EXPERIMENTAL INVESTIGATION INTO TOOL WEAR OF CEMENTED CARBIDE CUTTING INSERTS WHEN MACHINING WEAR RESISTANT STEEL HARDOX 500

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Abstract:

This paper deals with testing and investigation of changeable coated carbide cutting inserts with the hard rough face milling process. All realized cutting tests have been performed on CNC vertical milling machine tool at Department of Engineering in Trencin within the scope of the European Union Foundation ITMS project code 26110230099. The main aim of this paper is to focus experimental investigation on the impact of the various applied values of cutting speeds while hard machining the material Hardox 500. Testing cutting tool materials used in this research are coated cemented carbide changeable inserts produced by DORMERPRAMET Company. Tested machined material was hard abrasion resistant steel Hardox 500. The cutting speeds (55.7 m.min^{-1}, 78.5 m.min^{-1} and 111 m.min^{-1}) are investigated with variable parameters, whereas the cutting depth and feed rate are constant parameters. The pictures of new and worn changeable cutting inserts geometry and the graph of dependence on variable cutting speed are shown as a result of this realized investigation.

1 Introduction

Machining technology of hard materials has been a great challenge for several years. Hard machining can also be an alternative to grinding technology or electro discharge machining with a scope to improve machining times, productivity increasing, capital expenses decreasing, and reduced environmental waste [1, 2]. Grinding technological processes belong to traditionally final finishing operations of hard materials. In recent decades, the hard machining operations have been considered an alternative to traditional finish grinding operations. By hard machining, the same surface quality as grinding technological processes can be achieved when appropriate cutting conditions are employed [3]. However, reliability of hard machining is often unpredictable [4]. The main factors which significantly affect the reliability of hard machining are surface integrity and tool wear [5]. One of the problems in hard machining is especially tool wear, which particularly affects the machinability of hard steels [6]. After application of heat treatment, the final shape has to be machined. Apart from grinding technological processes, the machining with geometrically defined cutting edges is established to

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machine hardened steel components as a substitution method. Compared to grinding technology, the advantages of hard machining are short machining times, high material removal rates and retrenchment of cutting fluid. However, one disadvantage of hard machining is an increase in tool wear compared to machining materials being not in a hardened state [6]. Due to the fact that these hardened parts are exposed to high loads, the surface quality and surface integrity have to present required characteristics. Thereby, the tool wear has a great influence on the surface integrity of each component [1]. One major drawback is tool wear, which is a result of high thermo-mechanical stress exerted on the cutting tool. Tool wear rate can be influenced by the cutting tool geometry and the types of coatings. A further approach is to modify the flank face of the cutting tool, which leads to geometrical limitation of the flank wear [7]. Rough face hard milling is an efficient method in machining high strength steels. This article investigated a hard milling technological process of Hardox 500 using a cutting tool with coated cemented carbide inserts with regard to the tool wear [5]. Tool life is an important parameter in evaluation of the performance of the cutting tools and inserts. Tool wear significantly affects surface quality of the workpiece and it is also one of the important criteria in specifying tool life. When the cutting tool wear reaches its allowable wear limit, the cutting edge fails to be efficient and cannot be used further. Current investigation aims to increase the tool life in hard machining. Not only the selection of the cutting tool substrate and the cutting conditions, but also the shape design of the cutting edge significantly affect the tool wear behaviour [8]. Tool wear is usually a sequential process and therefore tool wear rate depends on workpiece materials, cutting tool geometry, coolant, cutting conditions and machine-tool features. Tool wear in machining significantly influences overall tool life and it is the most important criterion in determining tool life. This paper presents experimental investigations into face rough milling process on wear resistant steel Hardox 500. Realized experiments are performed to study performance investigations into cutting conditions such as the cutting speed, feed rate and depth of cut with consideration to multiple responses such as tool wear, which evaluates the performance of carbide cutting inserts. It has been observed through the optical microscope Nikon Eclipse LV100ND (shown in Fig. 3 and 4).

2 Materials and methods

2.1 Basic information

Hardox steels are ultra-high strength martensitic steels with excellent abrasive resistance produced by Swedish company SSAB Oxelosund. The main application fields of these steels are heavy machines in mining or civil engineering industry. Hardox steels are resistant against sliding, impact and squeezing wear [9]. Steels need high hardness and strength to achieve the condition of high wear resistance. These specific properties are achieved by meeting strict requirements on chemical purity (H, N, P or S content) and specific production process, finalized by very rapid quenching and tempering. The chemical purity in combination with very rapid cooling brings good toughness of material despite tempering at very low temperatures. These specific properties and production processes require special tools for secondary processing of Hardox steels by machining. Due to very high surface hardness, and therefore to high wear of used tool, the cutting edge made by cemented carbide must be used to mill the Hardox steels. This paper deals with tool wear rate determination with respect to the Hardox 500 steel used in milling.

2.2 Chemical composition of Hardox 500

Various Hardox steels with different hardness scales are offered by the producer. Higher hardness scale also means higher wear resistance. Hardox 500 was chosen as an experimental material and its chemical composition and basic mechanical properties are shown in the Tab. 1. Chemical composition was determined using atomic emission spectroscopy by the analyser Spectrolab Jr CCD. Hardox 500 steel is bendable and weldable abrasion resistant steel which is used in applications that demand higher wear resistance. The Hardox 500 steel has tempered martensitic structure without clear grain orders of the previous austenite (see in Fig. 1). Exposing the steel to the temperature above 250°C may lead to changes in the microstructure and consequently to degradations of mechanical properties, strength and hardness mainly [10].

Table 1. Chemical composition and basic mechanical properties of Hardox 500 steel [2]

<table>
<tr><td rowspan="4">HARDOX 500</td><td rowspan="2">Chemical composition [wt. %]</td><td>C</td><td>Si</td><td>Mn</td><td>P</td><td>S</td><td>Cr</td><td>Ni</td><td>Mo</td><td>B</td></tr>
<tr><td>0,27</td><td>0,56</td><td>1,51</td><td>0,019</td><td>0,01</td><td>1,32</td><td>1,42</td><td>0,57</td><td>0,003</td></tr>
<tr><td rowspan="2">Basic Mechanical properties</td><td>Tensile strength R_m [MPa]</td><td colspan="2">Yield strength $R_{p0.2}$ [MPa]</td><td colspan="2">Impact energy KV [J]</td><td colspan="2">Hardness HBW</td><td colspan="2">Elongation A_5 [%]</td></tr>
<tr><td>1550</td><td colspan="2">1300</td><td colspan="2">30</td><td colspan="2">499</td><td colspan="2">8</td></tr>
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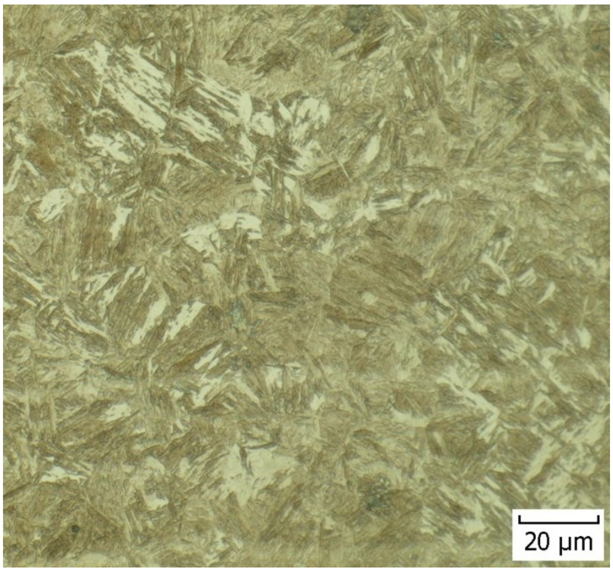

Figure 1. Microstructure of Hardox 500 in "as delivered" state.

2.3 The principle of method of least squares

Long-term cutting tool life testing in machining is defined by international standard ISO 3685-E-77-05-15. The values of tool life that are deducted from the characteristic curves of tool wear on a given criterion wear *VB* on the flank face of the cutting tool or *KT* (the depth of the groove on the rake face) and inserted into the table and then the graph. In implementing long-term tool life tests of the cutting tool depending on the cutting speed when face milling, variables are recommended to be determined three to five times, and the test is to be repeated using one variable at two to four times. Then the credibility of the results is statistically guaranteed and properly determined. The Criterion of tool wear VB_k = 0.6 mm is designated for roughing, respectively VB_k = 0.3 mm for finishing the structural steel. When machining hardened materials, it is necessary to specify the criterion VB_k for at least half of the values [2]. Taylor's equation of tool life has an explicit form [11]:

$$T = C_{Tv_c} . v_c^{-m} \tag{1}$$

Consequently, it is overwritten into the implicit form [11]:

$$v_c . T^{\frac{1}{m}} = C_{ISO} \tag{2}$$

With the help of linearization of decimal logarithms, the following form [11] is determined:

$$\log v_c - \frac{1}{m} \log T = \log C_{ISO} \tag{3}$$

When measured tool life was indicated as $y_i = \log T_i$ and variables of cutting speeds as $x_i = \log v_{ci}$, then determined linear regression of a single parameter is expressed in the form [11]:

$$\hat{y} = b_0 . x_0 + b_1 . x_1 = m.(\bar{x} - \log C_{ISO}) + m.(x_i - \bar{x}) \tag{4}$$

$$\text{while } \bar{x} = \sum_{i=1}^{N} \frac{\log v_{ci}}{N} \text{ and } \bar{y} = \sum_{i=1}^{N} \frac{\log T_i}{N} \tag{5}$$

are the mean values, where x_0 - is fictitious value, which is equal to 1 for the natural scale, but for the logarithmic scale it equals log 10 = 1, x_1 - is the independent variable, b_0 - is additive constant, which indicates an increase in the axis „ y“ = log C, b_1 - indicates tendency for the regression function $m = -b_1 = \mathrm{tg}\ \alpha$, which is angle line, and N - number of measurements (i = 1,2,3............12).

By adjusting equations with the method of least squares equation, the form for the $-b_1 = m$. It is necessary to get a function in the form: $y^T = a + b.x$

$$\sum_{i=1}^{n}(y_i^E - y_i^T)^2 = 0 \tag{6}$$

After adjusting, we obtain Equations (7), (8) for the calculation of parameters [11]:

$$b = \frac{\overline{x}.\overline{y} - \overline{x.y}}{\overline{x}^2 - \overline{x^2}} \tag{7}$$

$$a = \overline{y} - b.\overline{x} \tag{8}$$

According to Equation (7), parameter (8) is calculated, which in this case is exponent (m) from Equation [11]:

$$T = \frac{C_T}{v_c^m} = C_T.v_c^{-\frac{1}{m}} \tag{9}$$

$$m = -b = \frac{\overline{x}.\overline{y} - (\overline{x.y})/N}{\overline{x^2} - \left(\frac{\overline{x}}{N}\right)^2} \tag{10}$$

If $y_i = \log T_i$ and $x_i = \log v_{ci}$ is then:

$$m = \frac{\sum \log v_{ci}.\log T_i - \frac{\sum \log v_{ci}.\sum \log T_i}{N}}{\sum \log^2 v_{ci} - \frac{(\sum \log v_{ci})^2}{N}} \tag{11}$$

where: $\overline{x_i} = \frac{\sum \log v_{ci}}{N}$ $\quad \overline{y_i} = \frac{\sum \log T_i}{N}$

By multiplying Equation (10) [11] by $\frac{N}{N} = 1$, it gets Equation for the m:

$$m = \frac{N.\sum \log v_{ci}.\log T_i - \sum \log v_{ci}.\sum \log T_i}{N.\sum \log^2 v_{ci} - (\sum \log v_{ci})^2} \tag{12}$$

There is also the form of Equation [11]:

$$\sum \log T_i = N.\log C_T - m.\sum \log v_{ci} \tag{13}$$

3 Experimental details

3.1 Changeable cutting inserts

Cemented carbide testing cutting inserts were supplied by the DORMERPRAMET Company. Roughing type of cutting inserts, cemented carbide type 8230 P30 was tested by coating TiAlCN + TiN, used for face rough machining of the hard steels. (Surface images of cutting edge appearance before and after milling can be seen in Fig. 3, 4). As cutting tool, milling cutter type PN222460.12 dia. 50 mm was used (seen in Fig.2) with cutting edge geometry $z = 4$; $\chi_r = 75°$; $\gamma_o = -7°$; $\alpha = 7°$, $\lambda_S = -4°$; (NAREX). Cutting geometry for testing carbide cutting tool was chosen according to ISO 3685 norm – Tool Life Testing of Single Point Turning Tools [9]. All types of changeable cutting inserts, which are investigated, have a normalized shape SNHF 1204EN-SR-M1.

3.2 Cutting parameters

These cutting parameters were chosen by the manufacturer who recommended cemented carbide, but also according to the experience of the resolver. The following cutting parameters were chosen for testing these types of cutting materials (Table 2):

Table 2. Cutting parameters

Cutting parameters				
Cutting speed	v_c [m.min^{-1}]	55,7	78,5	111
Spindle speed	n [min^{-1}]	355	500	710
Feed rate per tooth	f_z [mm.tooth^{-1}]	0,056		
Depth of cut	a_p [mm]	2		

3.3 Machining times and achieved tool lives

During the hard milling process, these values of machining times and values of tool lives were achieved:

t_{As1} = 8,86 min, t_{As2} = 6,29 min, t_{As3} = 4,40 min

T_1 = 223 min; T_2 = 135 min; T_3 = 39,6 min.

Figure 2. An overall view to rough face hard milling process of Hardox 500 steel.

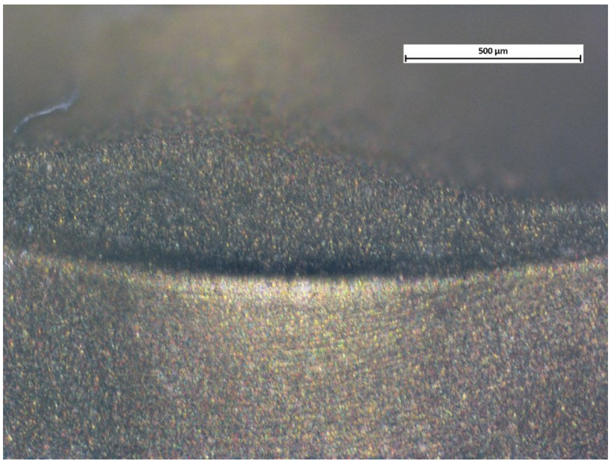

Figure 3. Surface morphology of cutting tool edge geometry before the start of milling (50x).

4 Results and discussion

To determine the dependence of $T = f(v_c)$, not only the conditions v_{cmax} = 2,5 and v_{cmin} [11] but also tool wear criterion of VB_k = 0,2 mm is to be satisfied. Each investigation is conducted twice with the same cutting parameters and after changing the position of each cutting insert in the milling cutter, which meets the general recommendations from the literature [1, 2, 3, 6, 11]. Achieved results of tool wear and achieved tool life are reported in Tab.3 and in the resulting graph (see Fig. 5), $VB = f$ (time). Hard milling experiments were carried out at these values of cutting speeds v_{c1} = 55,7 m.min^{-1}, v_{c2} = 78,5 m.min^{-1}, v_{c3} = 111 m.min^{-1}. In this present experimental investigation, a criterion of average flank wear VB_k = 0.2 mm was considered for the tool life measurement. After each tool path, tool wear tests on carbide cutting inserts were performed to measure tool wear and define wear progress.

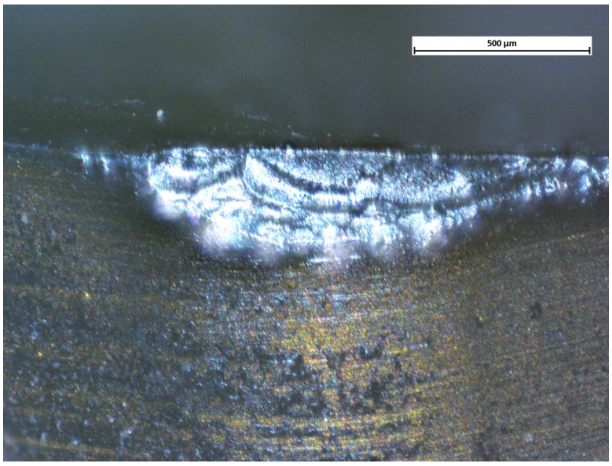

Figure 4. Surface morphology of worn cutting insert investigated with optical microscope Nikon Eclipse LV100ND (50x).

Substituting the appropriate values from Table 3 into Equation (12) [11] for the exponent (m), we get this Equation in the following form:

$$m = \frac{N.(\sum \log T_i . \log v_i) - \sum \log T_i . \sum \log v_i}{N.\sum \log^2 v_{ci} - (\sum \log v_{ci})^2} =$$

$$= \frac{3.(6{,}075.5{,}684) - 6{,}075.5{,}684}{3.10{,}814 - (5{,}684)^2} = -2{,}609 = -b_1$$

Constant C_T can be determined by substituting the calculated value for exponent $m = b$ into Equation (13) [11] so that and we get the following form:

$$\sum \log T_i = N.\log C_T - m.\sum \log v_{ci}$$

$$\log C_T = \frac{\sum \log T_i + m.\sum \log v_i}{N} =$$

$$= \frac{6{,}075 + 2{,}609.5{,}686}{3} = 6{,}97$$

then $C_T = 10^{\log C_T} = 10^{6,97} = 9{,}33.10^5$

After substituting the calculated values, we have obtained the linear regression equation (1) [11] following the form:

$\hat{y} = b_0 \,.\, x_0 + b_1 \,.\, x_1 = 6{,}97 \,.\, x_0 - 2{,}609 \,.\, x_1$

The introduction of substitution for the $b_0 = \log C_T$ and for the $\hat{y} = \log T$ is then:

$C_T = 10^{\,6,97} = 9{,}33.10^5$

Then the value is tg α = 2,609 thereof α = arctg 2,609 and consequently the size of the angle is α = 69º. The inclination angle of the line in logarithmic coordinates is $-b_1 = m =$ tg α, from which we obtain the value of the angle α. The shape of the linear regression for the tool life has the following form [11]:

$$\log T = \log C_T - m \,.\, \log v_c \qquad (14)$$

The resulting dependence of T = f(v_c), obtained from graphs and processed by the method of least squares, can be seen in Fig.6, in a logarithmic coordinate system. The final version for tool life T = f (v_c) used for machining of Hardox 500 is represented in Equation (14, by following the form [11]:

$m = 2{,}609 = \text{tg}\,\alpha \quad \alpha = \text{arctg}\, 2{,}609 = 60{,}88\,^{\circ} = 69^{\circ}$

Accordingly, the final version is:

$$T = \frac{C_T}{v_c^m} = \frac{9{,}33.10^5}{v_c^{2,609}}$$

Three points of measurement in T =f (v_c), according to the relevant equation, determine the shape of the curve as linear in the logarithmic coordinates (see in Fig 6). For the calculation, we use values directly from Table 3. Tool life testing of v_cT curve is presented in Fig. 6.

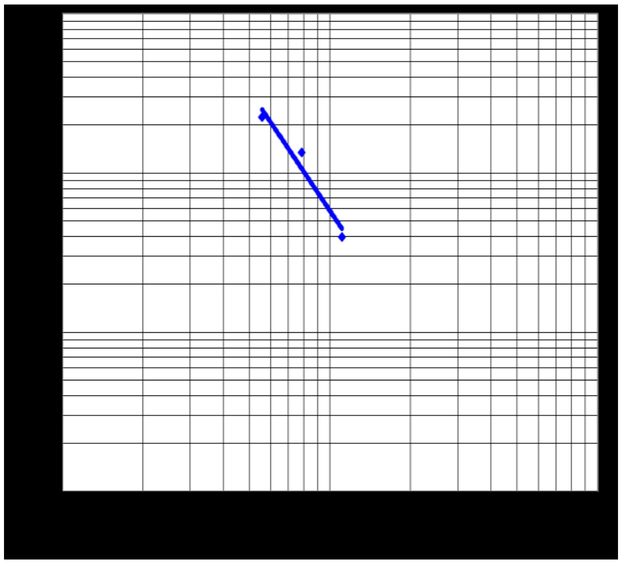

Figure 6. Tool life testing of v_cT curves.

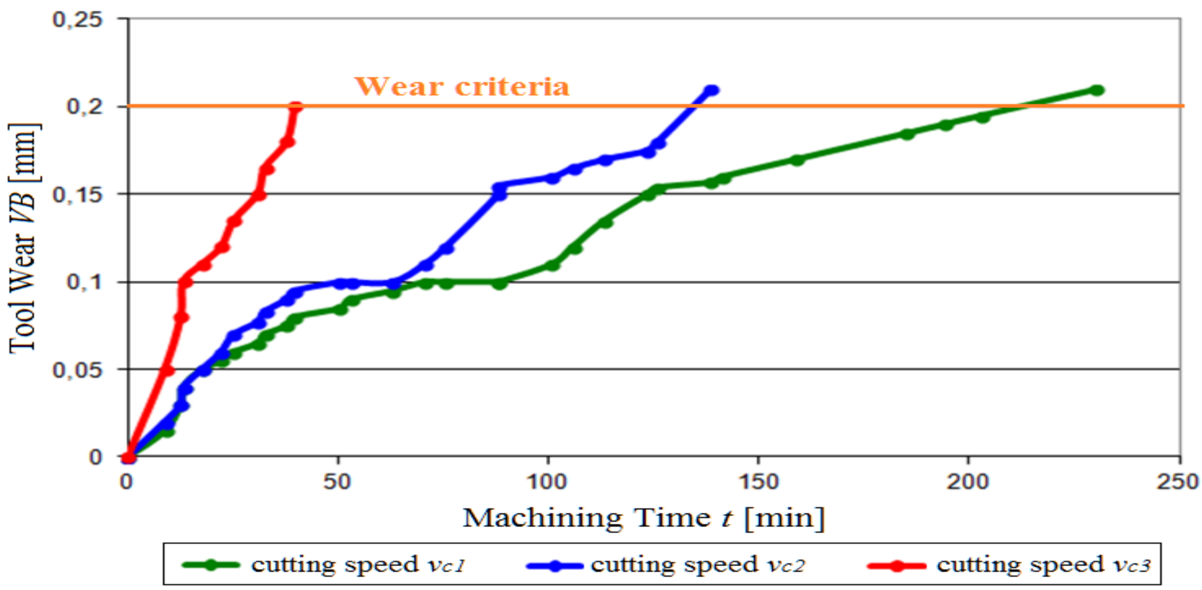

Figure 5. Graphical presentation of dependence of tool wear on machining time in rough milling of Hardox 500 steel with cemented carbide cutting tool inserts to determine the dependence of $T = f(v_c)$.

Table 3. The calculation table to determine the tool life T [min]

N	v_{ci}	T_i	$\log T_i$	$\log v_i$	$\log T_i \cdot \log v_i$	$\log^2 v_i$
1	223	55,7	2,348	1,745	4,0972	3,045
2	135	78,5	2,130	1,895	4,0363	3,591
3	39,6	111	1,597	2,044	3,2643	4,178
Σ	-	-	6,075	5,684	11,3978	10,814

5 Conclusion

Presented experimental investigation is focused on the fundamental relations between tool wear and tool life while hard machining Hardox 500 steel. The key results can be summarized as follows:

(1) The main aim of this presented study is the experimental determination of the tool life depending on the cutting speed according to Taylor while machining Hardox 500.
(2) Cutting speed (as studying cutting parameter) has the most significant influence on the flank wear (in contrast to the f_z or a_p).
(3) The acquired values and results are statistically processed by the linear regression analysis according to the method of the least squares. All measured and calculated results and values are shown in Table 3, and graphical presentation of the flank wear VB_k shows that this is a time dependent process.
(4) The study of the size and location of the flank wear in worn coated cemented carbide insert was also monitored with the optical microscope Nikon Eclipse LV100ND (shown in Figures 3 and 4).
(5) The exposed substrate material widened during hard milling, and this caused the increase in the cutting temperature. The elemental analysis of the worn area confirmed that there is high dependance of the workpiece sample on the cutting inserts face concerning the temperature growth, causing the formation of seizure areas on the rake and flank faces of carbide inserts.

In terms of defined cutting parameters, the most significant impacts have cutting speed v_c, then the feed rate f and finally the depth of cut a_p. However, some other parameters of tool life, T = f (f_z), respectively relativity of T = f (a_p), and i.e., the size of the observed flank wear have not yet been studied, which gives a new opportunity for further research in this area. Further research and experiments with respect to the dependence T = f (fz, a_p) on different cutting parameters with respect to wear behaviour and surface integrity will be conducted.

Table 4. Nomenclature

VB_k [mm]	wear criterion on flank face
KT [mm]	wear criterion on rake face
T [min]	tool life
C_{Tvc}	constant for T (v_c)
C_{ISO}	constant
m	experimentally determined exponent
χ_r [°]	Cutting edge plan angle
λ_S [°]	cutting edge inclination angle
z	number of teeth
a [°]	clearance angle
γ_o [°]	orthogonal rake angle
$\hat{y}$	linear regression of single parameter
b_0	additive constant
x_0	fictitious value
b_1	additive constant
x_1	independent variable
v_c [m.min^{-1}]	cutting speed
N	number of measurements
$\overline{x}$	mediate selection value
$\overline{y}$	mediate selection value
t_{As} [min]	machining time
f_z [mm.tooth^{-1}]	feed rate per tooth
a_p [mm]	depth of cut
C_T	constant
E	mediate value of tool life
$P30$	coated carbide type
CNC	computer numerical control

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