Modelling tool life in the machining of strain-hardening material - Alloy 718

Ståhl, Jan-Eric; Avdovic, Pajazit; Bushlya, Volodymyr; Zhou, Jinming

2011

Development of Model for Tool Life during Machining of Strain-Hardened Work Material – Alloy 718

Jan-Eric Ståhl[1], Pajazit Avdovic[1,2], Volodymyr Bushlya[1], Jinming Zhou[1]

[1]*Division of Production and Materials Engineering, Lund University, 22100 Lund, Sweden*
[2]*Siemens Industrial Turbomachinery AB, 612 83 Finspång, Sweden*

Abstract

This publication presents a model that describes the lifetime of a tool when used for cutting work in strain-hardened material. The model is known as the Shortcut-Wear-Model (SWM) and can be compared with the established model based on Colding equation. The extent of this work has been limited to the turning of the nickel-based alloy 718 with fibre reinforced ceramic cutting tools. This model has been verified with the help of experimental data from laboratory tests and during regular production of turbine components.

Key words: *Cutting, machining, turning, tool wear, life, ceramics, model, Colding, Alloy 718, strain hardening*

1. Introduction

To be able to predict the lifetime of a cutting tool is of great importance within industrial production. Tool life and the time it takes to complete a workpiece is decisive for the extent of tool usage per part. The lifetime of the tool is governed by the machinability of the material, the characteristics of the tool, the selected cutting data regarding cutting speed v_c, rate of feed f, depth of cut a_p and the characteristics of the machining system. In general, increased cutting data will result in reduced tool life. However, within certain points of the cutting data, the opposite relationship can arise. These special circumstances are applicable for working materials where marked cases of strain hardening arise; these include nickel-based alloys (e.g. Alloy 718) and titanium (Ti4Al6V) as well as material with steel structures which are partly or entirely austenitic (316L, 2205).

It is difficult to describe unambiguously the influence of cutting data on tool life with the help of mathematical models. One reason for this is the variation of process conditions. In the production environment the cutting data is often changed during machining, which in turn complicates the use of mathematical models. The production time may be expressed in terms of cutting parameters, and an extension of the Taylor tool life equation bonds the tool life to the cutting speed, feed rate and depth of cut [1]. One of the most important considerations in metal cutting is an economic cutting tool life. The main factors have to be determined for operating with optimal cutting conditions. Taylor 1906 was first to study this subject. Today there are many different distribution functions in existence which are suggested in literature [2].

Variations in a given working material's analysis and structure are factors that contribute to the extent of machinability and in turn the lifetime of a tool. This relationship demands that statistical models are used to describe the variations in tool life. Tool life is a statistical quantity and the nature of its distribution probability has been investigated by various researchers. Much of the research into machining economics has been concerned with finding the optimum basis for a deterministic tool life concept [3]. Awareness of the connection between the analysis and structure of the working material as well as its relationship to machinability and tool-life can limit the variation or distribution of tool life and the sequence of tool changes.

Traditional methods for predicting tool wear are the result of pioneering work by Taylor [4]. This illustrates a convenient relationship between tool life and cutting speed. The Taylor equation gives an indication of the expected tool life for various cutting conditions [5]. Many researchers have studied tool life which can be estimated to follow different distributions, like *gamma* (Ramalingam [6], Wiklund [7]), *normal* (Wager and Barach [8], Ramalingam [6], Rosetto and Zompi [9], Kaspi and Shabtay [10]), *lognormal* (Wager and Barash [8], Ramalingam [6], Rosetto and

Zompi [9], Wiklund [7]), *Weibull* (Ramalingam and Watson [11], Wiklund [7], Liu et al. [12]) or *exponential* (Ramalingam and Watson [11]).

Regarding [5] Taylor's formula could be used to exactly determine a tool's economic life according to the selected cutting speed.
A number of researchers, among them Colding [13] and Hägglund [14] have developed Taylor's equation in order to increase its validity. Codling's model for tool life could be adapted for a complex tool wear process [15] when machining material such as Maxthal which is an intermetallic alloy based on Ti_3SiC_2 with smaller amounts of the abrasive carbide TiC. Maxthal has a machinability that is 5 times lower than for Alloy 718. Experimental data has been adapted for Colding tool life model.
These models normally demand that the lifetime of the cutting tool diminishes significantly as a result of cutting data (v_c, f and a_p). This relationship reflects the fact that the same wear mechanism or the same balance between several wear mechanisms prevail throughout the entire lifetime of the cutting tool.

Regarding Vilenchich [16] and Taylor [17, 18]; these assumed a second model with logarithmic transformation for developing a tool life equation by response surface methodology, as it was observed that the extended Taylorian tool life equation cannot express the phenomenon completely [19].

Notch wear is the most dominant in round inserts [20]. Also, regarding [21, 22, 23, 24] the most known tool wear when cutting Alloy 718 is notch wear formed at the depth of cut due to high thermal combination, high work hardness, as well as the high strength of the work piece and abrasive particles. Flank wear is often selected as the tool life criterion. The reason for this is it determines the diametric accuracy of machining, its stability and reliability. At the same time flank wear is considered when using an aged Taylor's tool life equation [25].

A disadvantage with these models, primarily from a scientific point of view, is the fact that they are built upon curve adaption/ formation resulting from life-length and cutting data rather than having a more physical basis.

2. List of symbols

a_p	Cutting depth	[mm]
e_T	Contact length up until T for α= 1.0	[m]
f	Feed	[mm/rev]
h_1	Theoretical chip thickness, $a_p > r$	[mm]
h_{1max}	Maximum chip thickness	[mm]
h_{1min}	Minimum chip thickness	[mm]
h_e	Equivalent chip thickness	[mm]
h_{mean}	Mean chip thickness	[mm]
h_x	Chip thickness parameter x	[mm]
K_{IC}	Fracture toughness	[N/m $^{3/2}$]
k_i	Model constants	[-]
n_{def}	Strain hardening	[rev]
r	Nose radius	[mm]
r_β	Edge radius	[mm]
T	Length of tool life	[min]
T_L	T in laboratory conditions	[min]
T_P	T in production conditions	[min]
v_c	Cutting speed	[m/min]
α	Taylor exponent	[-]
ε_{III}	Extent of deformation	[mm]

3. Objective and problem description

The effect of strain-hardened material is that cut surfaces are harder than the rest of the material that is unaffected. During the following revolution the cutting tool comes into contact with the strain-hardened surface. Different parts of the edge line will cut through the strain-hardened material depending upon the thickness of the strain-hardened layer. An increased chip thickness h_1 will lead to less of the cutting edge operating in the strain-hardened materiel whilst at the same time, the accumulated deformation is reduced. These conditions lead to the prospects of extended tool life at a certain interval with increased feed f and a_p.

In the relevant group of materials with low thermal conductivity, the strain-hardened layer ε_{III} will increase with the cutting speed v_c, which means that the cutting speed has a stronger influence on tool deterioration in this material group than in others.

A model capable of describing the relationship between the lifetime of the cutting tool and the cutting data for strain-hardened material must also include one or several parameters that take into consideration the strain-hardening of the working material. From a cutting-technical point of view, variations in selected cutting data will lead to the material having varying cutting-technical qualities due to varying levels of material deformation.

When brittle cutting material is used, e.g. ceramic inserts for machining in materials with high temperature strength, the prediction of tool deterioration becomes problematic, which results in a relatively large variation of tool life. This relationship can be explained by the fact that materials with high temperature strength, such as Alloy 718, involve high and varying load scenarios whilst ceramic tools have low fracture toughness (K_{IC}) and show a high sensitivity to notch fatigue.

In this work, an additional model is presented to describe tool lifetime T during machine cutting; a model that also includes a description of the strain-hardening of the working material.

4. Extent and implementation

The extent of this work is limited to the lathing of Alloy 718. Experimental studies are carried out under the following:

- P, production conditions
- L, laboratory conditions.

The mean value of the length of tool life T will form the basis for the analysis carried out here. The distribution or variation of tool lifetimes and their causes are taken up in a separate report [26]. This work limits itself to the use of ceramic inserts. The tests carried out under production conditions are intended to give a realistic picture of the possibilities of quantitative usage of the tool lifetimes presented. Testing under laboratory conditions has been carried out with the purpose of minimizing the variations in process conditions, caused, amongst other things, by lack of stability and variations in machining allowance (a_p).

This study has focused upon the influence of the theoretical chip thickness h_x on the lifetime of the tool according to table 5. For this reason, variations in cutting speed have been limited.

4.1 Tests under production conditions

Tests have been carried out by turning along as shown in table 1. The machining of forged materials for turbine discs was carried out as shown in figure 1.

A number of measurement series have been conducted (A-L), 11 of them altogether. The main differences between each series are the insert shapes used and the variations in cutting data, see table 2. In 3 of these series the depth of cut a_p has varied due to differences in machining allowances after rough turning, something which is expected to give some variation in tool lifetime.

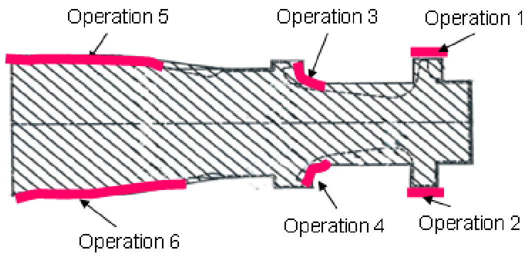

Figure 1 *A work piece used for production purposes with different machining operations.*

Table 1 *General data for tests under production conditions.*

Machine type:	Vertical lathe SCHIESS 16DSC	
Workpiece:	Forged material Φ1200x200	[mm]
Cutting tool:	RNGN (op.1, 2, 5, 6)	R
	DNGN (op. 3, 4)	D
Cutting speed, v_c	250 – 280	[m/min]
Feed rate, f	0.15 – 0.25	[mm/rev]
Depth of cut, a_p	0.25 – 2.0	[mm]

Table 2 *Cutting data and insert shape for measurement series A-L in production conditions with N; number of individual tests, Var. = variation in* a_p.

	Insert R/D, r	**f** [mm/rev]	**a_p** [mm]	**v_c** [m/min]	**N**
A	R, 6.35	0.20	1.3	250	6
B	R, 6.35	0.20	Var.	250	6
C	R, 6.35	0.25	0.25	250	5
D	R, 6.35	0.25	0.50	250	6
E	R, 6.35	0.25	2.0	250	6
F	R, 6.35	0.25	Var.	250	5
G	R, 6.35	0.15	2.0	280	15
H	R, 6.35	0.15	Var.	280	16
J	D, 1.2	0.15	0.25	250	7
K	D, 1.2	0.15	0.28	250	4
L	D, 1.2	0.15	0.33	250	5

4.2 Tests under laboratory conditions

Tests have been carried out in the form of longitudinal turning along a bar of material as shown in tables 3 and 4.

Table 3 *Data for tests under laboratory conditions.*

Machine type:	Turning lathe SMT 500	
Workpiece:	Φ70 x 400	[mm]
Cutting tool:	DNGN	D
Cutting speed, v_c	200 – 300	[m/min]
Feed rate, f	0.11 – 0.27	[mm/rev]
Depth of cut, a_p	0.22 – 0.53	[mm]

Table 4 *Cutting data and insert shape for measurement series 1-18 in laboratory conditions.*

	Insert D, r	**f** [mm/rev]	**a_p** [mm]	**v_c** [m/min]
1	D, 1.2	0.11	0.53	250
2	D, 1.2	0.13	0.53	250
3	D, 1.2	0.15	0.53	250
4	D, 1.2	0.19	0.53	250
5	D, 1.2	0.22	0.53	250
6	D, 1.2	0.25	0.53	250
7	D, 1.2	0.25	0.53	250
8	D, 1.2	0.13	0.31	250
9	D, 1.2	0.17	0.31	250
10	D, 1.2	0.21	0.31	250
11	D, 1.2	0.16	0.22	250
12	D, 1.2	0.22	0.22	250
13	D, 1.2	0.27	0.22	250
14	D, 1.2	0.15	0.53	200
15	D, 1.2	0.22	0.53	200
16	D, 1.2	0.22	0.53	300
17	D, 1.2	0.15	0.53	300
18	D, 1.2	0.11	0.53	300

5. Creating a model for tool life

Colding model (see equation 1) has been used successfully to describe the relationship between cutting data and tool lifetime T. This model is based on the assumption that the same wear mechanisms are dominant throughout the entire course of the tool's deterioration.

$$T = e^{\frac{-(H^2 - 2H\cdot\ln(h_e) + \ln(h_e)^2 - 4K\cdot M + 4M\cdot\ln(v_c))}{4M(N_0 - L\cdot\ln(h_e))}}$$
$$T = T(h_e, v_c) \tag{1}$$
$$\rightarrow$$
$$v_c = \exp\left[K - \frac{(\ln(h_e) - H)^2}{4\cdot M} - (N_0 - L\cdot\ln(h_e))\cdot\ln(T)\right]$$

The main variables in Colding equation are the equivalent chip thicknesses h_e and the cutting speed v_c. The equivalent chip thickness h_e is an approximate combined variable that was introduced by Woxén [27, 28] with the purpose of integrating feed rate f, cutting depth a_p, nose radius r and setting angle κ as seen in equation 2.

$$h_e = \frac{A}{l} = \frac{a_p \cdot f}{\frac{a_p - r(1-\cos\kappa)}{\sin\kappa} + \kappa\cdot r + \frac{f}{2}} \tag{2}$$
$$h_e = h_e(f, a_p, r, \kappa)$$

Woxén equivalent chip thickness h_e is intended to describe a thermal balance in the cutting process between the cutting tool's chip side and clearance side. The principle is that the same equivalent chip-thickness value forms the origin of the same thermal load on the cutting tool, regardless of the combination of parameters entered, thus resulting in the same rate of wear. These assumptions are entirely correct during machining at lower cutting speeds v_c < 20 m/min, which was applicable when the relationship was formulated [29]. This entails that Woxén theory bears lower relevance when it comes to the use of modern cutting tools. In practical terms the use of h_e gives fully acceptable results in straightforward cases of tool wear. The modern interpretation of h_e is that this parameter describes a thermal and mechanical mean load along the edge line. The result of Colding equation when h_e is used can lead to an overestimation of tool lifetime during fine machining, i.e. machining with low feed and cutting depth values.

Colding equation contains 5 constants (K, H, M, N_0, L), which can be determined with the help of at least 5 individual tests. Experience has shown that 2 pairs with the same equivalent chip thickness should be used. Each pair should be combined with different cutting speeds. The individual test (an extra point) can be most suitably chosen within a recommended span of cutting data. Colding constants can be calculated with the help of curve adaption and the minimization of deviation concerning the obtained measurement points for more than five individual tests. There is no direct link between the parameters entered in Colding equation and the physical performance in the cutting process.

The cutting tool is subjected to mechanical, thermal and tribological load; the combination of which leads to the deterioration of the cutting tool. The lifetime of the tool T is obtained when the selected wear criteria has been reached. In cases where the cutting tool suffers straightforward abrasive wear, the length of tool life will be determined purely by the tool's length of contact e_T. This relationship is the equivalent of Taylor's exponent α = 1.0 as seen in equation 3. The value of the exponent α will be reduced when thermal load increases.

$$v_c \cdot T^\alpha = e_T$$
$$T = \left(\frac{e_T}{v_c}\right)^{\frac{1}{\alpha}} \tag{3}$$

The effect of strain hardening can be taken into consideration by reducing the length of tool life T with a term that correlates with the working material's strain hardening during the cutting process. The cutting process leads to strain-hardening in the cut surface as shown in figure 2. Depending on the geometrical relationship in the cutting process and how it combines with the extent of strain hardening and deformation zone $\varepsilon_{III,}$ successive deformation will occur in front of the edge line during a number of revolutions n_{def} (see figure 3). The extent of deformation ε_{III} can be determined by measuring the microhardness for example, or by studying the deformation in the cut surface (see figure 3). The actual extent of deformation with regard to the deterioration of the cutting tool is, however, greater than what can be observed visually with a microscope.

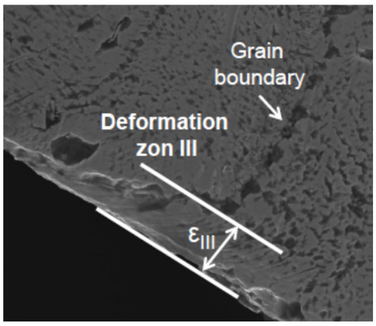

Figure 2 *The Principle for measuring the visible extent of deformation ε_{III} in Alloy 718.*

The parameter n_{def} can be described according to equation 4, see figure 3.

$$n_{def} \cdot f = \sqrt{(r+\varepsilon_{III})^2 - r^2} - \frac{f}{2} \rightarrow$$
$$n_{def} = \frac{2\sqrt{\varepsilon_{III}{}^2 + 2r \cdot \varepsilon_{III}} - f}{2f} \quad (4)$$
$$n_{def} = n_{def}(f, r, \varepsilon_{III})$$

The relationship as shown in equation 4 has previously been presented by Byrne [30] with the purpose of describing the mechanism for the creation of a surface by means of multi-stage deformation.

The influence of thermal and mechanical stress on the lifetime of the cutting tool (as seen in equation 3) is dealt with in the same way as the effect of strain hardening. Depending on the choice of wear criteria, various parameters of chip thickness h_x can be used to describe the thermal and mechanical load that affects the cutting tool.

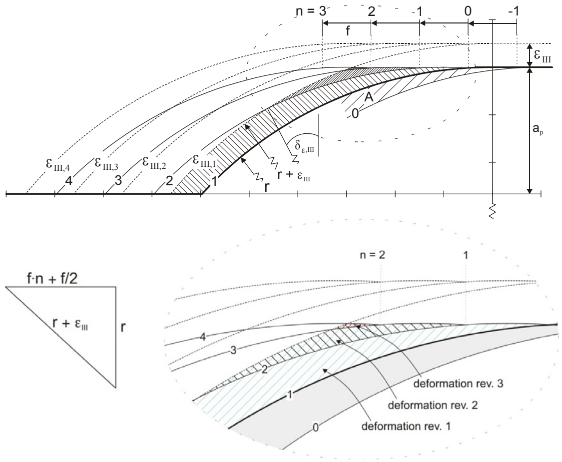

Figure 3 *Deformation in front of the edge line during longitudinal turning n, revolutions with the nose radius r and the extent of deformation ε_{III}.*

In table 5 there are examples of chip-thickness parameters h_x which can be used for various wear-criteria options.

Table 5 *The relationship between chip-thickness parameters h_x and lifetime criteria.*

h_x	Description	Lifetime criteria
h_{1max}	Maximum chip-thickness	Notch wear with maximum chip thickness, edge chipping and tool breakage, plastic deformation
h_e	Equivalent chip thickness	Uniform flank wear, VB_{max}
h_{mean}	Mean chip thickness	Uniform flank wear, VB_{max}
h_{1min}	Minimal chip thickness	Notch wear with minimal chip thickness

The Parameter h_{1max} can be calculated according to equation 5, [29]. Different relationships are applied depending on whether the depth of cut a_p is greater or smaller than the nose radius r.

$$h_{1\max} = r - \sqrt{f^2 + r^2 - 2f\sqrt{2a_p \cdot r - a_p{}^2}}$$
$$a_p < r \quad (5)$$
$$h_{1\max} = f \cdot \sin(\kappa)$$
$$a_p > r$$

By means of the combination of the above effects a tool lifetime model can be formulated as seen in equation 6.

$$T = \left(\frac{k_1}{v_c}\right)^{k_2} - k_3\left(\frac{1}{2} + n_{def}\right)^{k_4} - k_5 \cdot h_x^{k_6} \quad (6)$$
$$T = T(v_c, n_{def}, h_x)$$

Equation 4 can be described in its entirety with the help of figure 4. The parameter n_{def} includes 3 variables; feed f, nose radius and the extent of deformation ε_{III}. The assumed value equal - ½ for $\varepsilon_{III} = 0$. The term that takes into consideration the working material's strain hardening will assume the value 0 for the extent of deformation $\varepsilon_{III} = 0$.

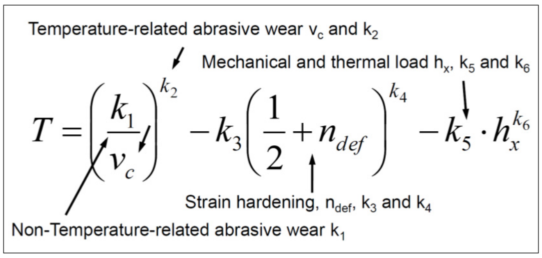

***Figure 4** General model for describing tool life during machining in strain-hardened work material.*

The choice of chip-thickness parameter h_x is governed in turn by the choice of wear criteria (see table 5). The model according to equation 6 demands 2 constants per entered variable, i.e. 6 constants. In figure 5 and figure 6 equation 6 is exemplified with constants as seen in table 6.

***Table 6** Example of model constants k_i during machining of Alloy 718 with fibre-reinforced ceramic cutting inserts.*

k_1	k_2	k_3	k_4	k_5	k_6
1900	1.15	1.20	0.50	40	1.05

The constant k_1 can be compared with Taylor's constant e_T and k_2 can be compared with the registered value of Taylor's exponent α as seen in equation 3.

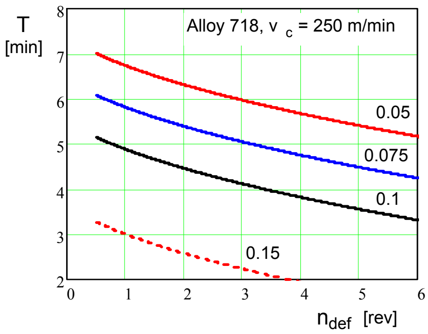

***Figure 5** Example of the modelled length of tool life T as a function of n_{def} for 4 different values of the equivalent chip thickness h_e.*

By inserting the parameter n_{def} as seen in equation 4 and the equation for $h_x = h_e$ according to equation 2 in equation 6 (Shortcut-Wear-Model) the length of tool life T can be expressed directly in the form of cutting data and other included variables (equation 7).

$$T = \left(\frac{k_1}{v_c}\right)^{k_2} - k_3\left(\frac{1}{2} + n_{def}(f, r, \varepsilon_{III})\right)^{k_4}$$
$$- k_5 \cdot h_x(f, a_p, r, \kappa)^{k_6}$$
$$T = T(v_c, f, a_p, r, \kappa, \varepsilon_{III}) \tag{7}$$
$$\rightarrow$$
$$v_c = \frac{k_1}{\left[T + k_3\left(n_{def} + \frac{1}{2}\right)^{k_4} + k_5 \cdot h_x^{k_6}\right]^{\frac{1}{k_2}}}$$

In figure 7 the appearance of the cutting tool's lifetime T is exemplified as a function of f for 2 different nose radii r.

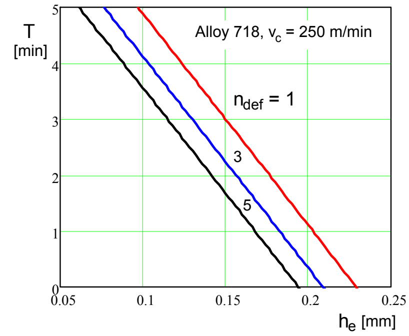

***Figure 6** Example of the modelled length of tool life T as a function of the equivalent chip thickness for 3 different values of n_{def}.*

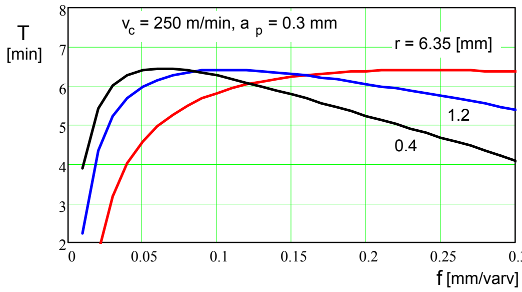

***Figure 7** Example of the modelled length of tool life T as a function of feed f and nose radius r during the machining of Alloy 718 with a_p = 0.3 mm, cutting speed v_c = 250 m/min and ε_{III} = 0.07 mm.*

I figure 7 it can be noted that for each respective nose radius r there is an optimum rate of feed f_{opt} in order to achieve maximal length of tool life T. This feed rate results in an optimum minimal aggregate load caused by strain hardening and direct mechanical load resulting from the theoretical chip thickness h_1 for the given cutting speed v_c.

The characteristics of tool lifetime T can be illustrated according to figure 8 by studying every individual term in equation 6.

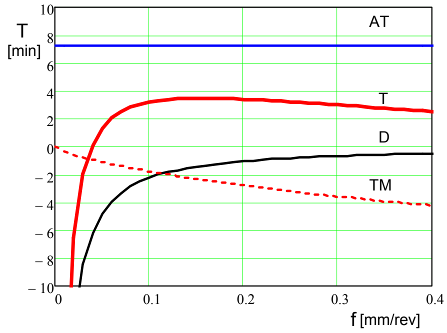

***Figure 8** Principle characteristics of tool lifetime T where AT = Abrasive thermal deterioration, D = Effect of the working material's strain hardening and TM = Thermal and mechanical effect.*

6. Experiment and result

As stated in part 3 the experiment was conducted in both production and laboratory conditions. The experimental values gained concerning tool lifetime have been adapted to Colding equation (equation 1) as well as the relationship as seen in equation 6; this was done with the help of least square method. Tool lifetimes T_P obtained under production conditions have been adapted to statistical functions of distribution. These results are presented in a separate report [26]. The estimated mean value of T_P forms the basis of the determination of the constants included in equation 1 and equation 6.

In this study, the wear criteria, maximal flank wear VB_{max} = 0.30 mm, has been applied. The wear times that are presented are linearly interpolated or extrapolated on the basis of the levels of wear recorded for each individual test.

The distribution or variation in tool lifetime is significant under production conditions. In figure 9 the length of tool life is presented together with its distribution for the selected measurement series (A, C, D, E and G). Other conditions are presented in tables 1 and 2. The calculated mean values for T_P are represented by shaded symbols. The diagram shows indications of a maximum in T_P as a function of the equivalent chip thickness h_e. In figure 10 the length of tool life T_L under laboratory conditions is presented. The prerequisites for the diagram are presented in tables 3 and 4.

In table 7 and table 8, the calculated constants for Colding equation and equation 6 are presented (as used in production and laboratory conditions respectively). For the calculation of the constants $k_1 - k_6$ the mean extent of deformation ε_{III} has been determined to 70 µm. This value has been used in all calculations.

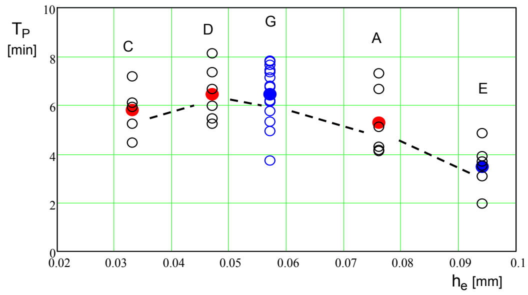

***Figure 9** The length of tool life T_P and its distribution as a function of equivalent chip thickness h_e during machining under production conditions for selected measurement series. The calculated mean value of T_P is represented by shaded symbols.*

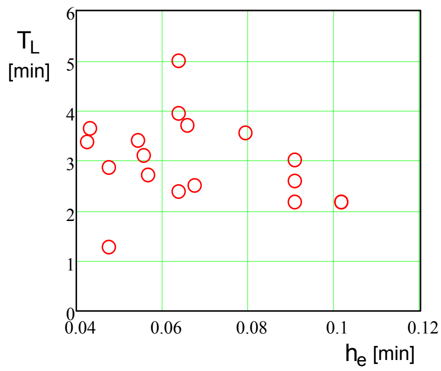

***Figure 10** The length of tool life T_L as a function of equivalent chip thickness h_e during machining in the laboratory under varying conditions as seen in table 4.*

***Table 7** The calculated constants for **Colding equation** under production conditions P and laboratory conditions L.*

	K	H	M	N_0	L
P	5.8664	- 2.7058	0.5838	0.5322	- 0.1284
L	5.8761	- 2.6096	0.6487	0.8309	- 0.1947

***Table 8** Calculated constants for **SWM** under production conditions P and laboratory conditions L.*

	k_1	k_2	k_3	k_4	k_5	k_6
P	1887	1.1384	1.1985	0.4969	38.88	1.029
L	3918	0.7193	0.4688	1.100	20.04	0.707

By comparing the experimental length of tool life T_j with the modelled length of tool life T the mean error can be calculated in each respective measurement point according to equation 8.

$$E_X = \frac{100}{m}\sum_{j=1}^{m}\left|T_j - T(f_j, a_{p,j}, r_j, v_{c,j}, \varepsilon_{III,j})\right| \qquad (8)$$

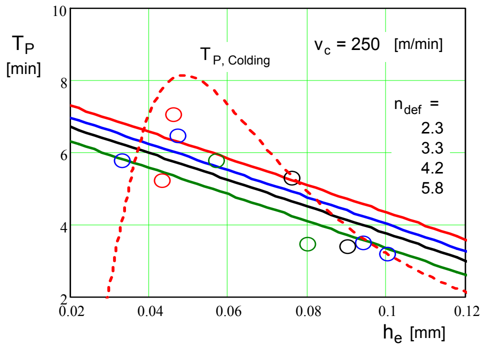

Figure 11 *Modelled length of tool life T_P with Colding equation, and, in accordance with SWM, for the measurement series A-K.*

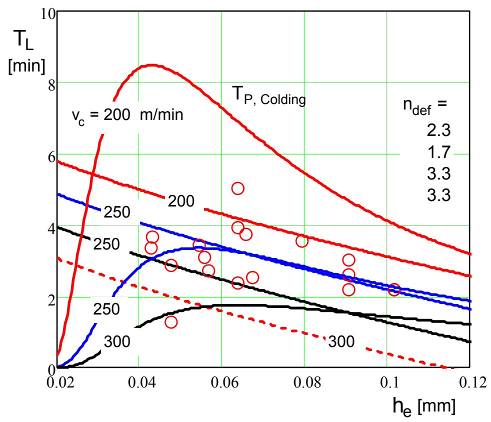

Figure 12 *Modelled length of tool life T_L with Colding equation and according to SWM.*

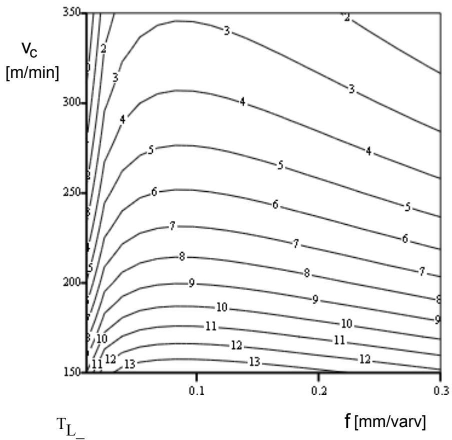

Figure 13 *This exemplifies how various combinations of feed f and cutting speed v_c result in different tool lifetimes T_L, for r = 1.2 mm, a_p = 0.3 mm and ε_{III} = 0.070 mm.*

In table 9 the calculated mean error $E_{T,P}$ and $E_{T,L}$ is presented in the form of percentages for each respective model.

In table 10 the calculated mean error $E_{vc,P}$ and $E_{vc,L}$ is presented as a percentage for each respective model.

Table 9 *Calculated mean error E_T as a percentage for T_P and T_L for each respective model.*

	$E_{T,P}$	$E_{T,L}$
Colding equation	19.0	18.1
SWM	17.4	16.5

Table 10 *Calculated mean error E_{vc} as a percentage for $v_{c,P}$ and $v_{c,L}$ for each respective model.*

	$E_{vc,P}$	$E_{vc,L}$
Colding equation	5.3	2.9
SWM	8.0	5.6

7. Conclusion and discussion

Two different models have been compared to describe the length of tool life during longitudinal lathing of the nickel-based Alloy 718. Also, two types of test have been carried out; one under production conditions where machining was performed on forged turbine discs and another under controlled laboratory conditions. One of the objectives with the study is to investigate the possibility of using a model for the description of tool life; a model which also directly takes into consideration the strain hardening of the working material during machining.

The production-based tests that were carried out include a considerable amount of data. The variation or distribution in tool life is relatively significant when compared with conventional steel for example. The distribution in tool life can primarily be traced to the following:

- Variation in the characteristics of the working material resulting from variations in analysis and heat treatment.
- The effects of using cutting material with low breakage toughness and with low values of flexural strength tension.
- The deterioration of the cutting tool results in a successively varied and increased edge radius, which in turn leads to increased and varied zones of deformation $\varepsilon_{III;}$ this results in an increased and varying value for n_{def}. This parameter is included directly in the length of life equation, as seen in SWM.

Two models for lifetime have been presented in the study; Colding equation and equation 6 (Shortcut-Wear-model). Both equations result in a relatively large model error when calculating the length of life T as a function of cutting data. The model as seen in equation 6 however does give a slightly better result according to table 9, which can be explained by the fact that the extent of deformation ε_{III} is taken into consideration and that an additional model constant has been applied. One of the main reasons why Colding equation gives a greater model error is that it does not take into consideration the change in the working material's characteristics resulting from strain hardening during the cutting process. The model error connected to equation 6 is believed to depend mostly upon the fact that the extent of deformation ε_{III} is assumed to be constant throughout the time the cutting tool is in use. A mean value for the extent of deformation ε_{III} has been used during the entirety of the lifetime of the cutting tool.

The model error when calculating a cutting speed for a given wear time is less than the equivalent error when calculating wear time for a given cutting speed (see tables 9 and 10). This can be explained by the fact that a too limited number of cutting speeds were used during all the tests and that a cutting speed of 250 m/min is dominant in the basis of this study. In this case, Colding equation gives a lesser model error than equation 6, which can be explained by the fact that Colding equation is primarily developed for the purpose of determining cutting speed for a given lifetime (see equation 1). The determination of the constants in each model with respect to h_e has not been carried out, i.e. the establishment of h_e for a given lifetime T and cutting speed v_c.

The length of tool life under production conditions is better than under laboratory conditions due to the fact that the forged materials have significantly better cutting characteristics than the bar materials. The more difficult cutting characteristics of the bar materials are explained by their higher content of free carbides in the form of TiC and NbC as seen in figure 14. The forged materials also have a more restrictive material specification than what the standard for Alloy 718 normally allows.

When establishing the model constants for Colding equation and the ShortCut-wear-model according to equation 6, it is necessary to have a starting value for the iteration included in the least square method. A number of various minima for the model error can be obtained depending on the start values given.

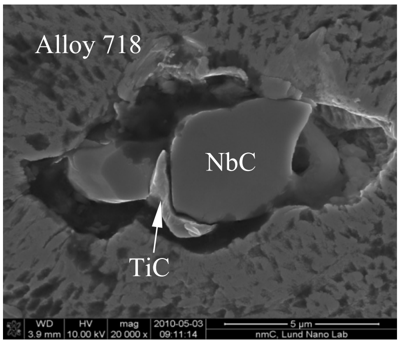

Figure 14 *Free carbides in the form of TiC and NbC in Alloy 718, (20 000x).*

The start values for Colding equation are largely based on established experiences. A model as shown in equation 6 is based upon physical performance where an ideal tool life is reduced because of abrasive wear resulting from the effects of mechanical, thermal and tribological load. This principle construction means that the constants $k_1 - k_6$ have to be positive. At the same time, it can be stated that several constants, among them k_2 and k_6, describe the strength of the thermal load which leads to varying start values in the iteration, which in turn can lead to varying start values for the constants at the same as the model error has a minimum. The values of the positive constants presented give the lowest model error. The connection between the constants means that the constant k_2 cannot directly be compared with Taylor's $1/\alpha$ as seen in equation 3.

The Shortcut-wear-model results in a maximum length of tool life for a given value for h_e (see figure 13) due to the balance between the working material's strain hardening and increased thermal and mechanical load. For somewhat larger values of $0.10 < h_e < 0.20$ [mm] both models presented will approach each other as seen in figure 12 as the effect of strain hardening decreases. In general, the validity of the models can be described according to table 11. During the machining of Alloy 718 with hard metal cutting tools for example, the effect of the working material's strain hardening will have a limited influence on the length of tool life, as it is usual that $h_e > 0.10$ [mm]. It is however always problematic to apply models outside of the scope of the cutting data which has been used to calculate the model constants.

Table 11 *Area of validity for each model with regard to the equivalent chip thickness h_e.*

Shortcut-Wear-Model	$h_{1min} < h_e < 0.12$ [mm]
Colding equation	$h_e > 0.10$ [mm]

Depending on the extent of deformation ε_{III} , different limits will be obtained for h_e; reduced values for ε_{III} will lead to Colding equation having increased legitimacy for lower h_e values.

8. Further Studies

The following additional work is ongoing or planned:

1. Statistical analysis to explain the distribution that exists within experimental tool lifetimes determined under production conditions (see figure 9), [26, 31].
2. The use of a variable, extent of deformation ε_{III} in equation 6 (Shortcut-Wear-Model).
3. Analysis of how the extent of deformation ε_{III} is affected by other parameters, such as, for example, cutting speed and edge type (r_β).
4. Calculation of the model error $E_{he,P}$ and $E_{he,L}$.

Acknowledgements

This work forms part of the Shortcut project financed by SSF/ProViking, which is also included in the strategic effort SPI (Sustainable Production Initiative). The authors would like to express their gratitude for the support they have received from Bengt Högrelius and Sören Hägglund at SECO TOOLS in Fagersta. We would also like to thank nmC, Lund nanoLab at the University of Lund for granting us access to their laboratory equipment.

References

[1] Dvir Shabtay, Moshe Kaspi, Optimization of the machining economics problem under the failure replacement strategy, Optimization, Int. J. Production Economics 80 (2002) 213-230.

[2] Moshe Caspi, Dvir Shabtay, Optimization of the machining economics problem under the periodic control strategy, Int. J. PROD. RES, 2001, Vol. 39, NO. 17. 3889-3900.

[3] R. G. Fenton, N. D. Joseph, The Effects of the Statistical Nature of Tool-Life on the Economics of Machining, Tool Des Res Vol.19, pp 43-50, Pergamon Press Ltd, 1997. Printed in Great Britain.

[4] Taylor F.W. On the Art of Cutting Metals, Trans. ASME 28, 31, 1907.

[5] Martin Noel, Bernard F. Lamond, Manbir S. Sadki, Simulation of random tool lives in metal cutting on a flexible machine, International Journal of Production Research, Vol. 47, No.7,1 April 2009, 1835-1855.

[6] Ramalingam S. 1977. Tool life distributions. part2: Multiple-injury tool-life model. Journal of Engineering for Industry, Transactions of ASME, 99, 523-530.

[7] Wiklund,H.,1988. Bayesian and regression approaches to on-line prediction of residual tool-life. Quality Reliability Engineering International,14,,303-309.

[8] Wager J. G. and Barash M. M. 1971. Study of distributions of the tool life of HSS tools. Journal of Engineering for Industry. Transactions of ASME, 93, 1044-1050.

[9] Rosseto,S. and Zompi,A.,1981.A stochastic tool-life model. Journal of Engineering for Industry, Transactions of ASME, 103, 126-130.

[10] Kaspi M. and Shabtay D. 2003. Optimization of the machining economics problem for multistage transfer machine under failure, opportunistic and integrated replacement strategies. International Journal of Production Research, 41, 2229-2247.

[11] Ramalingam S. and Watson J.D. 1977. Tool-life distributions ,part 1: single-injury tool. life model. Journal of Engineering for Industry, Transactions of ASME, 99, 519-522.

[12] Liu P.H. Makis V. and Jardine A. K. S. 2001, Scheduling of the optimal tool replacement times in a flexible manufacturing, IIE Transactions, 33, 487-495.

[13] Colding B. (1981) The Machining Productivity Mountain and its Wall of Optimum Productivity 9th NAMRC p. 37.

[14] Hägglund S. Global Optimaization of Cutting Processes, licentiate report Chalmers University of Technology, ISSN 1651-0984, Göteborg 2002.

[15] Ståhl J-E, Högrelius B. Skärbarhet och skärdata för arbetsmaterialet Maxthal, Forskningsrapport redovisad inom ramen för SSF Proviking-Shortcut, Fagersta, Lund 2006 (In Swedish).

[16] R. Vilenchich, K. Strobele and R. Venter, 13th IMTDR conf. 261.

[17] J. Taylor, Proc. 18th IMTDR conf. 379.

[18] J. Taylor, Proc. 8th IMTDR conf. 487.

[19] C. Sikdar, S. S. Babu, A. B. Chattopadhyay and V. C. Venkatesh, Effect of bevelling of carbide turning inserts on chip formation and cutting forces. Journal of Materials Processing Technology, 28 (1991) 15-24 Elsevier.

[20] A. Albin, M. Nalbant, A. Taskesen, The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools, Materials and Design 28(2007), 2518-2522.

[21] Khamsehzadeh H. Behaviour of ceramic cutting tools when machining superalloys. Ph.D. thesis, University of Warwick 1991 p. 125.

[22] Wang Z M. Titanium Alloys and theirs machinability with coated carbide inserts. Ph.D. thesis, South Bank University, London, UK; 1997, p. 78-9, 247.

[23] Bhattacharya S. K. Pashby, I. R, Ezugvwu E. O. Machinability of Inconel 718 and Inco 901 Superalloys with Sic-whisker reinforced Al_2O_3 composite ceramic tools Prod. Eng. 1987: 17-81.

[24] Bhattachary S. K. Jawid A, Levis M. H. Behaviour of sialon ceramic tools when machining cast iron. In Proceeding of the 12th North American manufacturing research conference; 1984 p. 265-70.

[25] Viktor. P. Astakov, The assessment of cutting tool wear, International Journal of Machine Tools & Manufacture 44(2004), 637-647.

[26] Ståhl J-E. Statistisk analys av keramiska verktygs livslängd vid svarvning i Alloy 718 under industriella produktionsförhållanden, Rapport inom ShortCut, SSF/ProViking Lund 2011 (In Swedish).

[27] Woxén R. Theory and an Equation for the Life of Lathe Tools, Ingenjörsvetenskapsakademin, Handling 119, Stockholm 1932.

[28] Woxén R. Teknisk Tidskrift, Häfte 4 April 1931 (In Swedish).

[29] Ståhl J-E. Metal Cutting – Theory and Models, Lund University, Lund Sweden 2011.

[30] Byrne G. A New Approach to the Theoretical Analysis of Surface Generation Mechanisms in Machining, Annals of the CIRP Vol. 41/1/1992.

[31] Avdovic P. Nicolescu M. Ståhl J-E. Weibull analysis of tool life when machining Alloy 718, Report within ShortCut, SSF/ProViking Lund, Finspång, Stockholm 2011 (under publication).