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Analysis and Optimization of Sintered Carbides Turning with PCD Tools

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Abstract

The paper presents the results of the cutting forces research (F_f, F_p , F_c) when machining of sintered carbides WC-Co (25 % Co) with tools made of polycrystalline diamond PCD. Inserts with three different nose radii r_ε were used during the study. Each cutting test was carried out on the distance 54 mm at the constant depth of cut 0.2 mm. The biggest increase of passive cutting force component F_p was indicated. In addition, the mathematical models for cutting force value prediction as the cutting path increases are presented. The paper presents also the algorithm of optimization and control of the super hard materials turning process.

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Keywords: turning; sintered carbides; polycrystalline diamond; mechanical model; optimization

1. Introduction

Environmental considerations during technological processes [1,2] and development of new tool materials [3-6] cause a rapid increase in the use and development of the machining technology of super hard/difficult-to-cut materials. These types of materials have hardness above 60 HRC (for instance: sintered carbides with different content of cobalt as a binder material) or materials based on titanium alloy [7-13]. Super hard/difficult-to-cut materials can be machined by the tools which edges are made of a diamond (synthetic or natural) or a cubic boron nitride CBN [14-17].

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Nowadays, classical machining methods (grinding, electro discharge machining EDM) for the machining of hard materials are a time- and energy-consuming as well as require to use of the coolant or electrolyte liquid. Super hard materials machining has many advantages over the classical methods, the most important examples of the advantages are presented following: low energy consumption, possibility of dry machining, multi-level processing, the quality of the work piece after machining process comparable to the quality after classical methods (described by the surface roughness parameters) [18-20].

One of the constraints to use the machining process (turning or milling) for super hard/difficult-to-cut materials is a significant low durability of machining tools due to the properties of tool materials as well as an unsuitable selection values of cutting data (v_c, a_p, f) or a type of cutting tool [15-18]. For this reason the research of the influence of three different factors (v_c, f, r_ε) on the values of the total cutting force components (F_f, F_p, F_c) with 54 mm of the turning length was performed. Growth of cutting forces causes the increase of the energy demand and permits an identification of the natural tool wear or the critical tool wear phenomenon. The tool's wear causes a deterioration of the surface quality after the machining process.

In this study, sintered carbides WC-Co shaft with content of 25% Co (HRA 85.4) was subjected to the turning process with PCD tools (MD220 diamond type). Polycrystalline diamond is a one of the hardest tool materials. PCD has a low resistance to fracture toughness. Therefore, in the case of the WC-Co turning by PCD tools a proper selection of the cutting data values is required in order to prevent a rapid wear of the tool edge (especially, avoid the critical tool wear) or a damage of the work piece surface [6-10,15-16,21].

The investigation shows the result analysis of the recorded total cutting force components (F_f, F_p, F_c) during WC-Co with 25% Co turning. Based on the obtained results the mathematical equations were designated to predict the growth values of the cutting force during WC-Co turning with PCD tools. Additionally, the main principle of the own algorithm, which main task is to optimize the super hard/difficult-to-cut materials turning process (for instance, sintered carbides WC-Co) based on a mechanical model describing the suitable turning process was characterized.

The presented researches are the part of new development trend in the world of machining due to attempts displaces the classical machining processes, which are very cost- and energy-consuming processes (i.e. grinding process or EDM process) by the machining process, for example: sintered carbides turning with PCD tools. Nowadays, the super hard machining of sintered carbides with PCD tools will be used separately or equally with classical machining processes in order to obtain work piece with proper quality after the finishing machining. In the near future, the sintered carbides turning will be a new branch of the super hard machining.

Nomenclature

F_c	main cutting force
F_p	passive force
F_f	feed force
F	total cutting force
v_c	cutting speed
f	feed
r_ε	nose radius
Co	cobalt
PCD	polycrystalline diamond

2. Research

Turning tests of sintered carbides (WC-Co shaft with content of 25% Co) were made by the inserts with three different nose radii r_ε (0.2; 0.4; 0.8) mm. The cutting data (v_c, f) was defined according to the previous research results of the sintered carbides turning with different content of cobalt (10, 15, 25% Co) by PCD tools [22-23]. Selected values of v_c and f identify the surface roughness for which the largest values of roughness after turning process by tools with different nose radii at constant depth of cut a_p = 0.2 mm were measured. Three tests of WC-Co turning were conducted for the same values of turning length (54 mm). The selected values of the cutting data (v_c, f)

are shown in Table 1. The test stand for recording of the total cutting force *F* components (F_f, F_p, F_c) was built based on the precision lathe, WC-Co shaft with 25% Co, inserts TNGA type, holder, piezoelectric dynamometer Kistler, charge amplifier and computer with appropriate software for cutting force components analysis (DynoWare), Fig. 1.

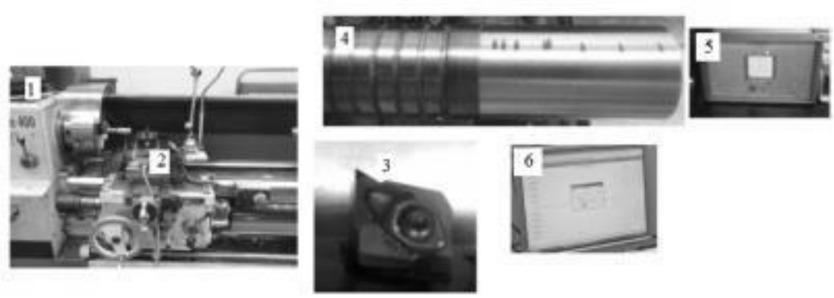

Fig. 1. The test stand for recording of the cutting force components (F_f, F_p, F_c) during WC-Co turning with PCD tools: 1) precision lathe, 2) dynamometer Kistler, 3) insert, 4) WC-Co shaft with 25%Co, 5) charge amplifier 6) computer with appropriate software.

Table 1. Cutting data values for particular turning trials.

No	v_c [m/min]	f [mm/rev]	r_ε [mm]
1	20		0.2
2	10	0.211	0.4
3	15		0.8

Characteristics of the cutting force components (F_f, F_p, F_c) for particular WC-Co turning processes are presented in Fig. 2-4. Separated characteristics (Fig. 2-4) illustrate the ranges of recorded cutting force values (min, mean, max) for corresponding time periods.

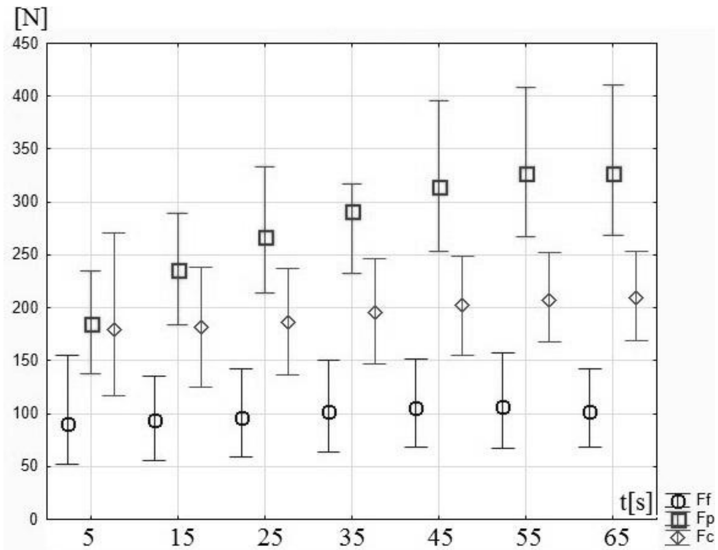

Fig. 2. Recorded values of cutting force components (F_f, F_p, F_c) during WC-Co turning by insert with nose radius = 0.2 mm for corresponding time periods.

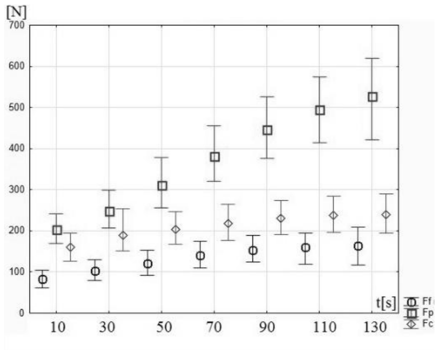

Fig. 3. Recorded values of cutting force components (F_f, F_p, F_c) during WC-Co turning by insert with nose radius = 0.4 mm for corresponding time periods.

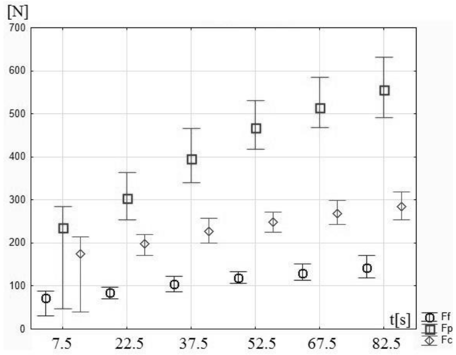

Fig. 4. Recorded values of cutting force components (F_f, F_p, F_c) during WC-Co turning by insert with nose radius = 0.8 mm for corresponding time periods.

Based on the recorded values of the cutting force components (F_f, F_p, F_c) it was noticed, the largest growth is for the passive force component F_p. In this situation there is a clear different distribution tendency of the cutting force components than for the classical difficult-to-cut material turning (for instance, titanium alloy turning), where the largest values of the cutting forces have been measured for the feed force F_f [3-9]. The largest values of the passive force F_p is probably caused by the large hardness of the work piece material (85.4 HRA) or by a special material structure (shaft made of WC and Co grains). Example of the work piece material structure is presented in Fig. 5.

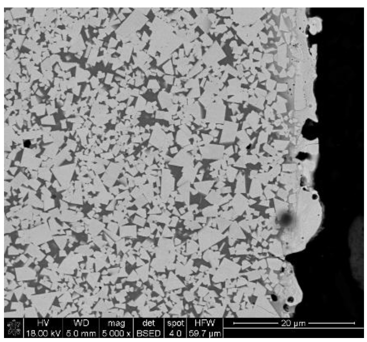

Fig. 5. SEM picture of the work piece's material structure, WC-Co with 25% Co.

The percentage growth of the separate cutting force components for the three WC-Co turning tests by PCD tools are presented in Table 2. The lowest influence r_ε on the growth values of the total cutting force F is for the insert with $r_\varepsilon = 0.2$ mm. Similarity growth of the cutting forces gained for the inserts with the nose radii = 0.4 and 0.8 mm, Fig. 3 and 4, respectively. The equations, which present variability of the cutting force component dependent on the machining time for particular WC-Co turning tests are shown in Table 3.

Table 2. The percentage growth of the cutting force components for three WC-Co turning tests by PCD tools.

No	$\%F_f$	$\%F_p$	$\%F_c$
1	12.95	77.52	16.56
2	97.75	158.73	49.55
3	99.85	136.4	63.19

Table 3. The equations of the growth of the cutting force components for WC-Co turning with PCD tools.

No	Force	Equations describe values for particular components of the cutting forces
I	F_f	$Ff(t) = -0.0003t^3 + 0.0249t^2 - 0.1814t + 90.577$
	F_p	$Fp(t) = -3E\text{-}05t^4 + 0.0042t^3 - 0.2401t^2 + 8.6685t + 146.82$
	F_c	$Fc(t) = -0.0003t^3 + 0.036t^2 - 0.4606t + 181.21$
II	F_f	$Ff(t) = -0.0046t^2 + 1.3348t + 67.994$
	F_p	$Fp(t) = -0.0002t^3 + 0.0382t^2 + 1.0399t + 189.18$
	F_c	$Fc(t) = -0.0052t^2 + 1.3644t + 149.51$
III	F_f	$Ff(t) = -5E\text{-}05t^3 + 0.0045t^2 + 0.9515t + 63.267$
	F_p	$Fp(t) = 3E\text{-}05t^4 - 0.0052t^3 + 0.3181t^2 - 1.5872t + 231.63$
	F_c	$Fc(t) = -0.0063t^2 + 2.0542t + 157.68$

3. Mathematical models describing the growth of the cutting forces during WC-Co turning process

Based on the literature, the phenomenon research can be described according to the following equation [24-27]:

$$Y = a_1 x_1^{a_2} \cdot x_2^{a_2} \cdot \ldots \cdot x_i^{a_i} \tag{1}$$

Where: Y – the value of the examined phenomenon dependent on the x_i factors (e.g. a component of the cutting force), a_i – constant coefficients, x_i – the studied factors which influence on the examined phenomenon (i.e. v_c, f).

Results of the previous investigations of the WC-Co turning process with different content of cobalt (10, 15, 25% Co) were used [28] in the construction of the mathematical models, describing the components of the total cutting forces (F_f, F_p, F_c). The influence factors on the values of the cutting forces were: v_c, f, r_ε, Table 4.

Basing on the equation (1) and Table 4, it is possible to designate the constant coefficients a_i. The mathematical models of WC-Co turning for the cutting force components (F_f, F_p, F_c) are presented in equations (2-4).

$$F_f = -0.501 v_c^{0.552} f^{-0.664} r_\varepsilon^{538.371} \tag{2}$$

$$F_p = -1.702 v_c^{1.574} f^{-2.067} r_\varepsilon^{558.355} \tag{3}$$

$$F_c = 0.833 v_c^{-0.597} f^{0.752} r_\varepsilon^{21.02} \tag{4}$$

The equations (5-7) describing the course of the total cutting force components depend on the machining time t [s] based on the data from the Table 5.

$$F_f(t) = 5e\text{-}06t^4 - 0.001t^3 + 0.0622t^2 - 0.3964t + 79.246 \tag{5}$$

$$F_p(t) = e\text{-}05t^4 - 0.0025t^3 + 0.1721t^2 - 0.1583t + 219.78 \tag{6}$$

$$F_c(t) = -0.0087t^2 + 1.8848t + 141.35 \tag{7}$$

Table 4. The values of the total cutting force components and the influence factors on the examined phenomenon used to build mathematical models of WC-Co turning process with PCD tools.

Force	[N]	v_c [m/min]	f [mm/rev]	r_ε [mm]
F_f	66.1	20	0.211	0.2
F_f	113.53	15	0.105	0.2
F_f	153.54	10	0.211	0.4
F_f	166.9	20	0.153	0.8
F_p	1.28	20	0.211	0.2
F_p	7.61	15	0.105	0.2
F_p	15.97	10	0.211	0.4
F_p	19.6	20	0.153	0.8
F_c	63.47	15	0.105	0.2
F_c	56.17	10	0.211	0.4
F_c	20.76	10	0.105	0.8
F_c	47.83	20	0.153	0.8

Table 5. Average values of the total cutting forces components (F_f, F_p, F_c) obtained during WC-Co turning tests with PCD tools.

No	F_f [N]	F_p [N]	F_c [N]
1	79.51	227.32	154.81
2	91.03	277.46	179.47
3	110.83	347.04	200.51
4	122.91	408.94	215.65
5	135.95	457.9	229.10
6	146.36	493.90	237.99

The expected values of the cutting forces increment during WC-Co turning process (25% Co content) with PCD tools (inserts with different nose radii r_ε), can be determined based on the difference between the cutting force after a given time and the initial value when turning by a new insert : $dF_i(t, v_c, f, r_\varepsilon)=F(t)_i-F_0(v_c, f, r_\varepsilon)$.

The expected values of the increment cutting force components are illustrated in the equations (8-10). These inverse equations will be used in the optimization process of WC-Co turning (according to the maximal metal removal rate Q_v) and to predict the time for replacement of an insert.

$$- dF_f(t)= 5E\text{-}06t^4 - 0.001t^3 + 0.0622t^2 - 0.3964t + 79.246 - (-0.501 v_c^{0.552} f^{-0.664} r_\varepsilon^{538.371}) \quad (8)$$

$$- dF_p(t)= 1E\text{-}05t^4 - 0.0025t^3 + 0.1721t^2 - 0.1583t + 219.78 - (-1.702 v_c^{1.574} f^{-2.067} r_\varepsilon^{558.355}) \quad (9)$$

$$- dF_c(t)= -0.0087t^2 + 1.8848t + 141.35 - (0.833 v_c^{-0.597} f^{0.752} r_\varepsilon^{21.02}) \quad (10)$$

4. Optimization algorithm of a difficult-to-cut materials turning

Figure 6 shows the principle of the algorithm which allows optimizing the difficult-to-cut materials turning (for instance, sintered carbides with different content of cobalt or materials based on titanium alloys). Using this algorithm, it is possible to obtain the element with appropriate dimension-shape accuracy with the maximal metal removal rate Q_v.

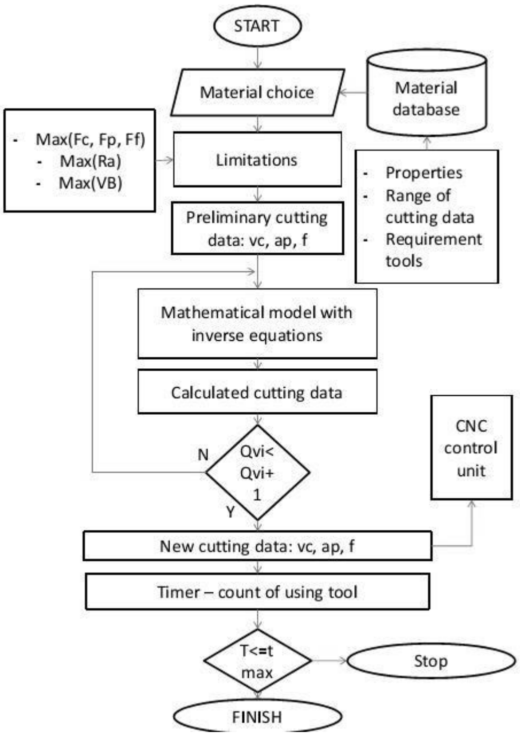

Fig. 6. Algorithm to optimize of turning process of difficult to cut materials.

Based on the type of the work piece material and data base, the system generates acceptable cutting parameters (v_c, f, a_p) and size of a nose radius.

Using the mathematical model, describing the WC-Co turning process (with 25% Co content) and the inverse equations, describing the course of the forming cutting forces, the cutting data can be determined for which there is a possibility of WC-Co turning with the maximal metal removal rate Q_v at the assumed limitations (e.g. maximal surface roughness parameter). At the same time, the system counts the time of using particular cutting tools. When the tools durability (tool wear) is exceeded, the system stops the turning process and allows to change the worn tool. New cutting data are sent to a CNC control unit.

Conclusion

The research of WC-Co turning process (with 25% Co content) with polycrystalline diamond tools are presented in the work. During investigation the insert with different nose radius r_ε were used. Particular turning tests were made at the constant depth of cut a_p = 0.2 mm. The largest growth of the cutting force is noticeable for the passive component F_p. There is a different distribution characteristic of the cutting force components than for the classical hard turning. The percentage increment of the particular cutting force components and the equations describing the increment of the cutting forces (dependent on the machining time) are also determined. The largest growth of the recorded cutting force was revealed for turning by insert with 0.4 mm nose radius. The increment of the cutting force for 54 mm turning length is almost 160%.

Obtained values of the cutting forces were used to determine the equations, describing the growth of the particular components of the total cutting forces, dependent on the machining time and tool wear. Determined equations can be used to optimize the WC-Co turning process (with 25% Co content) with PCD tools with the maximal metal removal rate Q_v at the assumed limitations (e.g. maximal cutting forces).

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