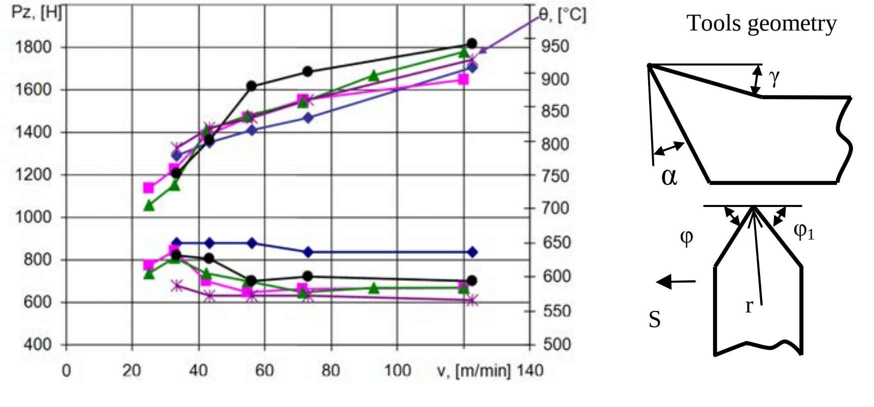

Fig. 2. The dependence of cutting force and temperature on cutting conditions and tool coatings: work material – Stainless steel EK26; Tool material – carbide material VK6R; tools geometry: φ = φ_1 = 45°, γ= 8°; α= 7°, r = 1.2 mm; cutting rate: t (depth of cutting) = 1 mm; S(tool advance) = 0.32 mm/rev; nanostructured coatings of tool: VK6R (without cover); (Ti;Si)N; (Ti;Si;Al)N; TiB2; Al_2O_3

Rys. 1. Wpływ siły skrawania i temperatury na warunki skrawania narzędzia pokrytego powłoką: materiał obrabiany – stal nierdzewna EK26, materiał narzędzia – węglik spiekany VK6R, geometria ostrza: φ = φ_1 = 45°, γ = 8°; α = 7°, r = 1,2 mm; parametry skrawania: t (głębokość) = 1 mm; S (posuw) = 0,32 mm/rev; nanostrukturalne powłoki na narzędziu: VK6R (bez powłoki); (Ti;Si)N; (Ti;Si;Al)N; TiB2; Al_2O_3

(B = tg β_1) is the quantity that defines the degree of the allowance of plastic deformation and the deformation of the part's surface layer. The quantity of shear plane angle β_1 was estimated through the following formula, and the chip reduction coefficient k_a, was determined experimentally **[L. 1]**:

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

Based on experimental research, the influence of different technological conditions on criterion B has been obtained. The quantity of shear plane β_1 of the coated tool increases by approximately 5–10%. However, experimental equations are limited by technological conditions of experiments and could not be used for other conditions or other coatings of tool. Therefore, the methodology for estimating criterion B for other coatings of tools has been developed. This methodology is based on taking into consideration the adhesive component of the friction coefficient f_M of the coated tool.

For the determination of the friction coefficient, an adhesiometer was used **(Fig. 3)**.

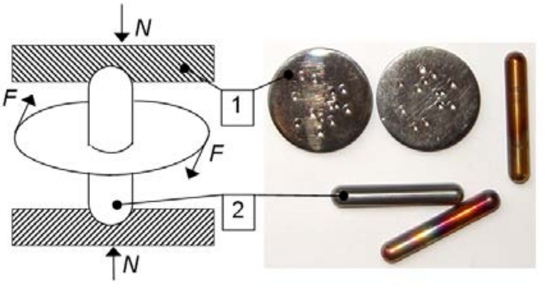

Fig. 3. The schematic of a one-ball adhesiometer; 1 – samples of the work material; 2 – indenter of the tool material; N – normal force, which impress the indenter [N]; F – peripheral force, which roll the disc, [N]

Rys. 3. Schemat przyrządu do pomiaru adhezji: 1 – próbki obrabianego materiału, 2 – wgłębnik z materiału narzędzia, N – siła normalna, która obciąża wgłębnik [N], F – siła, która obraca tarczę [N]

It is known, that the friction coefficient **[L. 3]** is

$$f = f_D + f_M \tag{3}$$

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

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

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

Figure 4 shows the friction coefficient, which was determined for different temperatures and combinations of work materials – coated indenter (pin).

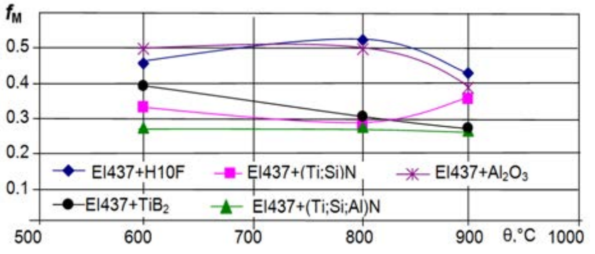

Fig. 4. The influence of temperature on the friction coefficient; work material – heat-resistant alloy EI437; tool material – carbide material H10F; nanostructured coatings of indentor: H10F (without cover); (Ti;Si)N; (Ti;Si;Al)N; TiB_2; Al_2O_3

Rys. 4. Wpływ temperatury na współczynnik tarcia, materiał obrabiany – żarowytrzymały stop EI437, materiał narzędzia – węglik spiekany H10F, nanostrukturalne powłoki na wgłębniku: H10F (bez pokrycia); (Ti;Si)N; (Ti;Si;Al)N; TiB_2; Al_2O_3

The comparison of optimal cutting speed and friction coefficient for the considered examples are given in **Table 1**.

Table 1. A comparison of optimal cutting speed and friction coefficient

Tabela 1. Porównanie optymalnej prędkości skrawania i współczynnika tarcia

Materials	VK6R–EK26	VK6R–EK26–(Ti,Si)N	VK6R–EK26–Al_2O_3
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

Based on the obtained results of experiments, the methodology for the calculations of technological conditions of turning, which provides the 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 the technological conditions of turning and estimate roughness, residual stress, and strain hardening. The algorithm for the calculation of required technological conditions of turning was implemented in the software **(Fig. 5).**

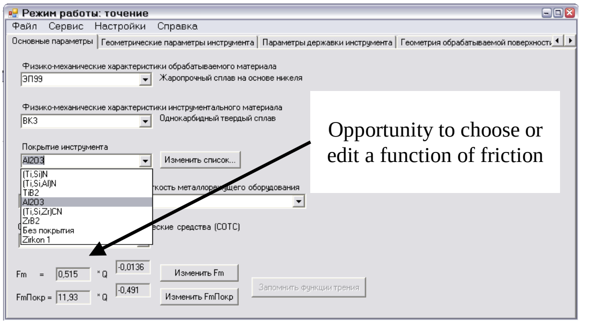

Fig. 5. A screenshot for the calculation of the required technological conditions of turning
Rys. 5. Rrzut ekranu programu do obliczania wymaganych parametrów technologicznych przy toczeniu

In order to check the obtained mathematical models, the comparison of the experimental and calculated data was performed. The investigations of the parameters of the surface layer were performed on a "ring" machined part. The conditions of turning are as follows: 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; and, S = 0.2 mm/rev; nanostructured coatings of tool – (Ti;Si)N; (Ti;Si;Al)N.

The results of experiments **(Table 2** and **Fig. 6)** have clearly shown that coated tools reduce the magnitude of the roughness, residual stress, and strain hardening in according with the magnitude of the friction coefficient. The calculation of the parameters of the surface layer was performed by means of mathematical models presented in **[L. 4]** and software. The parameters of the roughness Ra and Rz were reduced on the average 5%; therefore, the main cause leading to the formation of the roughness are tool geometry, feed rate, vibration, and so on, but not the coating of the tool. The strain hardening is reduced by 20% as compared to the uncoated tool.

Table 2. Experimental and calculated value of strain hardening h_C and parameters of the roughness Ra and Rz
Tabela 2. Dane eksperymentalne i obliczone głębokości zgniotu h_C oraz parametrów chropowatości R_a i R_z

Cover	Calc.	Exp.	Δ, %	Calc.	Exp.	Δ, %	Calc.	Exp.	Δ, %	Crit. B
	Ra, μm			Rz, μm			h_C, μm			
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

Note: Ra – arithmetic mean of the roughness, Rz – arithmetic mean of the roughness height five indentations and protrusions

In order to check our obtain data, we have compared the experimental and calculated distribution diagrams of tangential residual stress. Using coated tools leads to considerable reductions in adverse tensile residual stresses.

The distribution diagrams of the tangential residual stress are shown on **Fig. 6**.

The experimental distribution diagrams of the tangential residual stress were performed by means of the methodology of layer-by-layer electrochemical etching. Using coated tools leads to the considerable redaction of adverse tensile residual stress and its depth, and the calculated data correlates with the experimental data **[L. 5]**.

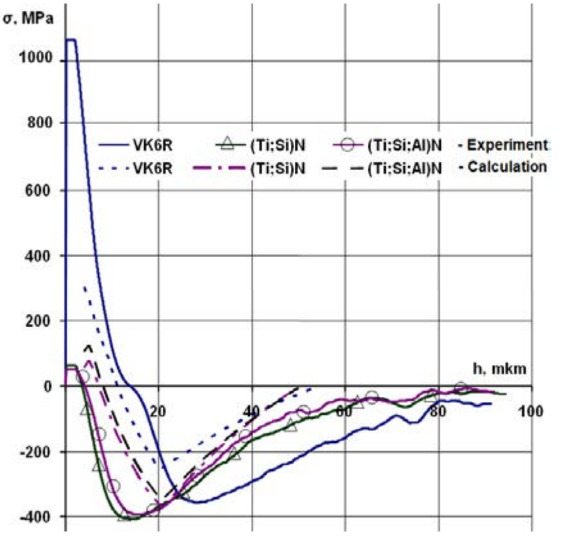

Fig. 6. Distribution diagrams of the tangential residual stress of machined parts
Rys. 6. Wykresy rozkładu naprężeń własnych stycznych w obrabianych elementach

CONCLUSION

1. The optimal cutting speed of coated tools exceeds the optimal cutting speed of uncoated tools, and the lower the coatings' friction coefficients, the more optimal is the cutting speed.
2. Using of coated tools leads to the considerable reduction of adverse tensile residual stress and its depth.

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Streszczenie

W pracy zbadano wpływ nanostrukturalnych powłok na narzędziach na proces skrawania i parametry jakościowe warstwy wierzchniej. Badaniom poddano, stosując szeroki zakres parametrów skrawania, wiele rodzajów obrabianych materiałów i narzędzi pokrytych powłokami. Podano także wyniki dla różnych kształtów narzędzi z węglika pokrytych powłokami. Bazując na otrzymanych zależnościach, opracowano równania obrabialności pozwalające na dobór optymalnej prędkości skrawania dla różnych kombinacji obrabiany materiał – narzędzi z powłoką. Została także określona zależność pomiędzy charakterystykami tarciowymi narzędzi pokrytych powłokami a kątem skrawania.

Na podstawie uzyskanych wyników badań opracowano metodologię obliczania parametrów technologicznych toczenia, dla których uzyskuje się wymagany poziom jakości i dokładności obróbki. Aby zweryfikować opracowane modele matematyczne, dokonano porównania wyników obliczeń z danymi eksperymentalnymi. Wyniki badań dowiodły, że dla narzędzi z powłokami redukcja chropowatości, naprężeń własnych oraz zgniotu koreluje z obniżeniem współczynnika tarcia.