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IMPACT OF CUTTING ELEMENTS ON FORCES AND ROUGHNESS OF SURFACE DURING TURNING HARD STEEL X160 CrMo V12 WITH CBN TOOL

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Original scientific paper
The goal of these researches is related to the analyses of the impact of elements of cutting mode on the change of cutting forces, quality of a machined surface and change of physical and mechanical properties of a surface layer of a CBN tool for turning of X160 CrMo V12 steel having a hardness of 60±2 HRC. The results of the analyses of tool surface wear indicate the presence of oxidation and changes of physical and mechanical properties in a tool surface layer. The evaluation clearly shows that a radial force (F_r) is dominant during the machining of this steel. The mathematical models of dependence of cutting force and a quality of machined surface were developed. It was ascertained that an oxidation of the tool surface, next to a contact zone tool-cutting chip, leads to the increase of their hardness and reduction of their strength, and it finally leads to the emergence of micro-wear of a cutting knife and rapid tool wear.

Keywords: *CBN (corundum and boron-nitride); force; roughness; turning; wear*

Utjecaj parametara rezanja na sile i hrapavost površine pri tokarenju kaljenog čelika X160 CrMo V12 alatom od CBN

Izvorni znanstveni članak
Cilj ovih istraživanja se odnosi na istraživanje uticaja elemenata režima rezanja na promenu sila rezanja, kvaliteta obrađene površine i promene fizičko-mehaničkih svojstava u površinskom sloju alata od CBN pri struganju čelika X160 CrMo V12, tvrdoće 60±2 HRC. Rezultati istraživanja habanja površine alata ukazuju na prisustvo procesa oksidacije i promene fizičko-mehaničkih svojstava u površinskom sloju alata. Evaluacija sile jasno pokazuje da je radijalna sila (F_r) dominantna pri obradi ovog čelika. Razvijeni su matematički modeli zavisnosti sila rezanja i kvaliteta obrađene površine. Utvrđeno je da oksidacija površine alata, neposredno uz kontaktnu zonu alat-strugotina, dovodi do povećanja njihove tvrdoće i smanjenja čvrstoće, što u krajnjoj meri dovodi do pojave mikrokrzanja reznog sečiva a time i ubrzanog habanja alata.

Ključne riječi: *CBN; habanje; hrapavost; sila; tokarenje*

1 Introduction

The machining of superhard materials demands the use of a cutting tool that will satisfy the needed conditions from the aspect of the processes emerging during a cutting. There are many sources comprising the researches related to the use of superhard materials (SHM) in the machining of high-hardness materials [1, 2]. Thence, the authors [3÷5] in their researches analyse the impact of a composition, hardness of tool and workpiece, as well as the elements of machining mode on the tool consistency and quality of the processed surface. Paper [6] is focused on the research problems related to the surface integrity of the machined surface from the point of application of tools coated with Al_2O_3, and the appearance of plasticization and the material flow in the processing zone, at different cutting speeds.

The authors [7, 8], analyse the impact of wear on the change of CBN tool geometry, especially the impact of a crater on lead surface of a tool. Regarding the CBN tool wear, three basic mechanisms can be mentioned: 1) chemical wear conditioned by interacting with workpiece material and oxidation; 2) formation of coating on the tool surface for high temperatures and 3) abrasive wear [9÷12].

Very interesting research is present in the domain of designing new structures of cutting tools for turning relative to the existing commercial ones. So authors [13], investigate the influence, of the position of the cutting edges and the tool tip on the surface roughness and the necessary energy cutting. The aim is to design tools of optimal geometry from the point of transition from the forehead to the cylindrical surface of the workpiece.

Many researchers analysed the impact of elements of cutting mode on cutting forces and surface roughness and the results indicate a dominant impact of a radial component of cutting force for the interval of cutting depth that is smaller than the radius of round tip of the tool [14÷17]. At the same time, they noticed the presence of smaller cutting forces during bigger cutting speeds as a consequence of thermal softening of the workpiece, namely the temperature rise.

A part of the researches is related to the contemporary methods for optimization of machining with tools based on PCBN [18, 19].

The main wear mechanism of CBN during the machining of steel emerges as a consequence of abrasion of hard carbide particles present in the workpiece [20÷22]. Many researchers compared hard metal and CBN during the processing of super hard steel and found that the cutting temperature for CBN tools is lower than for hard metal for the same machining conditions [23].

The state of the surface layer of cutting tool is mainly conditioned by actions of heat generated in the cutting zone. For the purposes of an increase of tool consistency, it is necessary to determine the border of the heat impact zone, where the phenomena related to the changes of chemical composition and mechanical characteristics of tool surface material layer can emerge as a consequence of oxidation.

These processes are expressed during the machining of steel and high strength alloys with CBN tools because the temperatures up to 1200 °C emerge in the cutting zone since the machining is executed without cooling [24]. A very significant aspect connected to the tool wear is related to the change of chemical composition and mechanical properties. A large number of works is devoted to the research of influence, the application of coolant, on the indicators of the quality of processing, from the aspect of cooling and the emulsion composition. Authors [25, 26], in their research came to the conclusion that in the processing of steel X10CrNi18-8 with cooling emulsion in the form of fog, reduced surface roughness is compared to the air under pressure cooling or treatment without cooling. This is explained in that way, the treated surface to form a chemical compound and of the active substance of the modifier, and as a barrier layer a positive effect on the cutting conditions and the reduction of friction.

Depending on the composition, various composites start interacting with oxygen leading to chemical processes. The experimental researches in the area of oxidation of PSTM based on CBN–ciborit show that the oxidation emerges at 800 °C. Further temperature rise leads to an intensive oxidation of material, evaporation of boron oxide and removal of free nitrogen.

This paper presents the results of the experimental researches of the impact of cutting conditions on the cutting forces and roughness of machined surface of X160CrMo V12 steel, with a particular emphasis on the changes of composition of the surface layer of CBN-ciborit.

2 Conditions for conducting experiments

The machining centre HMC 500/40 (Fig. 1), 15 kW power, main axle rotation up to 6000 rpm and tool of PCBN-ciborit (Institute of superhard materials, Kiev, UA) was used for the experiments. A two – component dynamometer Kistler 5007, cDAQ-9174 NI was used for the measurement of forces. Software for data acquisition LabWiew and Matlab, as well as a laser microscope LSM 510, and the device for measurement of the roughness Time TR200 were used.

The machined material is made of high–alloyed steel (X160 CrMo V12, produced by Bohler K105, W.Nr.1.2601) with high chrome content and dedicated for making of tools used in pharmaceutical industry. Tab. 1 gives the chemical composition and hardness of material.

Two types were used: CBN–ciborit, label CCGW 09T304 (α=7°, γ=0°) and CCGW120404 (α=6°, γ=−6°) whereby the elements of the machining mode are given in Tab. 2.

A triple-factor orthogonal plan of the first row with a shape of $2K$ (K = 3, v, f, a) was adopted for the plan of the experiment.

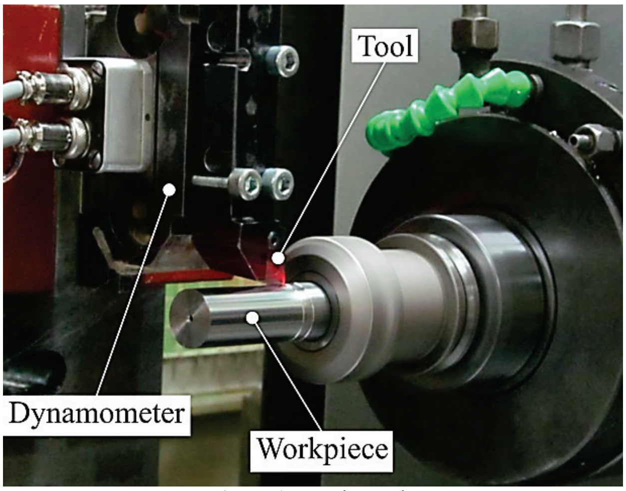


Figure 1 Experimental set-up

Table 1 Chemical composition of hardened steel X160 CrMo V12

No. of batch	A=3278
%C	1,63
%Si	0,36
%Mn	0,36
%P	0,024
%S	0,0012
%Cr	11,64
%Mo	0,54
%V	0,29
%W	0,48
Note: Material hardness 60±2 HRC	

Table 2 Elements of a machining mode

Level	Low	Medium	High
Cutting speed v / m/min	135	155	180
Feed f / mm/rev	0,05	0,10	0,20
Depth of cut a / mm	0,05	0,10	0,20

Table 3 Experimental results

Plan of matrices of experiments			Results					
Cutting condition			γ = 0°			γ = −6°		
v / m/min	a / mm	f / mm/rev	F_t / N	F_r / N	Ra / µm	F_t / N	F_r / N	Ra / µm
180	0,20	0,20	138,1	109,4	1,524	154,2	156,7	2,149
135	0,20	0,20	142,8	115,1	1,410	164,1	168,3	1,853
180	0,05	0,20	51,4	61,4	1,730	61,1	84,7	1,932
180	0,20	0,05	56,0	64,5	0,582	64,1	78,1	0,648
155	0,10	0,10	50,4	69,5	0,654	59,4	78,3	0,732
135	0,20	0,05	63,8	65,2	0,431	68,3	77,6	0,429
180	0,05	0,05	24,4	37,8	0,573	24,8	37,5	0,719
155	0,10	0,10	54,0	71,1	0,578	60,3	74,1	0,732
135	0,05	0,05	23,3	35,9	0,474	24,6	39,4	0,557
155	0,10	0,10	55,7	64,2	0,578	57,9	68,5	0,728
155	0,10	0,10	54,0	61,7	0,761	56,7	61,9	0,728
135	0,05	0,20	53,6	72,4	1,339	56,9	81,6	1,367

3 Results and discussion

Tab. 3 presents the measured results, medium values of ten repeated measurements having the deflections up to 5 %. Based on the experimental results, using a regression and dispersion analysis, the mathematical models were obtained (1, 2).

For machining with a CCGW 09T304 (α=7°, γ=0°) tool.

$$\begin{aligned} F_\mathrm{t} &= 2089{,}053 \cdot v^{-0{,}135} \cdot a^{0{,}686} \cdot f^{0{,}592} \\ F_\mathrm{r} &= 894{,}951 \cdot v^{-0{,}151} \cdot a^{0{,}392} \cdot f^{0{,}412} \\ Ra &= 0{,}118 \cdot v^{0{,}716} \cdot a^{-0{,}028} \cdot f^{0{,}774} \end{aligned} \tag{1}$$

For machining with a CCGW120404 (α=6°, γ=−6°) tool.

$$\begin{aligned} F_\mathrm{t} &= 1664{,}725 \cdot v^{-0{,}042} \cdot a^{0{,}713} \cdot f^{0{,}630} \\ F_\mathrm{r} &= 1181{,}584 \cdot v^{-0{,}068} \cdot a^{0{,}496} \cdot f^{0{,}544} \\ Ra &= 0{,}038 \cdot v^{1{,}009} \cdot a^{0{,}008} \cdot f^{0{,}820} \end{aligned} \tag{2}$$

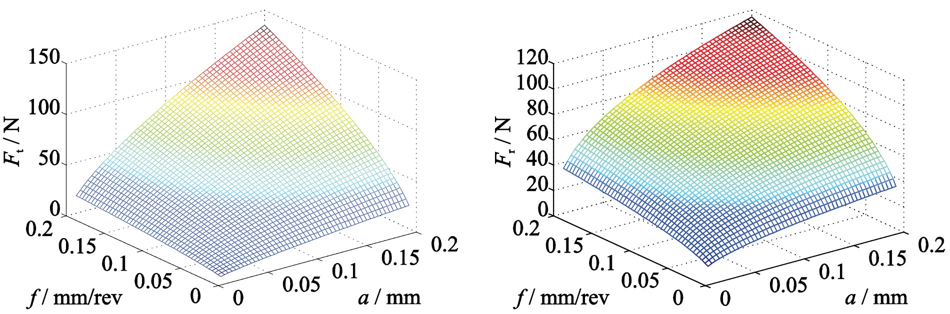
Based on the mathematical models (1, 2), Figs. 2÷4 present the diagrams of changes of components of forces F_r, F_t and roughness Ra.

3.1 Impact of lead angle

The lead angle of a tool (γ) impacts on the compression of chips and has no direct impact on the roughness of machined surface. Indirectly, a rise of lead angle facilitates the removal of chips, reduces both the elastic deformations of the machined surface and roughness. By a change of the lead angle from γ=0° to γ=6°, radial force (F_r) rises to 45 %, namely tangential force (F_t) to 12 % in the observed range of the research.

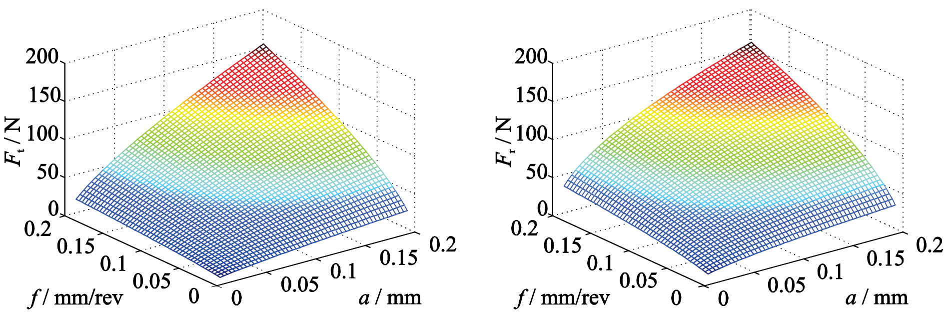
3.2 Impact of cutting parameters on cutting forces and surface roughness

The cutting depth has the strongest impact on the change of a component of cutting force F_r, while a step has the strongest impact on both tools on the F_t. The variations of cutting forces range in the interval of F_t=2,1÷2,7 and F_r=1,6÷2,3 (γ=0°), namely F_t=2,4÷2,8 and F_r=1,8÷2,1 (γ=−6°). With an increase of the cutting speed both components decrease as a consequence of an increased heating and softening of processed material. For both tools, a component of F_r force, in a range of the change of machining mode, is bigger than F_t. The graph in Fig. 4 presents the change of the surface roughness where the rise of roughness with the rise of cutting depth in the entire range of cutting can be observed. For smaller cutting depths, a relatively high roughness is present as the consequence of a scratching – ploughing instead of a cutting. With the rise of the depth, the ploughing effect is reduced and the better quality of surface is achieved in that way.



a) b)

Figure 2 Variation cutting force F_t a) and b) F_r (γ=0°, v=155m/min)



a) b)

Figure 3 Variation of cutting force F_t a) and b) F_r (γ=-6°, v=155 m/min)

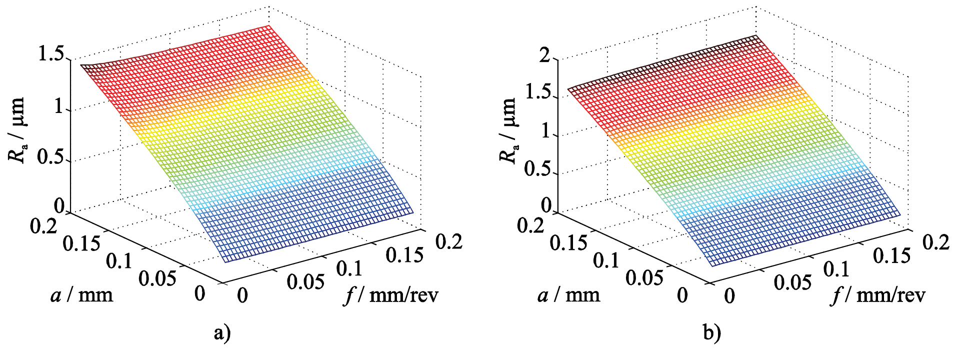


Figure 4 Variation in surface roughness, v=155 m/min (a) γ=0°, b) γ=−6°)

3.3 Tool wear

Fig. 5 presents the contact surfaces of the cutting tool after the machining of hard steel X160 CrMo V12. For a Ciborit tool (γ=0°), there is a region with brittle destruction on the back surface (Fig. 5a) indicating the bigger strain of lead tool surface and an insufficient strength of the composite in case of the exploitation in the conditions of high temperatures. The destruction of the cutting tool during the machining with speed of v=135 m/min (a=0,2 mm) emerged after 1,66 min. At a part of the lead tool surface, the layer of machined material that was pasted as a result of adhesion in the cutting zone can be observed (Fig. 5b). Based on the shape of the contact on the lead tool surface, it is possible to draw a conclusion about a significant impact of the mechanism of abrasive – adhesion wear on the cutting speed of the tool.

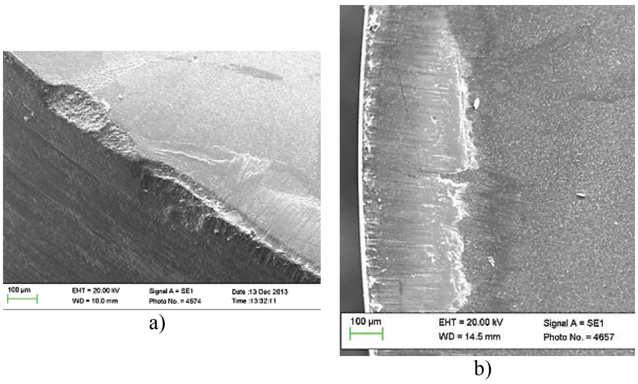


Figure 5 Tool contact surface after machining (v=135 m/min, a=0,2 mm, f=0,2 mm/rev)

Table 4 Chemical composition (%) of Ciborit thorax tool surface

Contact zone	B	C	N	O	Si	Ti	Fe
1	9,07	20,57	10,44	7,71	10,14	11,72	4,69
2	6,53	10,37	7,18	3,29	9,85	8,20	7,74
3	2,49	8,08	0,00	0,86	0,61	1,08	2,18
4	8,87	14,54	11,64	3,75	4,24	3,57	3,36
5	25,31	4,93	33,64	8,12	15,29	8,58	1,40
6	19,92	3,94	31,80	12,33	18,99	8,55	1,75
7	24,99	4,68	35,30	8,66	14,55	7,98	1,93
8	26,15	4,95	36,47	5,21	14,69	8,44	3,33
9	25,22	5,41	37,77	4,34	13,78	8,56	4,07
10	24,18	5,01	36,72	4,75	14,37	8,59	5,41
11	27,53	5,00	37,23	4,90	13,38	8,16	2,98
12	21,75	13,05	37,70	4,96	12,14	7,75	2,14

The chemical composition of the tool surface was determined by the method of micro x-ray spectroscopy analysis. Fig. 6 presents the position of measurement zones at the lead tool surface where the chemical composition was determined and is given in Tab. 4. The increased content of steel and oxygen on the tool surface is related to the gluing of particles of the machined material and products of interactions of contact materials.

Based on the data from Tab. 4 and Fig. 6, a diagram of distribution of oxygen on the lead tool surface of Ciborit, in the direction perpendicular to the main knife, (Fig. 7) was formed.

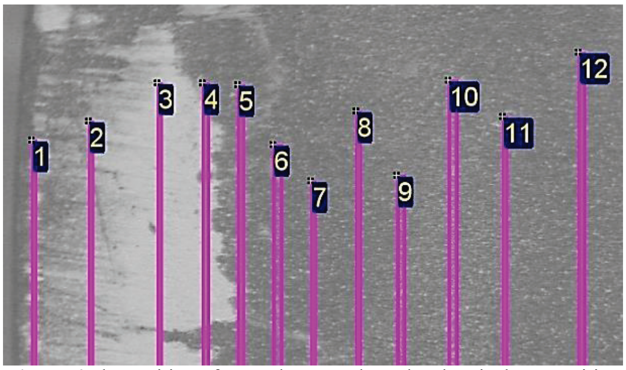


Figure 6 The position of control zones where the chemical composition of tool surface is determined, control zone

A low content of oxygen was observed at the distance of X=180÷200 μm from the cutting knife.

In cases of the contact of chips with the lead tool surface at a length of 120 μm, the effect of insulation of this area from the external surroundings occurs as well as the oxygen rise at the distance of X=300÷600 μm from the cutting knife. This effect can be explained by the fact that this area is situated in the interactions with air. Additionally, a liquid phase of product of interactions of contact material that also contains oxygen is fed into this zone.

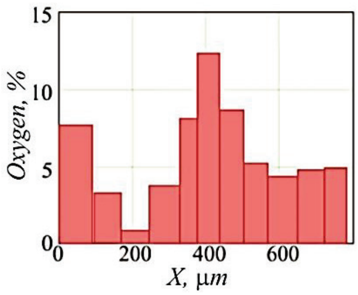


Figure 7 Diagram of oxygen distribution on Ciborit thorax tool surface (%)

4 Conclusion

During the machining of hard steel X160 CrMo V12 with CBN-Ciborit tool, the depth of cut has the biggest impact on a radial cutting force F_r, followed by a step, while a step followed by depth of cut has the biggest impact on a tangential cutting force. The same trend is represented also for tools with lead angles γ=0° and γ=−6°. For the machining by the tool with γ=0°, a lower roughness of the machined surface and more favourable removal of chips are achieved. Both components of forces are reduced by an increase of the cutting speed as the consequence of heating and softening of material.

For the machining by the γ=−6° tool, by an increasing of a step of f=0,05÷0,2 mm/rev, the rise of forces is almost identical for both depths of cut and is F_t for 2,46, F_r for 2,25 times (v= 180 m/min, a=0,05 mm), namely F_t for 2,31, F_r for 2,07 times (v=135 m/min, a=0,05 mm). For a depth of cut of a=0,2 mm, with an increase of a step of f=0,05÷0,2 mm/rev, a rise of forces is present, F_t for 2,4, F_r for 2 times (v=180 m/min), namely F_t for 2,40, F_r for 2,16 times (v=135 m/min).

The significant oxygen content in the tool surface is observed by the analysis of the chemical composition and it has the biggest value outside the contact zone at the distance of 0.5 mm from the knife. At the same time, the change of physical and mechanical properties on the tool surface leads to its rapid wear. For the evaluation process of the structural composition and mechanical properties of a CBN - based tool surface layer the following assumption can be applied: Oxidation of tool surface immediately to the contact zone tool-chip leads to the rise of its hardness and reduction of stiffness, that finally leads to the emergence of micro sliding of the tool composite as well as the rapid wear.

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