Application of General Tool-life Function under Changing Cutting Conditions

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Abstract: The traditional Taylor formula T=f(v_c) gives tool life of the cutting tool T as a function of the cutting speed at constant speeds in which the higher the speed, the lower the tool life. However, in a wider technological range, the function T=f(v_c) has extreme values as well, which can be described by the general tool-life function. Frequently the tool is used until full wear of the edge at changing or alternating speeds, for which the general tool-life function can be extended. By using this extension, the general tool-life equation can be defined even under manufacturing conditions. Its applicability is demonstrated for examples of taper-turning and cutting optimisation.

Keywords: hard turning; tool life; economical cutting

1 Introduction

Several characteristics of machining are known, such as the surface quality of the workpiece, the shape of the chip, etc., and undoubtedly a great deal of attention is paid to tool life. Most often it is calculated by the well-known Taylor formula [1]

$$v_c \cdot T^{-\frac{1}{k}} = C_v \tag{1}$$

where v_c is cutting speed and T is tool life, while $-k$ and C_v are constants that are functions of the cutting conditions. Such conditions include the characteristics of the workpiece and the tool, the tool geometry and the cutting parameters (feed, depth of cut). On the basis of the Taylor formula several new research results have been obtained, such as the study by El Baradie [2] examining how the workpiece diameter influences the tool edge, or the examinations by Arsecuralante et al., who measured the volume of the material removed till the wear off of the tool edge [3], and who explained the tool wear by thematically activated processes [4]. Sahin [5], through a multiple regression analysis, attempted to apply a quadratic model that takes the hardness of the tool into account and also handles the product of the hardness and cutting speed, as well as the hardness and feed as separate

technological variables. The cutting forces and chip morphology also were taken into account when examining coated tool materials as, for example, Chinchanikar and Choudhunry [6] did in their experimental study. Still, similarly to other cutting investigations, the common characteristic feature of these differently orientated studies applying different methods is that they summarise the results in Taylor-like formulas.

The tool life equation is just as important from the point of view of the theory and practice of cutting. When qualifying the surfaces of the workpieces, which is often complicated [7], the state of the tool also has to be defined accurately, in addition to the cutting parameters. In the case of complicated procedures like the 3D end ball milling of steels [8], the knowledge of tool wear is needed for the actual realisation of the theoretically expected surface roughness. In turning alloys which are difficult to machine, such as Inconel, the planning of tool wear is especially important [9], and when optimising the cutting technology it is essential [10].

However, there are two obstacles (limitations) to the general application of the Taylor formula. The first one is that v_c–T tool-life function is general, having extreme values but over a wide range of technological parameters rather than monotonously decreasing values, as is presented in Figure 1. The second obstacle is that the tool is used with alternating or changing cutting speed. A cutting test must be done where the cutting speed changes, both in the planning of practical technology and in the validation of the SEM simulation of tool wear [11]. In a case such as this not only the definition of tool life is questionable, but even its interpretation. Bridging these difficulties is the aim of this paper.
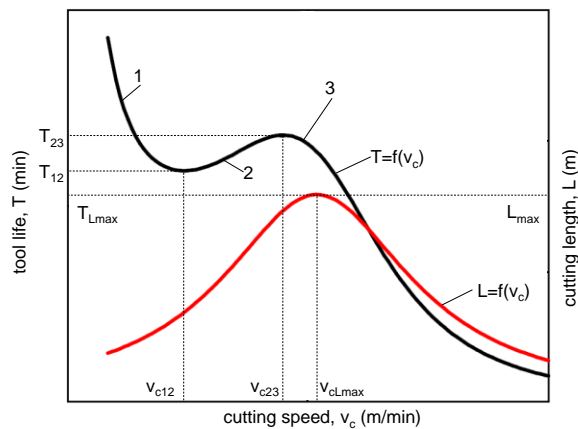

Figure 1
General tool-life function and the through cut length

2   General Tool-Life Function

Kundrák has demonstrated before that the general tool-life function worked out by him [12], which can be seen in Figure 1, describes the whole v_c–T function. Later other similar attempts became known [13] which rely on a rather complicated mathematical model, thus their practical application is laborious. The Kundrák formula that takes cutting speed into account can be written as:

$$T = \frac{C_{T1}}{v_c^3 + C_{T2} \cdot v_c^2 + C_{T3} \cdot v_c} \tag{2}$$

where C_{T1}, C_{T2} and C_{T3} are constants. At speeds v_{c12} and v_{c23} this function has an extreme value, which is naturally influenced by the technological parameters (feed f and depth of cut a_p):

$$v_{c12} = C_{v_{c12}} \cdot f^{x_{12}} \cdot a_p^{y_{12}} \cdot d_w^{q_{12}} \tag{3}$$

$$v_{c23} = C_{v_{c23}} \cdot f^{x_{23}} \cdot a_p^{y_{23}} \cdot d_w^{q_{23}} \tag{4}$$

$$T_{23} = C_{T23} \cdot f^{x_{T23}} \cdot a_p^{y_{T23}} \tag{5}$$

where d_w is the diameter of the workpiece, $C_{v_{c12}}$, $C_{v_{c23}}$, C_{T23} and x_{12}, y_{12}, q_{12}, x_{23}, y_{23}, q_{23}, x_{T23}, y_{T23} are constants that can be defined by technological examinations [12].

By their use already the constants of the general tool-life equation (1) can be calculated:

$$C_{T1} = T_{23} \cdot \left(v_{c23}^3 + C_{T2} \cdot v_{c23}^2 + C_{T3} \cdot v_{c23} \right) \tag{6}$$

$$C_{T2} = -\frac{3}{2} \cdot \left(v_{c12} + v_{c23} \right) \tag{7}$$

$$C_{T3} = 3 \cdot v_{c12} \cdot v_{c23} \tag{8}$$

It frequently occurs in technological planning practice that the length cut through the wear of the edge has to be examined or used, which, using (2), can be calculated by the formula:

$$L = T \cdot v_c = \frac{C_{T1}}{v_c^2 + C_{T2} \cdot v_c + C_{T3}} \tag{9}$$

This $L(v_c)$ function has only one extreme value (maximum) at speed

$$v_{L\max} = -\frac{C_{T2}}{2} \tag{10}$$

and its value can be calculated by

$$L_{\max} = \frac{C_{T1}}{0.75 \cdot C_{T2}^2 + C_{T3}} \tag{11}$$

The tool-life function and cutting length defined in this way can be used in a wide range of technological parameters [14, 15] and thus one of the problems mentioned in the Introduction in connection with the Taylor formula can be eliminated. Later we provide a solution for the frequently occurring cases of cutting alternating in stages or changing continuously. Henceforth, tool life at fixed (unchanging) speeds is indicated with $T_{vc,fix}$, while it is indicated with $T_{vc,vari}$ at variable (changing) speeds.

3 Tool Life when Changing Cutting Speed

The solution is based on the principle of the proportional degradation of the tool. If speeds change in stages, which is the case presented in Figure 2, as cutting is done at different speeds the wear of the tool is naturally cumulative [16].
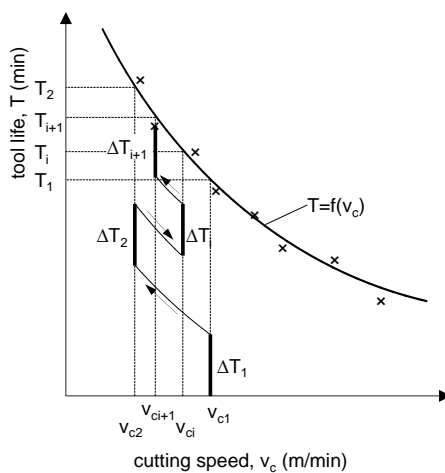

Figure 2

Tool life at changing cutting speed

It is a proved fact that if cutting is done for Δt_i time at cutting speed v_{ci}, the corresponding tool life is T_i, and the following equation is valid [16]:

$$\sum_{i=1}^{N} \frac{\Delta t_i(v_{ci})}{T_i(v_{ci})} \cong 1 \tag{12}$$

where N is the number of the cutting stages [16].

Although it can easily be proved that by means of the Zorev power function

$$VB = C_{VB} \cdot t^u \tag{13}$$

(u=0.5-1) [17] the sum of Equation (12) can be described exactly as 1 in wear functions, this is valid only until inflection is reached on the wear curve. In wear curves in which there is inflection, too, Equation (12) can be considered as an approximation before reaching the wear defined as tool-life criterion. As is known, the degradation of the tool is the consequence of the accumulated influence of several processes, where occasionally a sudden disorder occurs such as chipping away or pitting [18]. Such cases are not covered by this investigation. If cutting speed changes continuously, as in cross turning or taper turning, the equation takes the form

$$\int_{t_1}^{t_2} \frac{dt}{T(v_c)} \cong 1 \tag{14}$$

where $v_c = v_c(t)$ is a function of time [19]. By connecting Equations (2), (12) and (14), a general tool-life equation can be gained which is valid for a wide range of cutting speeds, in the case of both constant and changing cutting speed. For cutting speed changing in stages

$$\sum_{i=1}^{N} \Delta t_i \cdot (v_{ci}^3 + C_{T2} \cdot v_{ci}^2 + C_{T3} \cdot v_{ci}) \cong C_{T1} \tag{15}$$

however, for continuously changing cutting speed (e.g. taper turning or cross turning)

$$\int_{t_1}^{t_2} \left[v_c^3(t) + C_{T2} \cdot v_c^2(t) + C_{T3} \cdot v_c(t) \right] dt \cong C_{T1} \tag{16}$$

Using these equations and the general tool-life equation (12) valid for the cutting speed changing in stages,

$$T = \frac{\sum_{1}^{N} \Delta t_i (v_{ci}^3 + C_{T2} \cdot v_{ci}^2 + C_{T3} \cdot v_{ci})}{v_c^3 + C_{T2} \cdot v_c^2 + C_{T3} \cdot v_c} \tag{17}$$

and using Equation (14) at continuously changing cutting speed

$$T = \frac{\int_{t_1}^{t_2} \left[v_c^3(t) + C_{T2} \cdot v_c^2(t) + C_{T3} \cdot v_c(t) \right] dt}{v_c^3 + C_{T2} \cdot v_c^2 + C_{T3} \cdot v_c} \tag{18}$$

Equations (17) and (18), once we know constants C_{T2} and C_{T3}, can be handled numerically.

These functions are valid if all conditions with the exception of cutting speed v_c remain unchanged throughout the tool life. *T* calculated in this way cannot be considered as tool life in the strict sense, since tool life, according to the definition, means the time of cutting during which at a given v_c cutting speed a predetermined amount of wear – the tool-life criterion – develops on the tool. However, here the cutting speed is not unchanged till the edge wears off, rather it changes either periodically or continuously. The usual v_c–T data pair may occur if, besides the cutting time calculated by Equations (17) or (18), using Equation (2) $v_{c,eq}$ is also calculated which is considered constant, and T=T$_{eq}$ can really be considered as tool life. This has significance in the economic or technological optimisation of productivity.

Essentially there are two basic cases of the practical utilisation of Equations (17) and (18) in the tool-life function (1):

a) C_{Ti} constants of Equations (17) and (18) are known and identical tools are used in operations carried out at either periodically or continuously changing speeds. Now, to define the number of workpieces that can be produced before the tool wears off N_p, using the data of the operation plan and also Equations (12, 14),

$$N_p = \frac{C_{T1}}{\sum_1^N \Delta t_i \cdot (v_{ci}^3 + C_{T2} \cdot v_{ci}^2 + C_{T3} \cdot v_{ci})} \tag{19}$$

and

$$N_p = \frac{\int_0^{t_p} \left[v_c^3(t) + C_{T2} \cdot v_c^2(t) + C_{T3} \cdot v_c(t) \right] dt}{k \cdot (v_c^2 + C_{T2} \cdot v_c + C_{T3})} \tag{20}$$

can be applied, where

$$k = \frac{t_p}{v_c} = \frac{L_p \cdot D_w \cdot \pi}{1000 \cdot v_c \cdot f}, \tag{21}$$

where D_w (mm) is the diameter of the workpiece, f (mm/rev) is feed, L_p (mm) is the length that can be cut by the piece, t_p is the operation time. These parameters can be used for data collection during production as well if the approach is reversed: the number of the different machined parts is registered for the tool used until it is worn off. The results can be used for the refinement of Equations (15) and (16) that is the C_{Ti} constants, as well.

b) C_{Ti} constants of the equation are not known. Then data $N_{p,i}$ can be collected for the values of Δt_i and v_{ci}. There will be $N_{p,i}$ data, too, for all the worn out tools, for which Equations (12) and (14) are true. Many equations (15), (16) offer themselves for the unknown C_{T1} and other constants as the worn off edges; that is, a linear equation system with a minimum of three equations will be dealt with, from which these constants can be calculated.

4   Cutting Model Experiment

Hard turning was completed by cutting an Ø45 mm inner cylindrical surface of 100Cr6 hardened steel (HRC=62±2) on an E400-1000 centre lathe. The length of the machined bore hole was L_p=30 mm. The characteristics of the tool: CBN K10, γ=-5°, α=α'=15°, λ=0°, κ_r=45°, κ_r'=15°, the applied feed f=0.075 mm/rev., depth of cut a_p=0.1 mm. The constants of the tool-life formula given in Equation (2) related to the boring of this material are summed up in Table 1, and the v_c-$T_{vc,fix}$ tool life curve defined this way for cutting by fixed speed can be seen in Figure 3.

For the comparison of cutting at a fixed and at periodically changing speed, Table 2, for 5 chosen revolution values, displays the $N_{p,i}$ number of workpieces completed before a tool wears out; that is, tool life is indicated by the number of the turned bore holes. Table 3 summarises the model experiment series in which the number of pieces $N_{p,i}$ is measured that can be produced by turning at two speeds each, chosen from the 5 different speeds. Index I refers to the cutting speeds listed in Table 2, and $\Delta t_i = N_{p,i} \times t_{pi}$. These T_{meas} tool lives can also be seen in Figure 3.

Table 1

Constants of functions in Equations (3)–(5) with K10 tool [2][*]

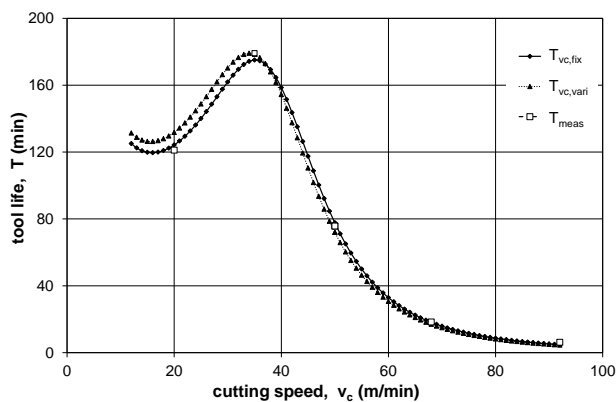| $C_{v_{c12}}$	$x_{v_{12}}$	$y_{v_{12}}$	$q_{v_{12}}$
1.06	-0.41	-0.40	0.19
$C_{v_{c23}}$	$x_{v_{23}}$	$y_{v_{23}}$	$q_{v_{23}}$
3.32	-0.24	-0.49	0.16
C_{T23}	$x_{T_{23}}$	$y_{T_{23}}$	$q_{T_{23}}$
13.99	-0.19	-0.09	0.48

[*]$[v_c]$=m/min, $[f]$=mm/rev., $[a_p]$=mm.

Figure 3

T-v_c curves defined by fixed speed ($T_{vc,fix}$), changing speed ($T_{vc,vari}$) and measured (T_{meas}) values

As Table 3 shows, the model experiment series consist of 3 variations each. The first part of the series covers the range of cutting speed where there is the maximum of v_c–T curve, at cutting speed v_{c23}.

Table 2

Technological parameters for fixed and periodically changing turning

Designation	Symbol	i=1	i=2	i=3	i=4	i=5
Number of revolutions	$n_{spindle}$ [1/min]	142	250	354	480	650
Cutting speed	$v_{c,i}$ [m/min]	20.06	35.33	50.02	67.82	91.85
Operation time	$t_{p,i}$ [min]	2.8169	1.6000	1.299	0.8333	0.6154
Piece number	$N_{p,i}$ [piece]	43	112	67	22	10
Tool life	$T_{vc,fix}$ [min]	121.1	179.2	75.7	18.3	6.15
	$T_{vc,vari}$ [min]	131.2	178	71.8	17.2	4.6
$T_{vc,fix}$: constant v_c, continuous cutting; $T_{vc,vari}$: variable v_c, periodical cutting						

Table 3

Number of bore holes turned with two speeds each until the wear off of the cutting edge

Number of experiment / Speed	1		2		3		4		5		6		$\Sigma\Delta t_i/T_i$
	$N_{p,1}$ [piece]	Δt_1 [min]	$N_{p,2}$ [piece]	Δt_2 [min]	$N_{p,3}$ [piece]	Δt_3 [min]	$N_{p,4}$ [piece]	Δt_4 [min]	$N_{p,5}$ [piece]	Δt_5 [min]	$N_{p,6}$ [piece]	Δt_6 [min]	
v_{c1} and v_{c3}	24	67.61	—	—	31	35.03	—	—	—	—	—	—	1.021
v_{c1} and v_{c2}	30	84.51	40	64	—	—	—	—	—	—	—	—	1.055
v_{c2} and v_{c3}	—	—	36	57.6	43	48.59	—	—	—	—	—	—	0.963
v_{c3} and v_{c4}	—	—	—	—	—	—	28	31.64	11	9.17	—	—	0.918
v_{c3} and v_{c5}	—	—	—	—	—	—	40	45.20	—	—	5	3.08	1.097
v_{c4} and v_{c5}	—	—	—	—	—	—	—	—	15	12.5	3	1.85	0.982
Numerical data of speeds from Table 2													

By means of Equation (15), in any part of the series 3 equations can be set up from which the constants C_{T1}, C_{T2}, and C_{T3} can be calculated. Table 4 summarises the constants defined from the results of the first part of the series.

The last column of Table 3 also contains the sums calculated by Equation (12), whose dispersion is indicated in Figure 4 on a so-called Gauss paper. Here on the vertical axis (ordinate) the scale was made on the basis of the error function; P_i, however, is the estimation of the error function calculated from the results

obtained by the formula given in Figure 4. The dispersion of the data $\Sigma\Delta t_i/\Delta T_i$ is typical in cutting examinations; their average, however, closely approaches the value 1 given in Equation (9).

By means of the constants summarised in Table 4, the values can be calculated of $T_{vc,vari}$ in the v_c–T curve which can be defined by turning at periodically changing speeds. The bottom line of Table 2 contains this data, while the close relationship of values $T_{vc,fix}$ and $T_{vc,vari}$ is presented in Figure 5.

The number of the parts produced with the tool edge until reaching the allowed value of wear (e.g. VB) can also be calculated from the data above. For the variations indicated in Table 3, the number of the parts is shown in Figure 6.

Table 4

Constants of function (2) at speeds changing periodically[*]

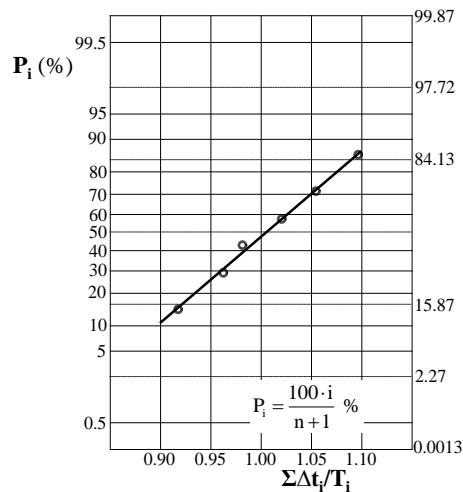| Constant C_{Ti}	Value
C_{T1}	1334540
C_{T2}	-74.51304
C_{T3}	1596.56

[*]Calculated from v_{c1}-v_{c3} data

Figure 4
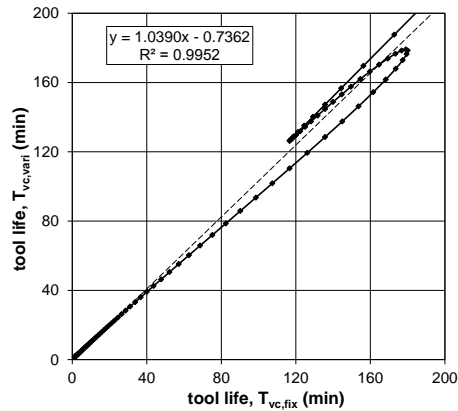
Dispersion of $\Sigma\Delta t_i/T_i$ values

Figure 5

The relationship of tool lives stated by $T_{vc,fix}$ fixed speed and $T_{vc,vari}$ changing speed cutting
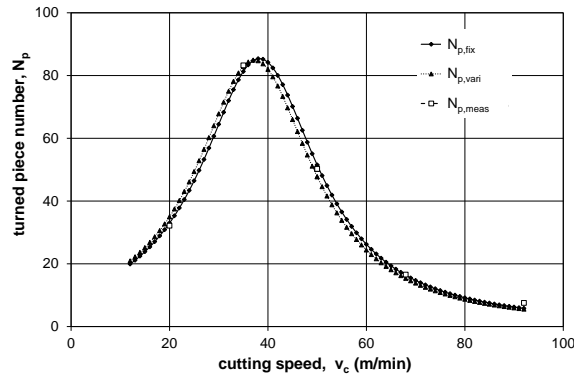

Figure 6

Number of parts as a function of cutting speed

5   Applications

The applicability of the general tool life function extended to the cutting with changing or alternate speed can be illustrated well in the examples of face turning and taper turning and also by the economic examination of tool performance.

5.1   Turning of Conical Surfaces

In the machining of internal cylindrical surfaces it has been found that constants C_{Ti} also depend on diameter of the workpiece D_w besides feed f and depth of cut a_p [12]. In these cases Equation (12) takes the form of

$$\sum_{i=1}^{N} \Delta t_i \cdot \frac{v_c^3 + C_{T2i} \cdot v_c^2 + C_{T3i} v_c}{C_{T1i}} \cong 1 \qquad (22)$$

with continuously changing cutting speed; however, in face turning or taper turning, for example, it takes the form of

$$\int_0^{t_p} \frac{v_c^3 + C_{T2} \cdot v_c^2 + C_{T3} \cdot v_c}{C_{T1}} dt \cong 1 \qquad (23)$$

In the frequent case when N_p parts are produced in sequence until the edge is worn off, on the right side of Equations (21) and (22) there is $1/N_p$ instead of 1.

For an example of the continuous change of cutting speed, the task is the hard turning of an internal cylindrical surface with a 1:5 taper made of 100Cr6 (HRC60±2) hardened steel. In this example the length of the cone is $\ell=40$ mm, the tool geometry, the feed f and depth of cut a_p are the same, however, diameter D changes:

$$D(t) = D_0 - \frac{n \cdot f}{5} t \qquad (24)$$

Therefore here the values v_{c12}, v_{c23} and T_{23} defining C_{Ti} constants also depend on time. Putting technological data into Equations (3)-(5) we obtain

$v_{c_{12}}=7.7007 \cdot D^{0.19}$

$v_{c_{23}}=24.1192 \cdot D^{0.16}$ \qquad (25)

$T_{23}=101.6348 \cdot D^{0.48}$

with which the constants C_{T1}, C_{T2}, C_{T3} can be calculated. The number of parts N_p that can be produced until the tool edge has been worn off can be simply calculated with a numerical method by means of Equation (23)

$$\int_0^{t_p} \frac{v_c^3 + C_{T2} \cdot v_c^2 + C_{T3} \cdot v_c}{C_{T1}} dt \cong \frac{1}{N_p}$$

The cutting time before the tool wears off

$T_{cut}=N_p \times t_p,$ \qquad (26)

where $t_p=\ell/(f \times n)$. The results of the calculation are shown in Figure 7. As can be seen, the character of the v_c-T_{cut} function can be compared with tool life T according to Figure 3; however, because of the continuous change of speed in taper turning, the locations of the extreme values are somewhat modified: they are shifted towards the higher values, however, their maximums are almost the same.
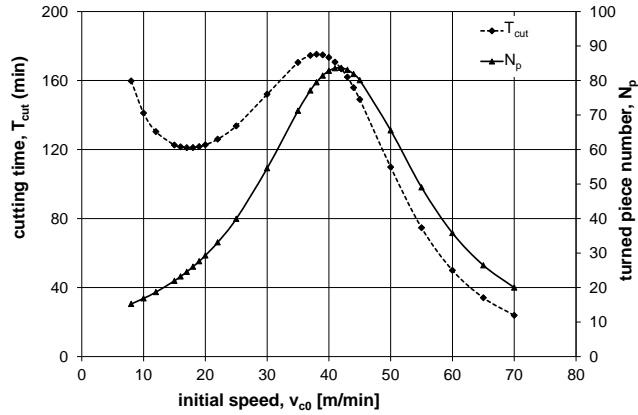
Figure 7

Number of parts and cutting time machined by taper turning until the wear off of the edge

5.2   Economics of Cutting

Several points of view have to be considered in economic examinations of cutting; however, in the present case the aim the economic analysis is to explore how the tool life influences the economy and productivity. So at first approach, the other cost factors of production beyond the technological parameters and the related different technological limits can be ignored.

Productivity can be characterised in the simplest way by the material volume cut during a time unit, that is, it can be calculated by

$$Q = \frac{a_p \cdot f \cdot v_c}{t_{ch} + T} \cdot T \ \ (\text{cm}^3/\text{min}) \tag{27}$$

where t_{ch} is the time needed to change the tool.

To define the cutting speed economically from the point of view of tool life, it is expedient to calculate the cost of cutting of the material quantity by unit of volume:

$$K = \frac{1}{a_p \cdot f \cdot v_c} \left[k_m + \frac{t_{ch} \cdot k_m + K_{tool}}{T} \right] \ (\text{€}/\text{cm}^3), \tag{28}$$

and here k_m is the so-called minute cost of the machine tool, however K_{tool} is the cost of one edge of the tool.

As is known, these specific economic indexes have extreme values depending on the cutting speed, the position of which can simply be expressed with formulas; in the case of the Taylor formula, by calculating the tool life that is optimal from the point of view of productivity and economy. In the case of the general v_c-T tool life

function the calculation of this optimal tool life would need the solution of a cubic equation originating from Equations (2) and (17), which can be handled by the Cardano method – a program can be created for it, but that would be rather labor intensive. However, by means of a direct numerical method, e.g. an ordinary spreadsheet program, all the necessary information on productivity and economy can be gained.

Functions (27) and (28) can be seen in Figure 8 with the experimental data of turning discussed in Section 4, where the time of the tool change is t_{ch}=5 min, the cost of the edge is K_{tool}=4 €, the minute cost of the machine tool is k_m=0.25 €/min and $a_p \times f$=0.0075 mm². So that the characteristic curve of $\mathbf{v_c}$ cutting speed and K specific cost of cutting as well as Q productivity can be illustrated in a diagram: Figure 8 shows a 20-fold K specific cost and a 120-fold Q specific chip output.

Here tool life T is an independent variable of the calculation; in reality, however, the aim is to define the cutting speed that is optimal from the point of view of productivity or expenditure. The characteristic curve of economic indices can be evaluated on the basis of Figure 8, then from the related spreadsheet table the $v_{c,opt}$ value, which is in Table 5, can be read with optional accuracy. It can be seen that the specific economic characteristics defined for turning with fixed speed and for turning with periodically changing speed are almost the same.
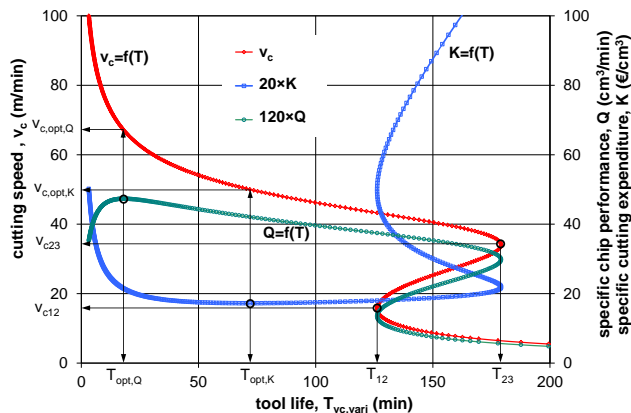

Figure 8

Specific cutting expenditure (K, €/cm³) and chip performance (Q, cm³/min) in hard boring

It follows from Equation (28) that the increase of tool expenditure K_{tool} increases the tool life optimal for economy. In an extreme case it may occur that $T_{opt,K}$ slides in between the borders of T_{12}–T_{23}, where – as can be seen in the T–v_c curve – up to three values offer themselves for the speed and consequently for machining cost K. Obviously, the most economically beneficial one is to be chosen from them if the other circumstances make that possible. When the application of optimal cutting speed defined in that way encounters some barriers, it can easily be decided what technology may closest approach the optimum.

Table 5

Comparison of specific characteristics of cutting in continuous cutting and cutting with changing speed

Cutting method	$v_{c,opt,Q}$ [m/min]	$T_{opt,Q}$ [min]	Q_{opt} [cm^3/min]	$v_{opt,K}$ [m/min]	$T_{opt,Q}$ [min]	K_{opt} [€/cm^3]
Cutting with fixed speed	67.5	18.8	0.400	51.0	71.1	0.847
Cutting with changing speed	67.8	17.3	0.400	49.3	76.9	0.881

Summary

The most important point of view of cutting ability is tool life. Usually it is described by the well-known Taylor formula, which, in the basic case gives the tool life as function of the cutting speed, but this is only valid for a monotonously decreasing T−v_c curve. To describe a T−v_c curve having extreme values as well, we introduced a general tool life function proved by cutting experiments. A frequent problem is, however, that cutting goes on sequentially with the same tool at several different speeds, and then this formula can be used only with difficulty. With periodically changing cutting speed the equation $\Sigma \Delta t_i / T_i \cong 1$ is valid theoretically and experiments have proven this. From this a general form of T−v_c curve can be deduced which can also be used with cutting at periodically changing cutting speeds. In the case of cutting at different speeds, an equivalent speed and the related tool life can be defined which can already been handled by the general Kundrák tool-life function. By the calculation of the equivalent speed it is possible to define the T−v_c curve under manufacturing conditions, even in cutting with changing speed, and the general tool life function can be defined by operational measurements. The applicability of this function is demonstrated by examples of taper turning and cutting optimisation.

Acknowledgements

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