Modelling of metal cutting tool wear based on Archard's wear equation

Ståhl, Jan-Eric; Andersson, Mats

Published in:
Proceedings of the Swedish Production Symposium, SPS 08 Stockholm

2008

Modelling of metal cutting tool wear based on Archard's wear equation

Jan-Eric Ståhl, Mats Andersson

Division of Production and Materials Engineering, Lund University, Sweden

mats.andersson@iprod.lth.se

ABSTRACT
This article deals with an essential problem in the metal cutting industry, the problem of predicting tool wear and tool life. This is also a problem that has been studied by academia for the last century, often with very little added knowledge. The possibility to replace a large number of systematic wear tests with only a few specially designed tests provides new potentials for rapid information collection and technology shifts. In the article a physically based model describing the tool flank wear during metal cutting is presented. The basis of the model work is a modified version of Archard's wear equation. The results from the wear model are compared to Taylor's well known tool wear diagrams. The two models are well correlated within the essential parameter range. The developed model requires a minimum of wear tests to provide the necessary basis for calculations. Only two experiments constitute the fixed point in the model. Other process conditions, that the actually tested, with other mechanical and thermal load, are interpolated or extrapolated around the experimentally fixed points. The mechanical and thermal loads are calculated and are a vital part of the model. The model generates tool wear diagrams and tool life predictions as function of cutting speed v_c and theoretical chip thickness h_1. A major part of this work has been performed in the SSF project Shortcut.

Keywords: metal cutting, tool wear, composite temperature, Archard, Taylor.

1. INTRODUCTION

Wear characteristics at metal cutting is a determining factor for the process outcome and robustness. The level of wear influences the product quality, process stability, downtime and the productivity of the process. The understanding and control of the tool wear progress and the tool life is therefore of vital importance to the total machining economy.

Taylor's wear equation [1] is the most used equation to determine the tool life of a cutting tool, based on the flank wear VB. Taylor's equation demands extensive cutting experiments and a huge amount of collected data in order to determine the necessary process constants. This in many cases is regarded as a major problem, especially in situations were new work materials, expensive work materials or new tools are being analyzed. Taylor's equation has no direct link to the physical properties of the work material and the cutting tool, and no link at all to the process conditions.

2. METHODS AND OBJECTIVES

This work is limited to comprise modeling of tool flank wear according to the figure. The presented modeling is 2-dimensional and the physical properties are linked together through the introduction of Archard's [2] wear equation in a modified form. The models are based upon the composite temperature θ_C of the cutting process, described by the authors [3, 4].

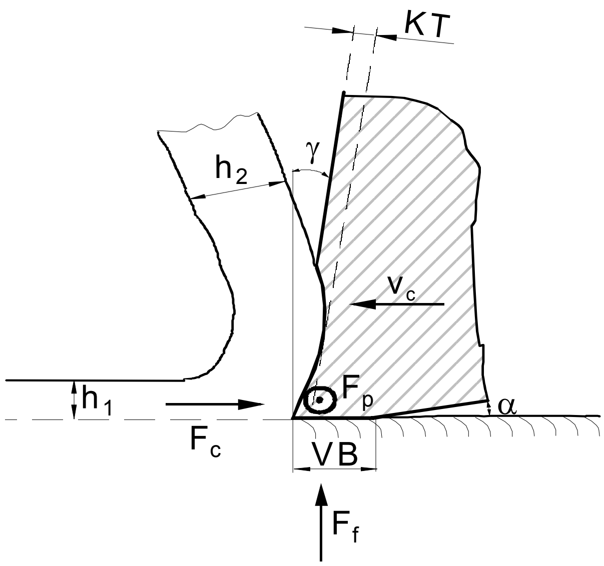

Fig. 1: An orthogonal, or 2-dimensional view of the cutting process.

3. FLANK WEAR

The flank wear appears on the flank face of the cutting tool, according to the figure. The magnitude of the flank wear VB, has a direct effect on the process temperature. For most machining operations, the process temperature increases with increased flank wear. Under certain conditions, a cooling effect through the contact surface on the flank face can occur, for example at low cutting speeds and with high values of the thermal conductivity of the workpiece [4].

An increased process temperature leads to an increased tool wear rate. Increased tool wear leads to higher cutting forces acting on the wear land, which increases the total energy losses due to tool wear. The level of flank wear is therefore directly influencing the change in tool wear rate, through the process geometry, the cutting forces, the wear energy losses, and the process temperature. This situation, where a direct regenerative relation between a functional value and it's derivate exists, usually results in functions partly or altogether based on the natural logarithm.

4. LIST OF SYMBOLS

V	Wear volume	mm^3
k_0	Archard's wear constant	mm^2N^{-1}
D_2	Normal force component on the tool flank face	N
D_{22}	Normal force component	N
D_{21}	Additional force due to growth of VB	Nmm^{-1}
r_β	Edge radius, mean value	μm
e	Tool engagement distance	m
p	Normal pressure between cutting tool and work material	Nmm^{-2}
A_c	Contact area between cutting tool and work material	mm^2
VB	Flank wear	mm
b	Theoretical chip width	mm
h_1	Theoretical chip thickness	mm
v_c	Cutting speed	ms^{-1}
t	Tool engagement time	s (min)
A_w	Wear land	mm^2
α	Relief angle	°
x, y	Coordinates	-
k_{01}	Wear constant	mm^2N^{-1}
k_{02}	Wear constant	K^{-1}
θ_C	Composite temperature	°C
T	Tool life	min
VB_T	Tool life criterion	mm
α_T	Taylor exponent	-
C_T	Taylor constant	m
T_T	Taylor tool life	min

5. WEAR MODEL

Archard's [2] modified wear equation can be written according to equation 1. The geometrical interpretations are illustrated in figure 2.

$$\begin{aligned} V &= k_0 \cdot D_2 \cdot e = k_0 \cdot p \cdot A_c \cdot v_c \cdot t \\ D_2 &= p \cdot A_c = p \cdot VB \cdot b \\ e &= v_c \cdot t \end{aligned} \tag{1}$$

Where k_0 is the wear function (constant), D_2 is the force component in the wear growth direction, and e is the tool engagement distance, which is the product of the cutting speed v and the tool engagement time t. The force component D_2 can be expressed as the mean normal pressure acting on the contact surface A_c. In the 2-dimensional case, the contact surface A_c is obtained as the product of the flank wear VB and the theoretical chip width b.

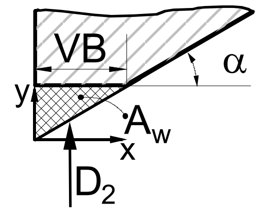

Fig. 2: Geometry with coordinates and cutting forces related to the flank wear in a cutting process.

The force component D_2 acting perpendicular to the contact surface can be expressed as a function of VB according to equation 2 [4].

$$D_2 = D_{22} + D_{21} \cdot VB \tag{2}$$

The constants D_{22} and D_{21} are determined through laboratory tests. The value of the constant D_{22} is primarily given by the micro geometrical design of the cutting edge, in combination with the chosen work material.

The wear volume V is geometrically defined in figure 2 as:

$$V = A_w \cdot b = \frac{y \cdot x}{2} \cdot b = \frac{x^2}{2} b \cdot \tan\alpha \tag{3}$$

Where:

$$\frac{y}{x} = \tan\alpha \qquad \frac{dy}{dx} = \tan\alpha \tag{4}$$

$$y = \frac{2 \cdot V}{x \cdot b} = \frac{2 \cdot V}{A_c} \tag{5}$$

Here, A_w is the wear surface, the variable x describes the flank wear progress, and the angle α is the tool relief angle. The wear progresses in the direction y. The wear rate is obtained as:

$$\frac{dy}{dt} = \frac{2}{A_c} \cdot \frac{dV}{dt} \tag{6}$$

By deriving Archard's modified wear equation the following equation is obtained:

$$\frac{dV}{dt} = k_0 \cdot D_2 \cdot v_c \tag{7}$$

Combining equations 2, 4, 6 and 7 gives:

$$dy = dx \cdot \tan\alpha = \frac{2k_0}{b \cdot x}(D_{22} + D_{21}x)v_c \cdot dt \tag{8}$$

Separation of the variables x and t gives:

$$b\int_{r_\beta}^{VB} \frac{x \cdot dx}{D_{22} + D_{21} \cdot x} = \frac{2k_0}{\tan\alpha}\int_0^t v_c \cdot dt \tag{9}$$

Integration gives:

$$\left[\frac{x}{D_{21}} - \frac{D_{22} \cdot \ln(D_{22} + D_{21} \cdot x)}{D_{21}^2}\right]_{r_\beta}^{VB} = \frac{2k_0 \cdot v_c \cdot t}{b \cdot \tan\alpha} \tag{10}$$

The time t can be calculated by inserting the limits of integration:

$$t = \frac{D_{21}VB + D_{22}\ln\dfrac{D_{22} + D_{21}r_\beta}{D_{22} + D_{21}\mathrm{VB}} - D_{21}r_\beta}{\dfrac{D_{21}^2 v_c \cdot 2k_0}{b \cdot \tan\alpha}} \tag{11}$$

For a given engagement time t and a determined flank wear VB, the wear constant and its progress can be calculated as:

$$k_0 = \frac{D_{21}VB + D_{22}\ln\dfrac{D_{22} + D_{21}r_\beta}{D_{22} + D_{21}\mathrm{VB}} - D_{21}r_\beta}{\dfrac{D_{21}^2 \cdot v_c \cdot 2 \cdot t}{b \cdot \tan\alpha}} \tag{12}$$

The wear function k_0 is strongly dependent on the process temperature in the cutting zone. Several different attempts to model the temperature dependence have been tried by the authors. We have found that an exponential relation according to equation 13 can be applied to wear situations with limited plastic deformation and no notch wear.

$$k_0 = k_{01} \cdot e^{k_{02} \cdot \theta_C} \tag{13}$$

Here k_{01} and k_{02} are constants determined by cutting tests. The composite temperature θ_C is a composite temperature which is acquired as a weighted mean value of the temperatures in the cutting process deformation zones. The composite temperature is calculated by thermodynamic equilibrium equations, based on cutting tests and physical data, Ståhl [4].

In the following figures 3, 4, and 5, examples of calculated composite temperatures θ_C as a function of the cutting speed v, theoretical chip thickness h_1 and flank wear VB are presented.

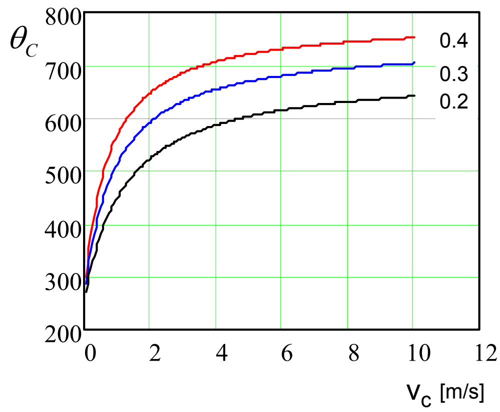

Fig. 3: The composite temperature θ_C as a function of cutting speed v_c. Theoretical chip thickness h_1 = 0.2, 0.3 and 0.4 mm with flank wear VB = 0.4 mm.

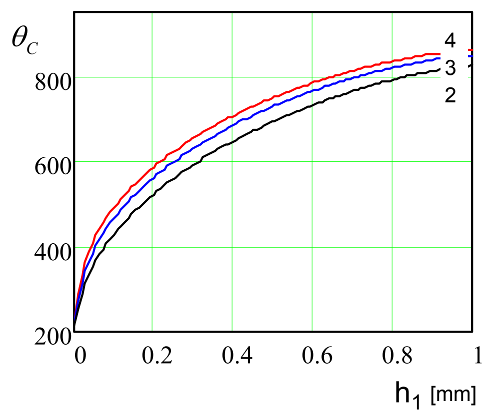

Fig. 4: The composite temperature θ_C as a function of theoretical chip thickness h_1. Cutting speed v_c = 2, 3 and 4 m/s with flank wear VB = 0.4 mm.

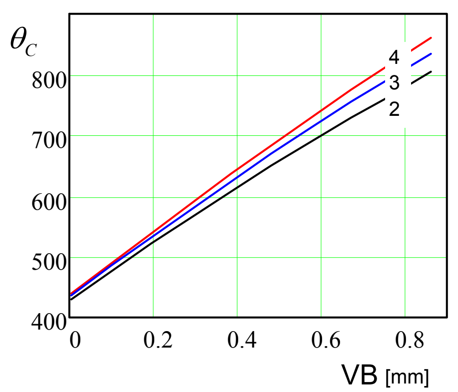

Fig. 5: The composite temperature θ_C as a function of flank wear. Cutting speed v_c= 2.5, 3 and 3.5 m/s with theoretical chip thickness h_1 = 0.3 mm.

For a known composite temperature θ_C, two cutting tests, I and II, are required to calculate the constants k_{01}

and k_{02} in the equation system 14. The wear constant k_0 is calculated using equation 12, with the conditions and parameters valid for test I and II.

$$k_0^I = k_{01} \cdot e^{k_{02} \cdot \theta_C^I}$$
$$k_0^{II} = k_{01} \cdot e^{k_{02} \cdot \theta_C^{II}} \qquad (14)$$

In tables 1 and 2, examples of test data and calculated constants k_{01} and k_{02} are presented. The tests were performed in a carbon steel, SS1672, using a coated carbide insert.

Table 1: Test data I

D_{21}	=	4300	N	h_1	=	0.4	mm
D_{22}	=	120	N	VB	=	0.4	mm
b	=	3	mm	v_c	=	3.5	m/s
α	=	6	º	t	=	8.5	min
$r_β$	=	40	µm	k_0	=	$1.5 \cdot 10^{-8}$	mm^2N^{-1}
				$θ_C$	=	685	ºC

Table 2: Test data II

D_{21}	=	4300	N	h_1	=	0.3	mm
D_{22}	=	120	N	VB	=	0.8	mm
b	=	3	mm	v_c	=	3	m/s
α	=	6	º	t	=	19	min
$r_β$	=	40	µm	k_0	=	$2.8 \cdot 10^{-8}$	mm^2N^{-1}
				$θ_C$	=	810	ºC

By calculating the composite temperature and solving the equation system 14, the constants k_{01} and k_{02} are obtained, given the conditions in tables 1 and 2.

$$k_{01} = 2.8 \cdot 10^{-9} \quad mm^2/N$$
$$k_{02} = 2.5 \cdot 10^{-3} \quad K^{-1}$$

Consequently, the wear function k_0 can be expressed using the composite temperature and variables controlling the composite temperature. In figures 6, 7, 8 and 9 the wear function k_0 is presented as a function of cutting speed v_c, theoretical chip thickness h_1, flank wear VB and finally the composite temperature $θ_C$.

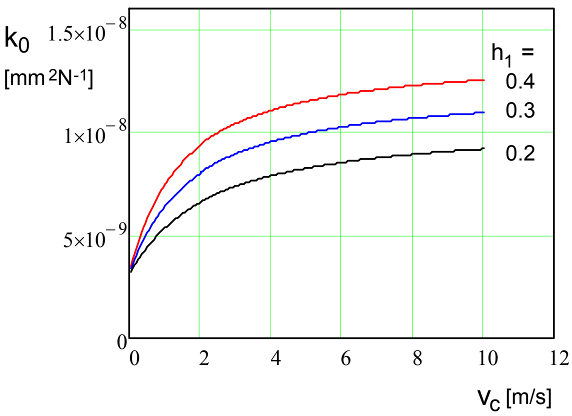

Fig. 6: The wear function k_0 as a function of cutting speed v_c, with h_1 = 0.2, 0.3 and 0.4 with VB =0.4 mm and α = 6º.

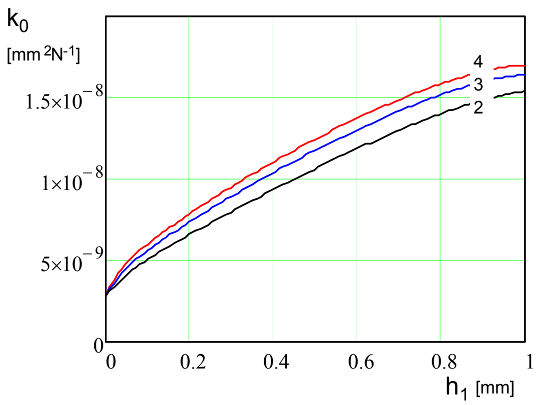

Fig. 7: The wear function k_0 as a function of theoretical chip thickness h_1 with VB = 0.4 mm for v_c = 2, 3, 4 m/s and α = 6º.

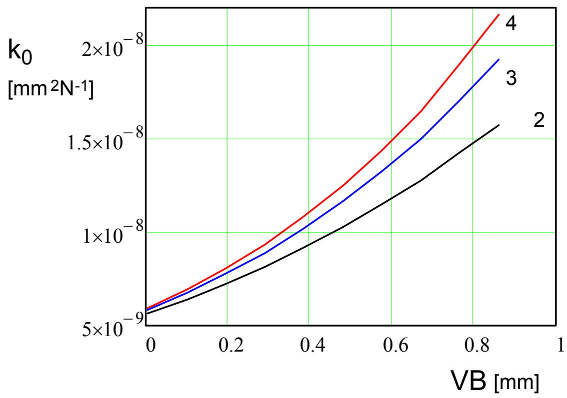

Fig. 8 The wear function k_0 as a function of flank wear VB with h_1 = 0.4 mm for v_c = 2, 3, 4 m/s and α = 6º.

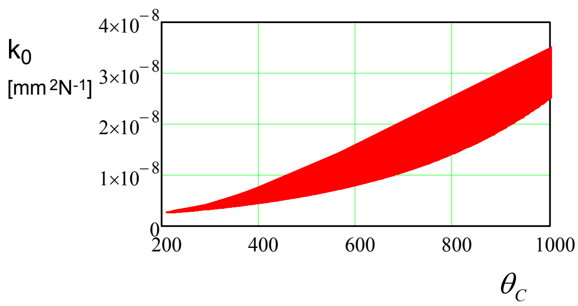

Fig. 9: The wear function k_0 as a function of the composite temperature $θ_C$ for all cutting data.

The temperature dependent wear function $k_0(θ_C)$ inserted into equation 11, will describe all combinations engagement time t and flank wear VB, for the whole range of variables and constants included in equation 11. Additionally, the wear progress is indirectly influenced by some other variables and constants, having an effect on the composite temperature θ_C. This can be exemplified by the influence of h_1 on the flank wear rate. The theoretical chip thickness is not included in equation 11, but has a significant and established influence on the wear rate via the process temperature, represented the composite temperature θ_C. In figure 10 and 11, the flank wear rate is illustrated, for different cutting speeds v_c and different theoretical chip thicknesses h_1.

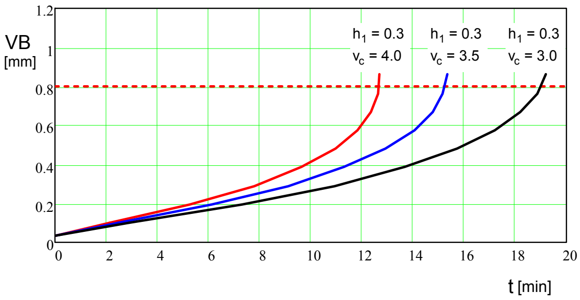

Fig. 10: Flank wear as a function of tool engagement time for 3 different cutting speeds, v_c = 3, 3.5 and 4 m/s, with h_1 = 0.3 mm and α = 6º.

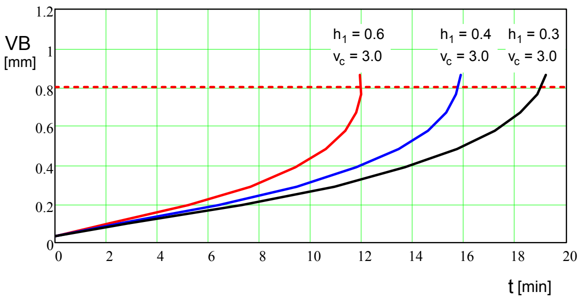

Fig. 11: Flank wear as a function of tool engagement time for 3 different theoretical chip thicknesses, h_1 = 0.6, 0.4 och 0.3 mm with v_c = 3 and α = 6º.

Choosing a wear criterion, for example VB_T = 0.8 mm, inserting in equation 14, makes it possible to calculate the tool life as a function of cutting speed v_c and theoretical chip thickness h_1.

$$t = \frac{D_{21}VB_{tl} + D_{22}\ln\dfrac{D_{22}+D_{21}r_\beta}{D_{22}+D_{21}\mathrm{VB}_{tl}} - D_{21}r_\beta}{\dfrac{D_{21}^2 v_c \cdot 2k_0(\theta_C)}{b\cdot\tan\alpha}} \qquad (14)$$

Where:

$$\theta_C = \theta_C(h_1, VB, v_c)$$

according to [3, 4], and as exemplified in figures 10 and 11. The tool life T = t(VB_T) calculated using equation 14 is presented in figures 12 and 13.

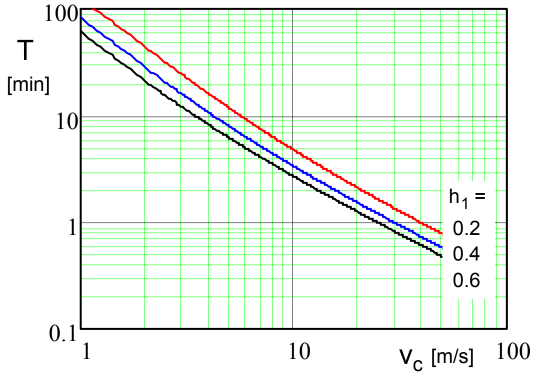

Fig. 12: Tool life T [min] as a function of cutting speed v_c, for different theoretical chip thicknesses h_1 = 0.2, 0.4, 0.6, and 0.8, setting VB_T = 0.8 mm and α = 6º.

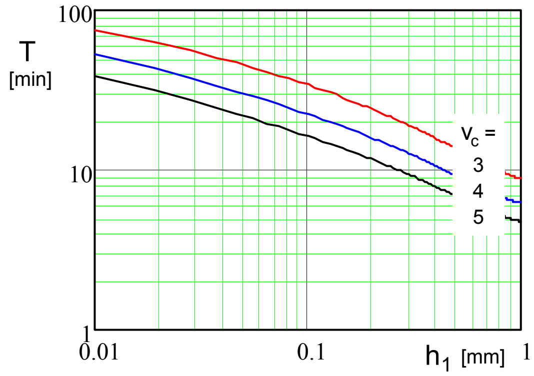

Fig. 13: Tool life T as a function of theoretical chip thickness h_1 for different cutting speed v_c = 3, 4 and 5 m/s, setting VB_T = 0.8 and α = 6º.

The tool life sensitivity and dependence of a given variable z, can for small variation Δz, ranges be calculated as:

$$\Delta T(z_i) = \frac{\partial T(z_i)}{\partial z_i}\cdot \Delta z_i \qquad (15)$$

The effects of process cooling can be calculated by studying the change of tool life with respect to θ_C according to equation 16.

$$\Delta T(\theta_C) = \frac{\partial T(\theta_C)}{\partial \theta_C}\cdot \Delta\theta_C \qquad (16)$$

When a variable, for example the cutting speed v_c, is directly dependent both on the tool life T and the composite temperature θ_C, ΔT can be calculated according to equation 17.

$$\Delta T(v_c) = \left(\frac{\partial T}{\partial v_c} + \frac{\partial T}{\partial \theta_C}\cdot\frac{\partial \theta_C}{\partial v_c}\right)\cdot \Delta v_c \qquad (17)$$

Figure 14 illustrates the effects of equation 16. The diagram shows the change in tool life when the composite temperature is decreased by one degree, i.e. $\Delta\theta_C = -1°$. It can be established from this example that a temperature decrease by one degree results in a increase in tool life in the interval of 3-7 seconds, depending of the initial value of θ_C.

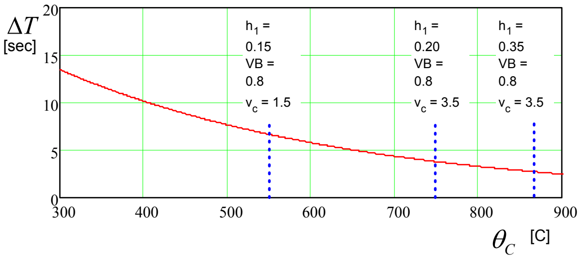

Fig. 14: The effect of one degree cooling of the cutting process, on the tool life.

Figure 15 illustrates, according to equation 17, how the tool life is affected by an increase of cutting speed v_c by 1 m/min. At a cutting of 180 m/min (3 m/s) a decrease of tool life by 10% per m/min is obtained. In this example, it can be noted that the largest tool life changes are obtained at the lower cutting speeds. This can be explained by the increased cooling effect through the contact area A_c, which is more influential at lower cutting speeds.

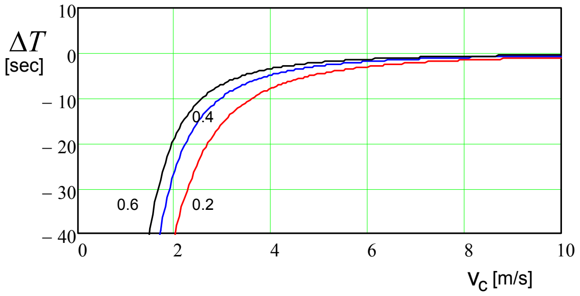

Fig. 15: The effect on tool life when the cutting speed v_c is increased by 1 m/min, for h_1 = 0.2, 0.4 and 0.6 mm.

Furthermore, at high cutting speeds, when the composite temperature approaches the adiabatic temperature of the cutting process, a change in cutting speed affects the tool life to a lesser extent, an expected effect due to the relatively small change in composite temperature.

The diagrams in figure 12 and 13 are easily recognizable as Taylor curves, and expressed according to equation 18.

$$v_c \cdot T_T^{\alpha_T} = C_T \tag{18}$$

From the diagram, or alternatively from the equation, the Taylor constants α_T and C_T can be determined. The exponent α_T as a function of theoretical chip thickness h_1 can be decided using equation 19. This relation is illustrated in figure 16.

$$\alpha_T(h_1) = \frac{\log(v_{c1}) - \log(v_{c2})}{\log(t_T(h_1, VB_T, v_{c2})) - \log(t_T(h_1, VB_T, v_{c1}))} \tag{19}$$

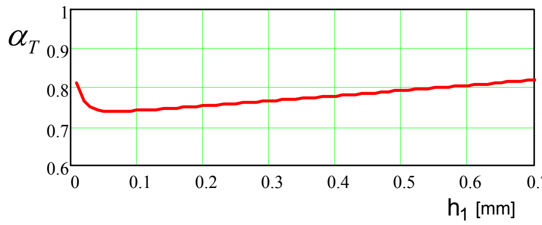

Fig. 16: The Taylor exponent α_T as a function of theoretical chip thickness h_1.

The Taylor constant C_T is determined by linear extrapolation of the curves in figure 13, originating from a chosen cutting speed in the interval $v_{cI} < v_c < v_{cII}$ to the tool life time T = 1.0. The cutting speed that results in a tool life T = 1.0 is also the numerical value of C_T. The calculated values of C_T as a function of h_1 are illustrated in figure 17.

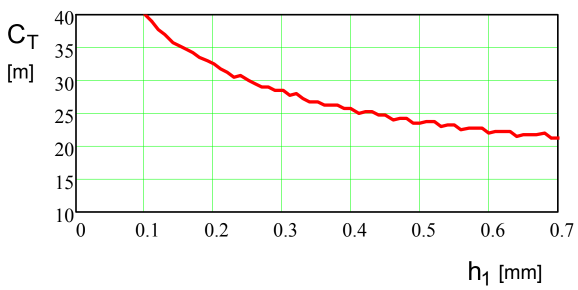

Fig. 17: The Taylor constant C_T modelled as a function of the theoretical chip thickness h_1.

Taylor's tool life equation can be written as:

$$T_T(v_c, h_1) = \left(\frac{C_T(h_1)}{v}\right)^{\frac{1}{\alpha_T(h_1)}} \tag{20}$$

In figures 18 and 19, equations 14 and 20 are illustrated in the same diagram, using both logarithmic and linear scales. As can be seen in the figures, the correlation is good in the essential areas.

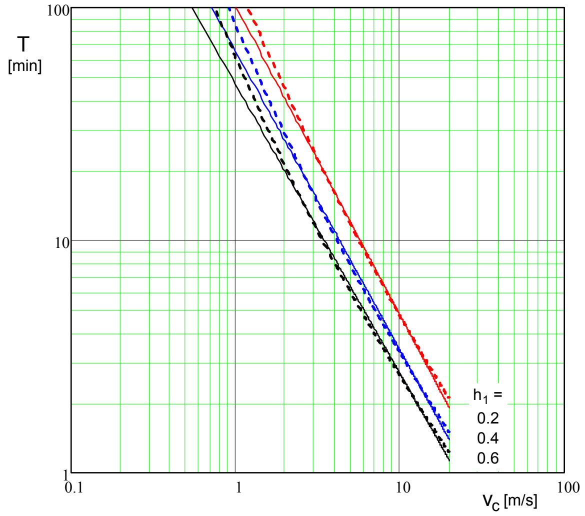

Fig. 17: A comparison between modelled tool life T (dashed lines) and calculated Taylor (solid lines). Theoretical chip thickness h_1 = 0.2, 0.4 and 0.6 mm, VB_T = 0.8 mm and α = 6º.

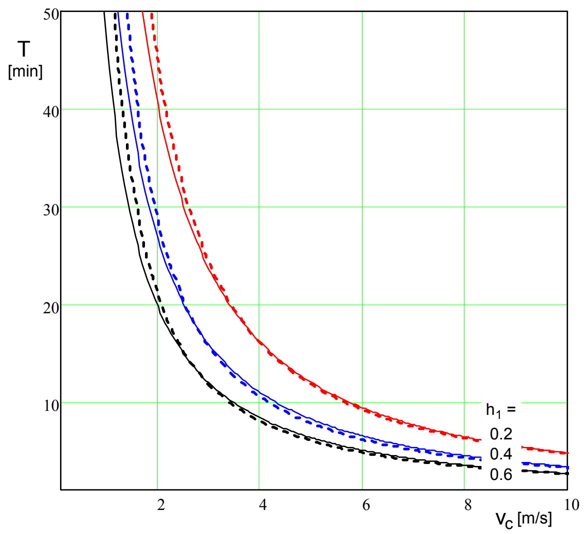

Fig. 18: Same diagram as in figure 17, but with linear scales.

6. DISCUSSION AND CONCLUSIONS

A modified wear equation according to Archard can be used to generically model the flank wear of a cutting tool. The wear model is based on physical material data, cutting forces and geometrical parameters, determined by experimental studies. The tool life prediction based on modelled analysis of flank wear is well correlated to Taylor diagrams based on experimental data. By introducing the modified Archard model, the Taylor constants are given a direct physical significance and a direct connection to cutting process.

If basic material data are known for a given work material or group of work materials, and for the used cutting tool, only a few, in this example 2, separate wear tests are required in order to establish the basis for the wear model. The model can describe the tool wear behaviour and tool life, for all combinations of cutting data and other parameters influencing the process temperature θ_C. Parameters influencing the composite temperature are by that also indirectly influencing the tool wear behaviour via the wear function, see equation 14.

The thermal influence on the tool wear is determined via the wear constant k_0, the added mechanical work due to increased, wear induced cutting forces is described by the product $D_{21}{\cdot}VB$, the geometrical change is described via the relief angle α as 1/tanα, and the linear wear load is described via the tool engagement distance, i.e. $v_c{\cdot}t$.

The corner stones of the presented model are the 2 cutting tests, the interpretation of these, and further on the determination of the composite temperature θ_C and implementation in the wear function $k_0 = k_0(\theta_C)$. The wear function $k_0(\theta_C)$ can be seen as a temperature dependent Archard constant k_0.

The 2 cutting tests represent 2 different wear conditions, with 2 different mechanical and thermal tool loads. The model allows for interpolation or extrapolation of process parameters influence on the mechanical and thermal load, where the 2 cuttings tests provide for the experimental fix points or reference points. Therefore, the model accuracy in these 2 fix points is 100 %. If the models describing the mechanical and thermal load lack some precision is therefore less important, for cases between and near the experimental fix points.

Thus, a consistent use of the models can be more important than the underlying models being 100 % accurate. The fix points calibrate the model and therefore minimize the model error. The data from the reference points must be calculated and analyzed in the same way as for the rest of the process parameter combinations. Enhanced process models will lead to an increased validity further away from the fix points, regarding mechanical and thermal load.

The accuracy of the model can be controlled in different manners. One of the 2 experimental fix points can gradually be substituted by new fix points. Consequently, new wear patterns can be analyzed and mapped. A variation in tool life can be determined by a comparison between model outputs based on different experimental fix points, measured under similar conditions.

The developed wear model is well suited to estimate different variables influence on tool life. However, substantial research work still remains in this area.

7. ACKNOWLEDGEMENTS

The presented work and the development of the simulation software ShortCut is financed by the SSF research programme ProViking. Professor Bo Jacobson at Division of Machine Elements, Lund University, has contributed with interesting discussions and important aid regarding the modification of Archard's wear function. Bengt Högrelius at SECO Tools AB has been an inspiring partner in the SSF ProViking project.

8. REFERENCES

[1] Taylor F. W. Trans. Am,Soc. mech. Engrs 28,31, 1907.

[2] Archard J. F.J. appl. Phys. 24, 981, 1953.

[3] Hans Walter, Jan-Eric Ståhl and Mats Andersson Modelling of the Composite Temperature θ_C in Metal Cutting Tools, Division of Production and Materials Engineering, Lund University, Sweden, Swedish Production Symposium, Göteborg 2007.

[4] Ståhl Jan-Eric Skärande Bearbetning – Teorier och modeller, KSF i Lund AB, Lund 2008 (In Swedish).

[5] Ståhl Jan-Eric Skäreggars spontanhaverier, LUTMDN-(TMMV-1006)/1-254/(1986) doktorsavhandling vid LTH Lunds universitet, Lund 1986 (In Swedish).