

The Change of Tool Life in a Wide Range of Cutting Speeds in Hard Turning

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Tool life changes according to a curve presenting two extreme values depending on the cutting speed. Besides the well-known Taylor formula, several other functions describe tool life, mainly for the 3rd speed range beginning with a tool-life maximum. In earlier studies the authors suggested a tool-life function valid for the whole speed range. Here the machinability of hardened steel is being investigated in a wide range of cutting speeds. The intention of this study is to work out a method for the physical interpretation of tool degradation defining the tool life. For this purpose the nonlinear differential equation of wear rate is applied. During the experimental work the tool life was measured when boring a 100Cr6 hardened workpiece of 75 mm diameter in the speed range $v_c=10\ldots120$ m/min with a feed rate of $f=0.075$ mm/rev, depth of cut $a_p=0.1$ mm, $\gamma_r=-5^\circ$ and the life criterion $W_{cr}=0.4$ mm. The results proved the supposition that at a speed smaller than the tool-life maximum it is abrasion and adhesion that causes the tool deterioration, while above this speed, the thermo-activated degradation process plays an increasingly large role as speed increases. Calculating from the results of the cutting examination, the activating energy of the degradation process is $Q=136\pm29$ KJ/mol, on the basis of which it is likely that the degradation of the tool material occurs through the recrystallization of the surface layer from cubic into hexagonal, causing the surface layer to wear out more rapidly.

Keywords: Hard turning, PCBN tool, Tool-life function, Wear equation

1 Introduction

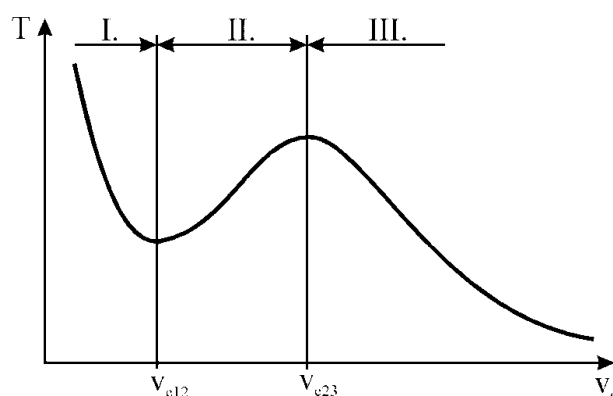


Fig. 1 The effect of cutting speed on tool-life

A variety of simple-shaped functions are applied in the technical literature for tool-life equations that aim to describe the effect of cutting speed on tool-life, approaching the real tool-life curves to lesser or greater degrees. The task is not simple, as wear behaviour of CBN tools is not the same as in conventional tools [1, 2, 3] and because as it is known the tool-life curve is rather complicated, as can be seen in Fig. 1. Several factors affect the cutting tool, influencing the material degradation with different intensity and occasionally in different directions [4, 5]. From the point of view of thermally activated processes, with decreasing speed, the decrease of the cutting temperature is beneficial. However, in connection with the so called built-up edge (BUE) formation, the adhesive/abrasive processes intensify when the cutting speed decreases below a well definable v_{c23} value. At this speed, the wear rate receives its minimum value, therefore on a v - T tool life curve as in Fig. 1 it appears as a maximum. Then, as a consequence of a further decrease of speed, the BUE

disappears, the adhesive/abrasive processes slows down and in the speed range below v_{c12} tool life begins to increase again. Thus, the general $T=f(v_c)$ tool-life equation has two extreme values by which the whole cutting speed range can be divided into three parts. Moving from the quite small speeds toward v_{c12} the tool life first decreases to a minimum, then by further increasing the speed, i.e. 2nd range, tool life increases and reaches its maximum at speed v_{c23} , after which it decreases again in the 3rd range.

From a practical aspect, the 1st speed range can be taken into account relatively rarely and only in special cases because of the unstable material removal process and also the small chip performance. The 2nd speed range is also limited to special cases since increasing the speed increases the tool life and thus the speed is worth increasing till at least v_{c23} if possible. As a consequence, it is advisable to choose the cutting speed value in the 3rd range that is $v_c > v_{c23}$. Naturally, the different technological parameters such as feed and depth of cut also influence tool life, and their change leads to different v_{c12} , v_{c23} speed limits. The economy of cutting and the choice of the mathematical model of cutting machining, as well as the definition of the optimal technological data, require the accurate specification of these limit values.

The different tool-life functions in the technical literature mainly concern the 3rd speed range. The summary given in Table 1 – naturally not intended to be exhaustive – presents these functions [6-14], organized into the same form so that they can be compared [6]. Beyond these, further authors construct similar functions (see [15]).

Although the “workpoint” of the practical technology is mainly in the 3rd stage of the v_c - T curve, there are situations where the applied technology is pushed into the 1st or 2nd stage due to different imperative circumstances. One example is when applying combined tools, and the technological circumstances may make one or another

tool life work at a lower speed. Thus, the lower ranges cannot be neglected. Therefore, in earlier studies of the authors the aim was to propose a general tool-life

equation [12, 17] which covers all three speed ranges presented in Fig. 1 and to apply it [12-14, 16]. In this paper, however, the machinability of hardened steel is being investigated in a wide range of cutting speeds.

Tab. 1 Tool life equations (where C_{T1} , C_{T2} , C_{T3} and C_{T4} are constants depending on the cutting conditions)

Taylor $T = \frac{C_{T1}}{v^{C_{T2}}}$	Szaferonov $T = \frac{C_{T1}}{C_{T2}^{C_{T3}} \cdot v}$	Temcsin $T = \frac{C_{T1}}{v^{C_{T2}} + C_{T3}}$
Wu $T = \frac{C_{T1}}{v^{C_{T2} + C_{T3}} \cdot v}$	Kronenberg $T = \frac{C_{T1}}{(v + C_{T2})^{C_{T3}}}$	Metchisen $T = \frac{v_c}{C_{T1} \cdot v^2 + C_{T2} \cdot v + C_{T3}}$
Granovszkij $T = C_{T1} \cdot v^{C_{T2}} \cdot C_{T3}^{C_{T4}} \cdot v$	König-Dépiéreaux $T = C_{T1}^{C_{T2}} \cdot v^{C_{T3}}$	Kundrák $T = \frac{C_{T1}}{v^3 + C_{T2} \cdot v^2 + C_{T3} \cdot v}$

2 Theoretical bases of general tool-life function

Examining the tool-life curves measured in cutting examinations it appears that the task is to study the simple functions that meet all of the following conditions [13, 16, 17]:

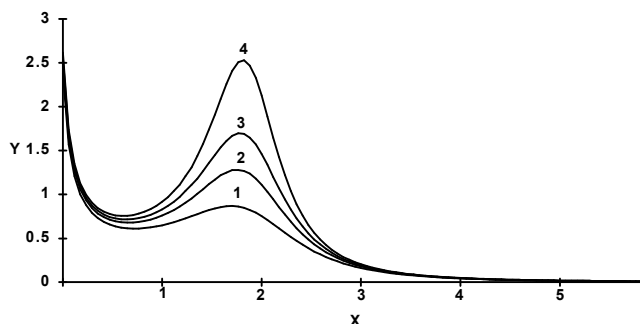
- $f(0, \infty) \rightarrow (0, \infty)$;
- $\lim_{x \rightarrow 0+} f(x) = +\infty$;
- $\lim_{x \rightarrow \infty} f(x) = 0$;
- there exists $0 < a < b$, for which $f(a) = f(b) = 0$;
- $\lim_{x \rightarrow 0+} f'(x) = -\infty$;
- $\lim_{x \rightarrow \infty} f'(x) = 0$.

Among the possible solutions meeting these conditions it is advisable to choose $f(x) = \frac{K}{P(x)}$, gr $P(x) = 1, 2$,

3 forms. If gr $P(x) = 3$, the solution for tool-life function can be found in the following form:

$$f(x) = \frac{K}{x^3 + Ax^2 + Bx + C} \quad (1)$$

Analysing the conditions, the following can be established:



- $K > 0$ on the basis of condition a),
- $C = 0$ on the basis of condition b),
- $A^2 < 4B$ on the basis of condition a),
- $A^2 > 3B$ on the basis of conditions e) and f),
- $A < 0$ and $B > 0$ on the basis of conditions e) and f)

on which Eq. (1) modifies as follows:

$$f(x) = \frac{K}{x^3 + Ax^2 + Bx} \quad (2)$$

If the behaviour of this tool-life equation is examined in respect of different values of A , B and K , the following typical examples summed up in Fig. 2 occur.

On the basis of the examples it can be stated that the chosen function is suitable for describing the real tool-life curve. The possible solution of the equation can be written down using the two local extreme values [12, 16], which can be defined on the basis of the following correlations:

$$x_1 = -\frac{1}{3} \left(A - \sqrt{A^2 - 3B} \right); x_2 = -\frac{1}{3} \left(A + \sqrt{A^2 - 3B} \right) \quad (3)$$

where x_1 is the value of the local minimum and x_2 is the value of the local maximum ($x_1 < x_2$).

After rearranging the correlations:

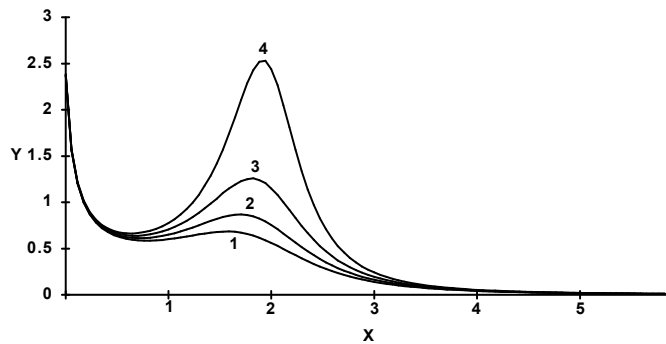
$$A = -\frac{3}{2}(x_1 + x_2); B = 3x_1x_2. \quad (4)$$

Effect of B

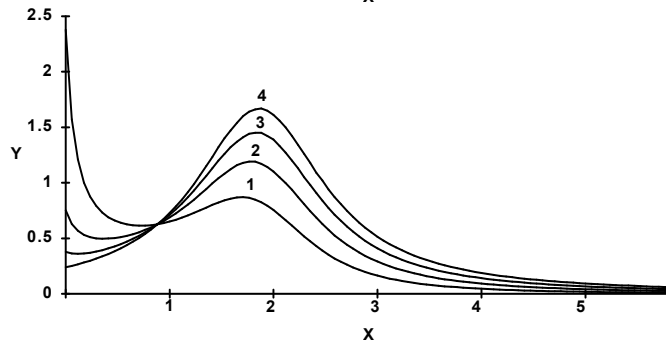
$K=1; A=-4$

(1) $B=4.6$ (2) $B=4.4$

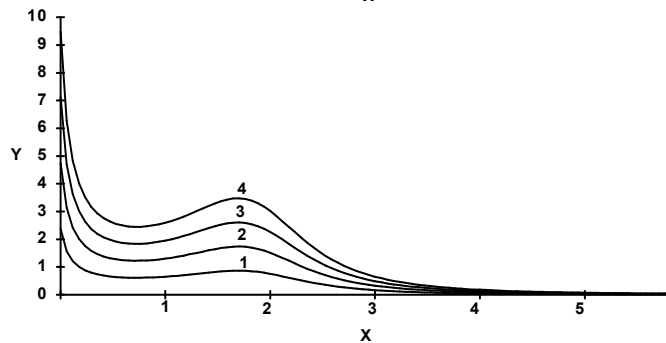
(3) $B=4.3$ (4) $B=4.2$



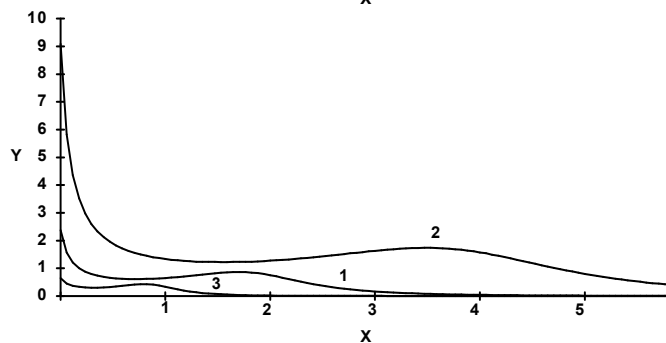
Effect of the A
 $K=1; B=4.6$
 (1) $A=-3.9$ (2) $A=-4$
 (3) $A=-4.1$ (4) $A=-4.2$



The effect of an x^a formed multiplication factor
 $(0 \leq a < 1)$.
 $K=1; A=-4; B=4.6$
 (1) $a=0$ (2) $a=0.5$
 (3) $a=0.8$ (4) $a=1.0$



Effect of the K
 $A=-4; B=4.6$
 (1) $K=1$ (2) $K=2$
 (3) $K=3$ (4) $K=4$



Effect of the A, B, K
 (1) $K=1; A=-4; B=4.6$
 (2) $K=16; A=-8; B=18.4$
 (3) $K=0.062; A=-2; B=1.15$

Fig. 2 Typical effects of the constants of Eq. (2)

On the basis of the cutting experimental results x_1 and x_2 can be defined, by means of which values A and B of the tool-life equation can be defined. K can be defined using the function value belonging to the local maximum x_2 . Thus, on this basis Kunderák [12, 17] suggested the following correlation, which is valid over the whole speed range and is suitable to describe the changes in tool-life expressed with the notation applied in cutting theory:

$$T = \frac{C_{T1}}{v_c^3 + C_{T2}v_c^2 + C_{T3}v_c}, \quad (5)$$

$$v_{c12} = -\frac{1}{3} \left(C_{T2} - \sqrt{C_{T2}^2 - 3C_{T3}} \right); v_{c23} = -\frac{1}{3} \left(C_{T2} + \sqrt{C_{T2}^2 - 3C_{T3}} \right). \quad (7)$$

where: T – tool-life of the cutting tool, v_c – cutting speed, and C_{T1} , C_{T2} , C_{T3} are constants that depend on other conditions of cutting.

Values A and B (that is C_{T2} and C_{T3}), as follows from (4), are:

$$A = C_{T2} = -\frac{3}{2} \cdot (v_{c12} + v_{c23}); B = C_{T3} = 3 \cdot v_{c12} \cdot v_{c23}. \quad (6)$$

On the basis of the defined tool-life equation, the extreme values can be determined by the following correlations, after rearranging Eq. (1):

The suggested Eq. (5) describes the polixtremal structure of the tool-life function well, while the place of the extreme values depends on the cutting parameters, namely feed, depth of cut and the machined diameter, the amount of wear, etc. The function $T=f(v_c)$ is the length that can be cut all along till the deterioration of the edge and it can be altered into function $L=T \cdot v_c=f(v_c)$ in which the cut length has one function with a maximum. This accurately reflects the results gained in experiments.

On the basis of extreme value calculation the cutting speed of the maximal length of cut can be defined, as can the maximal length of cut, in the following way:

$$v_{cL_{\max}} = -\frac{C_{T2}}{2}; L_{\max} = \frac{C_{T1}}{0.75C_{T2}^2 + C_{T3}}. \quad (8)$$

In this way a single, common tool-life equation is defined that can be considered for the whole cutting speed range in industrial application, and whose parameters depend on the conjugation of the tool edge material/workpiece material as well as the combination of feed/depth of cut. The physical interpretation of this general tool-life equation is the aim of this paper.

3 The physical interpretation of the general tool-life equation

Tool wear, and thus flank wear – often considered standard among the different forms of wear – is the result primarily of two different types of surface degradation, adhesion and abrasion [18], as well as different, thermally activated processes, which can be characterised by the so-called activation energy Q .

These degradation processes can be described with a single, nonlinear, autonomous, differential equation which is [19]:

$$\frac{dW}{dt} = \frac{v_c}{W} \left[A_a + A_{th} \exp - \frac{Q}{R\theta_f} \right] \quad (9)$$

referring to the flank wear rate of the tool.

Here W indicates flank wear (see Fig. 3), A_a is the constant characterising adhesion, abrasion wear, $R=8.29$ kJ/Kmol is the general gas constant, θ_f is the temperature of the tool flank surface and A_{th} is the coefficient of the thermally activated wear process. It is known that with increasing flank wear, the temperature increases, too, which in turn accelerates wear [20], that is

$$\theta_f \cong \theta_0 + C_w W \quad (10)$$

where θ_0 is the temperature developing on the flank surface of the undamaged tool and C_w is a constant. The value of θ_0 depends on the concrete technological conditions, the workpiece and the tool material, etc. Here a known formula is applied:

$$\theta_f = C_v v_c^x \quad (11)$$

with which Eq. (10) can be rewritten to:

$$\theta_f \cong C_v v_c^x + C_w W = C_v (v_c^x + KW) \quad (12)$$

and $K=C_w/C_v$. Eventually the differential Eq. (9) can be given the form:

$$\frac{dW}{dt} = \frac{v_c}{W} \left[A_a + A_{th} \exp - \frac{B}{v_c^x + KW} \right], \quad (13)$$

$$B = \frac{Q}{RC_v}, \quad (14)$$

where W is in μm , t in min, v_c in m/min, and A_a, A_{th} in μm . Though this equation cannot be solved in a closed form, it can be easily handled by numerical methods. Among other things, it can be used to define the physical content of the general tool-life Eq. (5).

As has already been mentioned, the cutting speed $v_c < v_{c23}$ does not fall into the intensive range of machining where the thermally activated wear process would be significant. Thus it is supposed that in such a case as in Eq. (13) the exponential part can be neglected, that is:

$$\frac{dW}{dt} \cong \frac{v_c A_a}{W}, \quad (15)$$

and this can be solved in a closed form, too. As an initial condition, if $t=0$ then W_0 can be the radius of curvature. Wear W_{cr} defined as tool-life criterion belongs to $t=T$ tool-life. By this, in speed ranges I and II of Fig. 1, the physically interpreted tool-life function matching the general tool-life function (5) is

$$T_{phys} = \frac{W_{cr}^2 - W_0^2}{2} \frac{1}{v_c A_a(v_c)}, v_c \leq v_{c23}, \quad (16)$$

i.e., the adhesion and abrasion wear determine the tool deterioration characterised by constant A_a . It is a fact based on experience that in Stages I and II the build-ups of the edge periodically breaking off generate the wear intensity, typically different at different speeds, which practically does not emerge at v_{c23} .

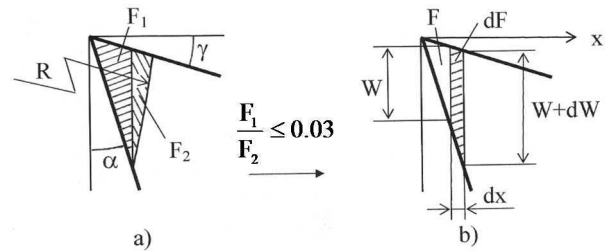


Fig 3 Geometry of flank wear

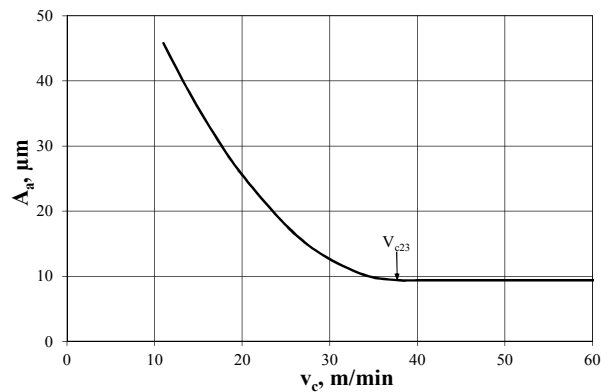


Fig. 4 Change of A_a wear coefficient

However, when decreasing the cutting speed, this material process of breaking off becomes more and more intensive, deteriorating the working surface of the tool more and more. In other words, the wear factor A_a becomes increasingly larger. Fig. 4 presents how the abrasion and adhesion wear factor A_a changes depending on the cutting

speed. In the range $v_{c23} \leq v_c$, i.e. in Stage III, A_a can be considered a constant independent of v_c .

In Stages I and II the power function can be applied:

$$A_a = av_c^2 + bv_c + c \quad (17)$$

for the A_a coefficient expressing the effect of the edge build-up. The last equation can be inserted in Eq. (16). Considering that C_{T1} can be written instead of $(W_{cr}^2 - W_0^2)/2a$, C_{T2} instead of b/a and C_{T3} instead of c/a , thus the general tool-life function in Eq. (5) is obtained. Counting directly from the typical points of the tool-life function – omitting the details – the constants of Eq. (16) are as follows:

$$a = \frac{W_{cr}^2 - W_0^2}{2} \left(\frac{1}{T_1 v_{c1}} - \frac{1}{T_{23} v_{c23}} \right) \left(\frac{1}{v_{c1} - v_{c23}} \right)^2 \quad (18a)$$

Here v_{c1} and T_1 can be substituted by any $v_c \leq v_{c23}$ speed and measured tool-life, respectively, belonging to v_{c23} . Using this

$$b = -2a \cdot v_{c23} \quad (18b)$$

$$c = \frac{W_{cr}^2 - W_0^2}{2v_{c23} \cdot T_{23}} + a \cdot v_{c23}^2 \quad (18c)$$

Tab. 2 Results of tool-life examination

v_c (m/min)	11	20	29	40	50	68	92	105	120
T (min)	166	153	189	222	132	34	11	7	5

Tab. 3 Typical values of the general tool-life function

C_{T1}	C_{T2}	C_{T3}	v_{c12} (m/min)	T_{12} (min)	v_{c23} (m/min)	T_{23} (min)
2.08×10^6	-82.2	1923	17	150	38	225

Fig. 5 presents the general tool-life function fitting for the measured results. For the physical interpretation of this tool-life function, in the $v_c \leq v_{c23} = 38$ m/min speed range, constants a , b and c of Eq. (17) are needed; however, in the $v_c \geq 38$ range the values A_{th} and B need to be determined. Referring to constants x and K , relying on the literature of the theory of cutting, mainly on the measurements by Lowack [21], taking into account that in Eq. (11) the empirical thermal function exponent x is not fully independent of cutting speed [22]. In the present case $x=0.4$ and $C_\theta=200 \pm 38$ K at a 95% level of reliability. In Eq. (12) the measurements of Barlier et al. [20] were used for determination of K , according to which $C_\theta=0.3$ K/ μ m and thus $K=0.002$. The expected development of FEM modelling of the cutting speed and the measurement technique of cutting promises future refinement of these constants, and the precise consideration of specific cases. At present they are calculated with approximate values created on the basis of measurement results taken from different sources. In speed ranges I and II of Fig. 1, using Eq. (18), the constants of the abrasion and adhesion wear factor A_a are $a=0.05$, $b=-3.8$ and $c=81.45$. This $A_a(v_c)$ function is presented in Fig. 4. Note that at $v_c \geq 38$ m/min cutting speed, in speed range III, A_a does not change any further from $A_a=9.36 \times 10^{-6}$ μ m. Here the thermally activated processes accelerate, too, which is characterised by the A_{th} and B constants of Eq. (13). Minimising the measured and calculated data of tool life, it is found that $B=82$ K, $A_{th}=12$ μ m. The results of the physical wear equation are presented also in Fig. 4.

In summary, the tool life, which depends on the cutting speed, is determined by an abrasion and adhesion coefficient which in Stages I and II also depends on A_a and cutting speed v_c due to the particular, periodically changing circumstances of chip formation. In Stage III, although increasing the cutting speed does not change A_a , the thermally activated degradation process becomes more and more intensive. Its character is indicated by activation energy Q .

4 Experimental verification

In hardened 100Cr6 steel, an inner cylindrical surface with 75 mm diameter was turned with a Composite 10 tool having a rake angle of $\gamma_f=-5^\circ$. The feed was $f=0.075$ mm/rev, depth of cut $a_p=0.1$ mm, tool-life criterion $W_{kr}=0.4$ mm. At the undamaged tool edge a value of $W_0=0.03$ mm was set. Table 2 sums up the results of tool life measurements, and Table 3 sums up the constants and typical values of the general tool-life function given in Eq. (5).

To demonstrate that the omission of thermal wear component in speed ranges I and II does not lead to gross error, it is worth comparing parts A_a and $A_{th} \cdot \exp(-B/(v_c^x + KW))$ presented in Fig. 6. At the border of speed ranges II and III the share of thermally activated processes in degradation can be ignored for cases of low wear; it is fairly small even reaching tool-life criterion $W=0.4$ μ m, hardly exceeding 10%. In Stage III the character of the dominant, thermally activated wear is indicated by the activation energy. Using Eq. (14) $Q=R \times B \times C_\theta = 8.29 \times 82 \times 200 \pm 39 = 136 \pm 29$ kJ/mol is obtained.

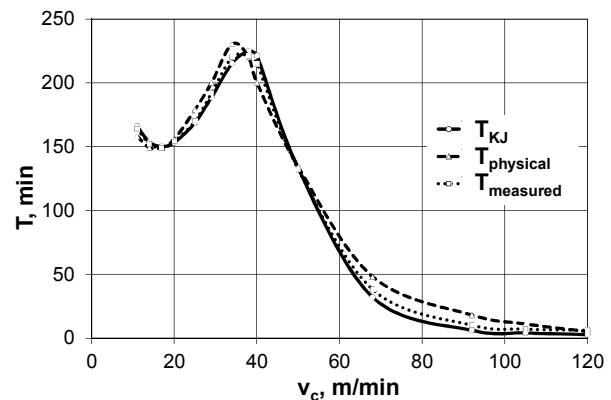


Fig. 5 General tool-life function fitted to the measurement results ($T_{measured}$), general tool-life function calculated with exponents (T_{KJ}) and the general tool-life function calculated on the basis of physical wear equation ($T_{physical}$)

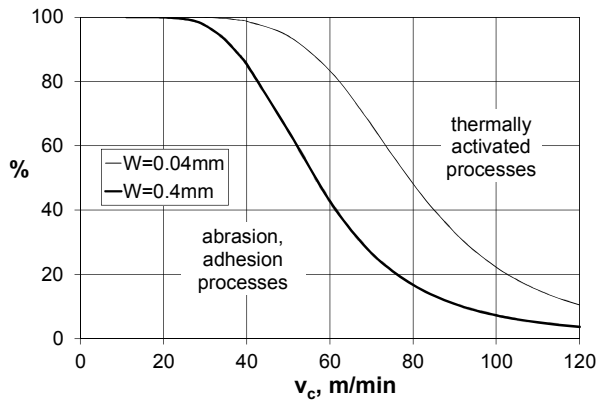


Fig. 6 Change of proportion of different wear processes depending on the cutting speed

The cutting tool employed in this investigation was polycrystal cubic boron nitride (PCBN). Different values can be found for the activation energy of this material in the technical literature depending on the nature of chemical processes. Hirano and Naka [23] give not more than a 46 kJ/mol value for the transition between the amorphous state and the cubic boron crystal structure, which is significantly lower than that which was experienced in the analyses presented in this paper. Thus, the supposition that the cubic crystal grid falls apart and so it wears off can be excluded. Another group of data from different chemical systems referring to CBN crystallisation gives values of 200-230 kJ/mol [24, 25], which on the other hand are too high. This statement refers to the oxidation, too, in which case, according to Katoku et al. [26] at the temperature of 900-1000 °C in the case of CBN with TiC content, the activation energy of oxygen penetration is 84 kJ/mol, since the experiments made in this work were completed with a tool having a low content of TiC. The latter implies that CBN does not change into some other compound on the tool surface. However, Turkevich et al. [27], investigating a concrete chemical system, found that the activation energy of the transformation between the cubic and the crystal structure of boron nitride is 170±40 kJ/mol. The value of 136±29 kJ/mol gained through the cutting examination extends into domain, which means that the degradation of the tool is likely to result from the transformation of the originally cubic crystal structure into a hexagonal one.

5 Conclusions

As is known, in continuous chip removal the tool life changes according to a particular curve having two extreme values, and this depends on cutting speed. From these extreme values the tool-life curve can be divided into three stages. In Stage I, with increasing cutting speed the tool life first decreases to a minimal value, from where – in Stage II – the tool life increases to a maximum, and then in Stage III it decreases again. To describe the changes in tool life several solutions exist besides the well-known Taylor formula, which is restricted mainly to the description of Stage III. In an earlier work by the authors a general tool-life equation was suggested which can be extended to all three stages. With the value pairs of v_c , T

referring to the extreme values and with additional v_c , T data, the constants of this function can be defined.

In this work the machinability of hardened steel is being investigated in a wide range of cutting speed. The aim was to determine the physical causes leading to tool degradation in the whole interpretation domain of the general $T(v_c)$ function. For this, a nonlinear differential equation of the wear rate was applied, which describes tool degradation as a result of abrasion and adhesion in Stages I and II. In Stage III the tool degradation results from a thermally activated process that increases with higher speed. This can be characterised by the activation energy determined by the results of tool-life examinations, by which the physical nature of the current degradation of a particular tool can be interpreted. The method was verified in the boring of hardened steel carried out with a PCBN tool. The measurement results proved that the tool degradation can be characterised by abrasion and adhesion in Stages I and II, while in Stage III activation energy was gained, making it probable that recrystallization occurs in the surface layer of the tool, modifying it from a cubic structure into hexagonal one.

A more profound knowledge of cutting tool wear and more exact description of its life are important information for technology planning, chose and optimization of cutting data.

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