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Wear and Tool Life of CBN Cutting Tools

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The wide application of precise high-quality components made of advanced structural materials is directly related to the accelerating use of superhard materials and tools made of them. When machining with these tools, the optimal choice of cutting process parameters is important, as the requirements concerning the parts can often only be satisfied by cutting under extreme conditions (small chip cross-section, high cutting speed, special materials, new wear forms, etc.). Polycrystalline CBN tools are widely used for the fine turning of parts made of construction, stainless, heat-resistant, acid-resistant or even hardened (60–70 HRC) HS steels. The experimental $T = T(v_c)$ *tool life curves are of "dromedary" type. The tool life maximum point moves up and down according to changes of depth of cut and feed-rate values. The reasons for polyextreme tool life curves and moving maximum tool-life points are discussed in the paper. A new general tool life Eq. is outlined which reflects the physical principles of cutting phenomena more completely and exactly. The suggested form describes the polyextreme structure of the tool life function, while the position of the extreme values (along the T- and* v_c*-axis) depend on the cutting parameters.*

Keywords: CBN; Cutting tools; Tool life

1. Introduction

Superhard tools with definite edges have been widely used in finishing, especially in precision and ultraprecision cutting. A composite 01 tool, which is one of the types of CBN tools used, has good cutting properties for machining hardened steels and cast irons of high hardness.

Wear and tool life of CBN tools in precision and ultraprecision machining are even more important than in average quality range machining because:

Parts and surfaces of high accuracy and quality are produced.

New, expensive structural materials are machined.

Favourable chip removal features occur only in a narrow range of conditions and specifications.

Materials for tools are expensive.

Exact data for the new, advanced tools' edge-performance and their life is an essential condition for their application. Comparative examinations of hard metals and the new advanced tools show that the latter are only more efficient than conventional tools under certain conditions. That is why the optimal conditions of application must be found, because any deviation from them leads to a loss of all the advantages of these tools. In this paper, it is shown that a new tool life equation can describe the real cutting process over the whole range of cutting speed and cutting length and also the maximum value of the cutting length during the tool life.

For the determination of technological data, regularities of chip removal have been investigated; relationships between characteristics of the cutting process and technological data have been summarised on the basis of experiments; a mathematical model of the cutting processes has been determined, and optimum values of cutting data have been calculated by means of a computer program.

2. Experiments with CBN Cutting Tools

The aim of the experiments was to investigate the regularities of chip removal, to examine the relationships between characteristics of the cutting process and cutting conditions and to determine new descriptive equation and a mathematical model of the cutting processes.

Most of our experiments were carried out when boring, as the chip removal during boring is characterised by more intensive processes, and the technical literature has already given several results for turning.

2.1 Experimental Conditions

The experimental conditions were as follows:

CBN cutting tools: composite 01 (K01) and composite 10 (K10).

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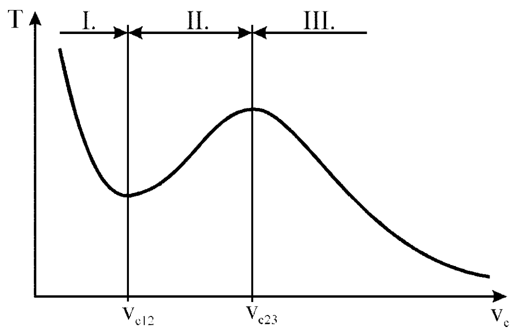

Fig. 1. Typical tool life curves.

Tool geometry: $\gamma = -5°$; $\alpha = \alpha' = 15°$; $\lambda = 0°$; $\kappa r = 45°$; $\kappa r' = 2°$; $\kappa r' = 15°$; $b\epsilon = 0.3$ mm.

Workpiece: hardened ball-bearing steel: 100Cr6 (HRC 62 ± 2) Diameter: $d = 45$ mm.

Machine tool: E400–1000 universal lathe.

The examined range of technological data: cutting speed: $v_c = 10-400$ m min^{-1}; depth of cut $a_p = 0.05-0.4$ mm; feedrate $f = 0.025-0.4$ mm rev^{-1}.

2.2 The Results of the Experiments

General Characteristics

Superhard materials are the advanced tool materials for precision and ultraprecision finishing. There are two basic groups of superhard materials – diamond and solid boron nitride, the latter is applied for cutting hardened steels and cast irons of high hardness.

The physical-mechanical properties (high hardness, good heat conductivity, considerable wear and heat resistance) and the polycrystalline nature of superhard materials produce well-defined characteristics in the process of chip removal.

The friction coefficient of superhard tools is low compared to other tool materials. The friction coefficient of boron nitride is lower without lubricant and is higher when using lubricant, when compared to that of diamond. The value of the friction coefficient of a tool composite 01 is larger than that of composite 10.

When cutting, the inner friction is determinant, that is why the chip formation differs only in its parameters not in its character, and small chip deformation is typical. This is due to the low friction coefficient and high heat generation between the tool and the material to be cut.

Plastic deformation and heat stress is higher when boring hardened steels, than in the case of turning.

The cutting tool wears slightly at the low temperature of the chip root, and the intensity of wear does not increase significantly up to a defined, relatively high temperature. After reaching this temperature (1300–1400 K), a decrease of the hardness of the tool and a phase-structure modification at the tool surface occurs. It also decreases the wear resistance effect of the accumulated layer.

2.3 CBN Tool Wear and Tool Life

The polycrystalline tool edge regenerates constantly during cutting. Because of the pressure on the tool edge and the temperature, microcracks and microfractures develop, and fine sharp crystals emerging from the deeper layers of the flank of the tool ensure its continued sharpness and cutting ability. The wear resistance of the tool is high, because the microcracks are shallow, as the grain boundaries localise them.

CBN tool wear is also defined by its polycrystal line character. Wear occurs mostly on the flank and it defines the tool life decisively. That is why flank wear is chosen to characterise wear, and 0.4 mm flank wear is chosen as a criterion. Up to that value of wear, CBN tools maintain their good cutting ability, the increase of cutting force is insignificant, and the roughness of the machined surface does not increase perceptibly.

The complete CBN tool wear mechanism was established on the basis of earlier tests [1].

Experiments show that the protection layer developing on the tool face has a significant influence on the cutting capability of a composite (CBN) tool. This determines the cutting process. In the first speed range ($v_c < v_{c12}$) the build-up just starts, but does not form a stable protection layer.

In the second range ($v_{c12} < v_c < v_{c23}$) the build-up becomes stable; however, in the third stage ($v_c > v_{c23}$), the layer is completely absent.

The experimental results show that tool life changes depending on the cutting speed, according to the typical curve in Fig. 1.

If the experiments are carried out with different cutting feeds and depths of cut, the tool life changes, but the form of the T–v_c curve remains.The results of the measurements are summarised in Tables 1 and 2.

3. Mathematical Description of Tool Life

The first tool life equation was published by F. W. Taylor in 1901 and it is still being used today [2]. It gives relatively reliable results only in a narrow cutting speed range. It is usual to call this relationship the simple Taylor equation, distinguishing it from its later generalised variation, which reflects the effect of feed and depth of cut on tool life. The simple Taylor equation and also the generalised Taylor equation give a relatively good approach only on the decreasing portion of the real tool life curve and it can be characterised by a large number of straight lines.

The well-known Konig–Depirieux tool life equation offers a good approximation of the experimental tool life curve over a wide range of v_c, and also in the decreasing portion of the T–v_c curve.

3.1 Tool Life Equations

In the case of a given tool life criterion, tool lives at different cutting speeds can be predicted using a T–v_c tool life curve ("Taylor-curve").

Table 1. Tool life, T (VB = 0.4 mm).

f (mm rev^{-1})	a_p (mm)	T (min)								
		v_c (m min^{-1})								
		11	20	29	50	60	68	92	105	120
0.025	0.1	357	241	230	276	256	220	81	50	28
0.075	0.1	249	198	209	157	101	66	18	10	6
0.125	0.1	203	183	184	103	51	30	8	5	3
0.05	0.05	328	238	246	258	190	142	43	25	15
0.05	0.15	258	194	203	216	136	93	25	14	8
0.05	0.25	229	179	184	183	108	70	18	10	6

Table 2. Length of cutting, L (VB = 0.4 mm).

f (mm rev^{-1})	a_p (mm)	L (m)								
		v_c (m min^{-1})								
		11	20	29	50	60	68	92	105	120
0.025	0.1	3922	4819	6678	13793	15385	14991	7407	5214	2924
0.075	0.1	2740	3968	6061	7843	6061	4494	1656	1096	643
0.125	0.1	2233	3670	5333	5128	3030	2020	756	510	302
0.05	0.05	3604	4762	7143	12903	11429	9655	3960	2664	1747
0.05	0.15	2837	3883	5884	10811	8163	6349	2328	1515	998
0.05	0.25	2516	3571	5333	9146	6452	4762	1690	1100	728

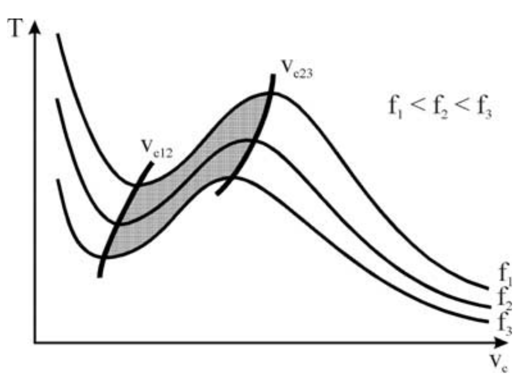

Fig. 2. Typical tool life curves at the changes of technological data.

The maximum allowable tool wear, which is the tool life criterion restrains the tool's adaptability in given circumstances.

The wear, which defines the tool life, develops through complex mechanical, chemical, thermal and electrical processes. With the change of cutting conditions, the tool's mechanical and thermal load changes, and the ratio of the wear components modifies so it is difficult to handle mathematically.

In recent years, suggestions have been made that the function should be simplified by the means of approximate curves [3]. For evaluation of the experiments we applied the new general tool life Eq. [4].

3.2 The New General Tool Life Equation

The suggested new general tool life equation for superhard tools reflects the physical principles of cutting phenomena more completely and exactly.

The relationship suitable to describe the complete tool life curve can be written in the following form using the symbols applied in cutting [4]:

$$T = \frac{C_{T_1}}{v_c^3 + C_{T_2} v_c^2 + C_{T_3} v_c} \tag{1}$$

(C_{T_1}, C_{T_2}, C_{T_3} depend on the circumstances of cutting).

Length of cutting:

$$L = T v_c$$

$$L = \frac{C_{T_1}}{v_c^2 + C_{T_2} v_c + C_{T_3}} \tag{2}$$

(See end of paper for definition of symbols.)

The suggested form describes the polyextreme structure of the tool life function, whereas the positions of the extreme values (along the T- and v_c-axis) depend on the cutting parameters.

Through changing the $T = f(v_c)$ function into an $L = f(v_c)$ function, we obtain a function for the length of cutting which relates to the tool life and which has a maximum, and which truly reflects the results obtained during the experiments.

The $T = f(v_c)$ relationship can be divided into three characteristic ranges. In the first one, i.e. increasing the cutting speed to v_{c12}, the tool life decreases to a minimum, then with further increase in speed (the second range) the tool life increases, and it reaches its maximum at the optimal speed, after that, it decreases again. This characteristic of the relationship persists at different feeds, depths of cut and bore diameters, but the values of the local minimum or maximum change depending on the technological machining data.

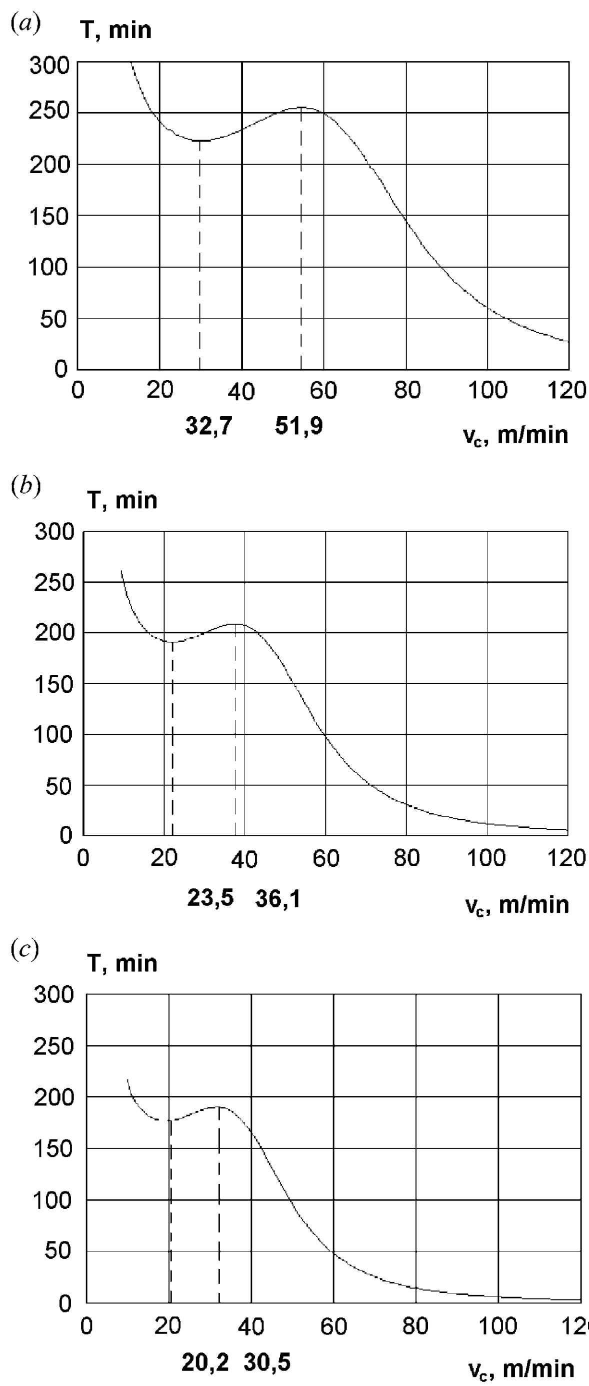

Fig. 3. Tool life and length of cutting of CBN tools. (*a*) f = 0.025 mm rev^{-1}; (*b*) f = 0.075 mm rev^{-1}; (*c*) f = 0.125 mm rev^{-1}. (Composite 01; a_p = 0.1; diameter 45 mm.)

The new equation has two local extreme values, that is, it reflects the real tool life curve as well.

The first speed range (whose limit is v_{c12}) does not cover the practically applied speeds (because of the small value of v_c, the instability of the process, etc.). In the second range ($v_{c12} < v_c < v_{c23}$) it is also unreasonable to cut, since with the increase of the speed the tool life increases, so it is worth increasing the speed to at least v_{c23}. As a consequence, the value of the suitably chosen cutting speed is $v_c > v_{c23}$. In practice, cutting tools are applied in the third range, thus v_{23} appears as the lower limit of the model.

Considering the Joint Effect of Technological Data

The equation may be rearranged and generalised. On the basis of experiments, v_{c12} and v_{c23} can be defined, and on the basis of these C_{T_2} and C_{T_3} values of tool life, an equation can also be defined. The value of the C_{T_1} constant in the function can also be defined if we know, for example, the v_{c23} function value (T_{23}), which relates to the local maximum.

According to the foregoing, the C_{T_1}, C_{T_2}, and C_{T_3} values are

$$C_{T_1} = T_{23}(v_{c23}^3 + C_{T_2} \cdot v_{c23}^2 + C_{T_3} \cdot v_{c23})$$

$$C_{T_2} = -\frac{3}{2}(v_{c12} + v_{c23})$$

$$C_{T_3} = 3v_{c12}v_{c23} \quad (3)$$

We can see, that C_{T_1}, C_{T_2} and C_{T_3} are functions of the cutting conditions. The cutting speed related to the maximum cutting length

$$v_{c_{L_{max}}} = -\frac{C_{T_2}}{2} \; L_{max} = \frac{C_{T_1}}{C_{T_3} - 0.25C_{T_2}^2} \quad (4)$$

For different cutting feeds and depths of cut, we define values v_{c12} and v_{c23} with a function which takes into consider-

Table 3. Values of constants.

f (mm rev^{-1})	A_p (mm)	Composite 01		
		C_{T_1}	C_{T_2}	C_{T_3}
0.025	0.1	15.87 × 10^6	−126,9	5091
0.075	0.1	4.71 × 10^6	−89.4	2545
0.125	0.1	2.63 × 10^6	−76.5	1848

Table 4. The values of the constants and exponents.

	Composite 01			
	C	x	y	q
V_{c12}	3.50	−0.30	−0.11	0.23
V_{c23}	3.50	−0.32	−0.08	0.34
T_{23}	52.65	−0.66	−0.18	0.16

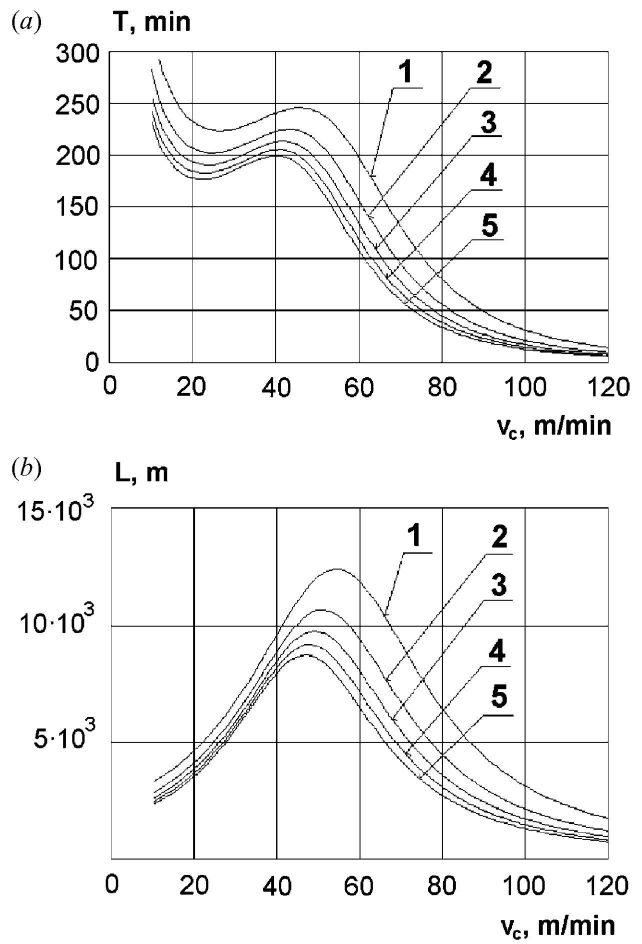

Fig. 4. Tool life and length of cutting of CBN tools. 1. a_p = 0.05; 2. a_p = 0.1; 3. a_p = 0.15; 4. a_p = 0.2; 5. a_p = 0.25 (mm). (Composite 01, f = 0.05 mm rev^{-1}; diameter 45 mm.)

ation the joint influence of technological data elements (Fig. 2). These can be determined (for example when boring with CBN tools) as follows:

$$v_{c12} = C_{v_{c12}} f^{x_{v_{c12}}} a_p^{y_{v_{c12}}} d_w^{q_{y_{c12}}}$$

$$v_{c23} = C_{v_{c23}} f^{x_{v_{c23}}} a_p^{y_{v_{c23}}} d_w^{q_{y_{c23}}} \quad (5)$$

$$T_{23} = C_{T_{23}} f^{x_{T_{23}}} a_p^{y_{T_{23}}} d_w^{q_{T_{23}}}$$

If we compare the new tool life equation with the other ones, the suggested relation describes the real relationships better. This is because on the one hand it is valid for a wide range of cutting speeds v_c and on the other, because the "constants" of the tool life equation are actually defined as functions of other technological data, so the calculations can also be carried out reliably in the case of other technological data. Using computers, the problems of complexity of equation can be solved very easily.

3.3 Tool Life Relation of CBN Tools

Figure 3 shows experimental results processed using the suggested tool life equation, with different values of cutting feed. Table 3 contains C_{T_1}, C_{T_2}, C_{T_3} values referring to them.

Experiments were carried out to examine the joint effects of technological data elements. On the basis of the experimental results we have defined the value of the tool life equation coefficients and exponents (Table 4). The tool life values can be defined with their help, relating to the given technological data. We present the results obtained from the calculation in Fig. 4.

4. Conclusions

With the appearance of superhard tools, the possibility of precision machining applications has significantly widened. The experiments carried out and results reported in this paper should help us to promote the economical application of CBN tools.

Application of a new tool life equation is suggested and its advantages have been shown, i.e. it is valid for the whole range of the cutting speed, it considers the joint influence of technological data elements, and it can be applied in practice. There remains the further task to produce a satisfactorily wide database, using data in the literature and tool life experiments.

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Notation

a_p	depth of cut
C_T	tool life
d	workpiece diameter
f	feedrate
L	length of cut
T	temperature
v_c	cutting speed
γ	tool angle
α	tool angle
λ	tool angle