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Tool Life and Wear Modelling in Metal Cutting, Part 3 - Assessment of Different Tool Life Models

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Abstract

In this work, eleven different combinations of work piece materials and tool grades have been evaluated in wear test when turning with cemented carbide insert. The most commonly used tool life models such as the Taylor model, the Extended Taylor model, the Coromant Turning model version 1 and the Colding model have been tested on the data and their accuracy is presented. The well-known Taylor model proves to have a limited ability to reproduce the data. The most accurate model is the Colding model, with an average model error of approximately 4.0 % and Woxén equivalent chip thickness proves to work well for all presented tool life models. This work also discusses the models ability to reproduce cutting data for finishing operations and possible limitations when extrapolating the models for smaller chip thicknesses.

Keywords: Machining, Tool life, Turning, Taylor Tool Life Model, Colding Equation

1. Introduction

The ability to predict and model tool wear and excepted tool life in metal cutting is of great importance to secure robust, predictable and stabile manufacturing systems. Tool life models are used by tool manufactures to assist end users with optimal cutting data published in catalogues or online web assistance applications. Dependent on the tool users' needs a manufacturing process can be optimized either for maximum productivity or to achieve the lowest production cost possibly. Nevertheless, a model dependent on cutting speed v_c, depth of cut a_p, feed f and tool geometry describing the expected time the tool can be engaged with the work piece material producing parts within a given quality is needed. A schematic outline of a generic tool life model based on curve fitting of measured data is presented in ***Fig. 1***.

A number of different tool life models have been published [1-6] and are being used in various software applications assisting operators, production planers, tool manufactures etc. selecting and/or publishing varying quality of cutting data. The aim of this work is to analyse the most commonly used tool life models and test their performance on different work piece materials, covering materials used in large quantities by the industry such as construction steels from low alloy to high alloy, stainless steel and cast iron. The selected tool material being used in this work is cemented carbide inserts, the most commonly used tool material in industrial applied metal cutting [7].

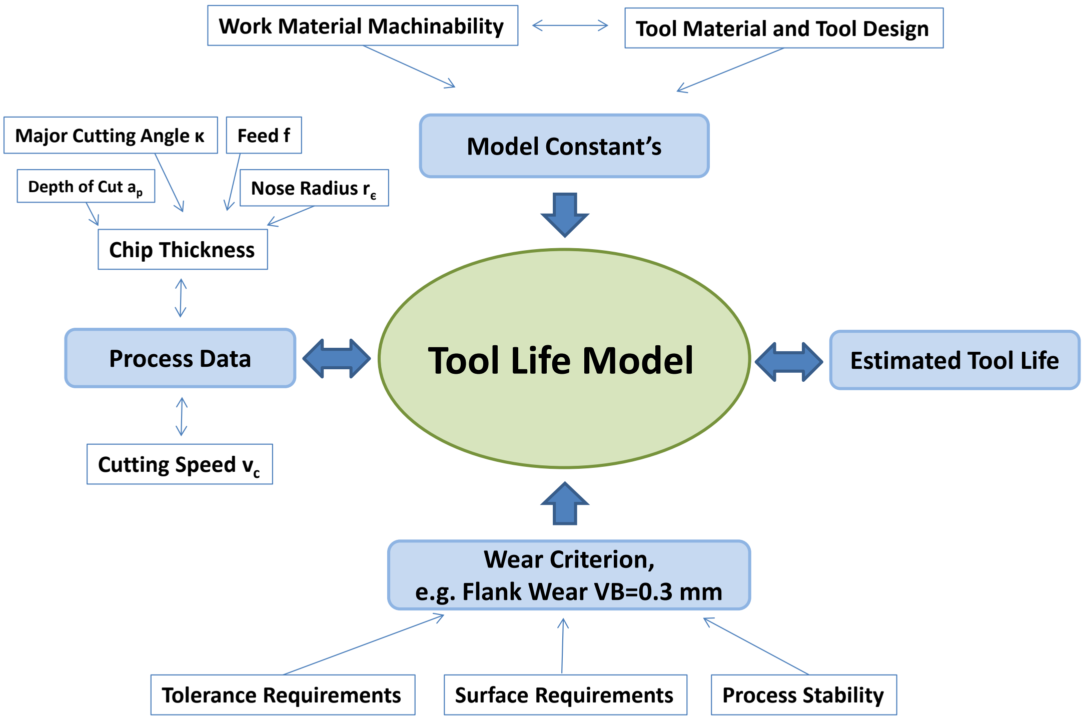
Work Material Machinability
Tool Material and Tool Design
Major Cutting Angle κ
Feed f
Model Constant's
Depth of Cut a_p
Nose Radius $r_ε$
Chip Thickness
Process Data
Tool Life Model
Estimated Tool Life
Cutting Speed v_c
Wear Criterion,
e.g. Flank Wear VB=0.3 mm
Tolerance Requirements
Surface Requirements
Process Stability

Fig. 1*: The principal of a generic tool life model based on curve fitting of measured data.*

2. Background

The Taylor's Equation for Tool Life Expectancy, formulated by F. W. Taylor 1906, provides a good approximation of tool life for varying cutting speed v_c [1]. The Taylor equation is presented in (1) where v_c is the cutting speed, T is the expected tool life and m and C_T are constants derived from measured data analytically or computed by curve fitting using the least squared method.

$$v_c \cdot T^m = C_T \qquad (1)$$

When examining tool wear for a specific metal cutting process, speed will be the most influential factor while the applied feed f will be of less importance to the tool life. The depth of cut a_p will only play a minor role on the tool wear as the load is distributed over a larger part of the tool but load per unit length will be the approximately the same [8]. To allow for a better tool life estimation, a number of suggested extensions to the Taylor's equation have been published [3-6]. One of the most commonly used extended Taylor, taking in to account the varying equivalent chip thickness h_e or feed f and depth of cut a_p by adding two more constants, p and q are presented in equation (2) (3).

$$v_c \cdot f^p \cdot {a_p}^q \cdot T^m = C_T \qquad (2)$$

$$v_c \cdot {h_e}^p \cdot T^m = C_T \qquad (3)$$

Were equivalent chip thicknesses h_e (4) as defined by R. Woxén [4] is a function of feed f, depth of cut a_p, major cutting angel κ and the nose radius of the tool r.

$$h_e = \frac{a_p \cdot f}{\frac{a_p - r(1-cos\kappa)}{\sin\kappa} + \kappa \cdot r + \frac{f}{2}} \qquad (4)$$

Another possible tool life equation is the Coromant turning model version 1 (5)

$$v_c = 10^{\frac{vca * f^2 + vcb \cdot f + vcc}{(\frac{TL_{act}}{TL_{nom}})^m}} \qquad (5)$$

Where vca, vcb, vcc, and m are constants and TL_{act} is the given tool life for a predefined wear criterion. TL_{nom} is the nominal tool life, in this work defined as 15 min. The feed f can be replaced with the chip thickness h_m (6) or equivalent chip thickness h_e (7) as defined by Woxén to account for varying major cutting angle κ.

$$v_c = 10^{\frac{vca \cdot {h_m}^2 + vcb \cdot h_m + vcc}{(\frac{TL_{act}}{TL_{nom}})^m}} \qquad (6)$$

$$v_c = 10^{\frac{vca \cdot {h_e}^2 + vcb \cdot h_e + vcc}{(\frac{TL_{act}}{TL_{nom}})^m}} \qquad (7)$$

Where the chip thickness h_m is defined as a function of the feed f and the major cutting angle κ (8).

$$h_m = f \sin(\kappa) \qquad (8)$$

The Colding equation, published by B. Colding 1981, [9] is as the pioneering work by Taylor, essentially based on empirical curve adjustments made between tool life and cutting data (9). The equations can be regarded as an extension of the Taylor equation which can be clearly observed in studies of Lindström's reformulation of the Colding equation [10]. The Colding equation has proven to work very well when modelling tool life, as shown by the authors [8, 11], where the average model error in some cases has proven to be less than 1 %.

$$v_c = e^{[K - \frac{(\ln(h_e) - H)^2}{4 \cdot M} - (N0 - L \cdot \ln(h_e)) \cdot \ln(T)]} \qquad (9)$$

The Colding equation is based on five constants K, H, M, N0, and L where cutting speed v_c is a function of tool life T and equivalent chip thickness h_e.

3. Experimental setup and calculations

A total of seven different work materials and three different tool grades were evaluated when turning using industry standard coated cemented carbide inserts. Tool grade A being a wear resistant grade, tool grade B a medium grade and tool grade C being a tougher grade. C 45E and 42 CrMo4 were tested with all three tool grades A, B and C and the other materials were tested with tool grade A, resulting in eleven different tool-work material combinations. Five tests or more were performed for each workpiece and tool material combination by varying cutting data covering a window of cutting data suitably for the tool geometry and chip breaker. A wear criterion was chosen, such as maximum flank wear VB_{max} = 0.3 mm or maximum depth of crater wear KT_{max} = 0.5. The cutting data as well as the time the tool was engaged with the work piece until reaching the wear criterion were recorded. The tool was removed from the tool holder and the attained wear was measured using a standard optical microscope. The work piece materials used are presented in **Table 1**. Workpiece material in metal machining are divided in to six different ISO groups, P (steel), M (stainless steel), K (cast iron), N (aluminium), S (heat resistant alloys) and H (hardened steel). In this work three material groups have been evaluated; P, M and K.

Table 1: *Workpiece materials evaluated.*

Workpiece	Material group
235JRG2	P
16 MnCr 5	P
C 45E	P
42 CrMo 4	P
100 Cr 6	P
X5 CrNi 18 9	M
EN-GJS-500-7	K

By using a least squares method through the built-in feature solver in the program MSExcell© the collected data was fitted to each tool life model and model constants thereby calculated. The models evaluated are presented in **Table 2**.

Table 2: *Tool life models.*

Model	Eq. no.	Base	Number of constants
Taylor	1	-	2
Extended Taylor	2	f, a_p	4
Extended Taylor	3	h_e	3
Coromant turning ver. 1	5	f	4
Coromant turning ver. 1	6	h_m	4
Coromant turning ver. 1	7	h_e	4
Colding	9	h_e	5

The models were then evaluated and rated based on the mean squared error ε_{err} between experimentally attained $v_{c,\ exp}$ and modelled cutting speed $v_{c,\ mod}$ for each model and work piece material combination. The error includes all possible errors such as variations in tool and work material, errors in measuring instruments and of readings as well as vibrations of the tool-work system and the limitations of the chosen tool life model.

When cutting data is normally presented, data to the left of the h-line, as defined by Colding, [12] is extrapolated to avoid decreasing cutting speed for a decreased chip thickness, ***Fig. 2***. However, there has been now scientific proof published showing this is the actual behaviour of the tool wear in i. e finishing operations or a limitation of the chosen tool wear model giving an un-valid model left of the h-line [8]. In this work, the extended Taylor and the Coromant turning version 1 models are presented as "levelled" (extrapolated left of the h-line) and the Colding models are presented both as unchanged "plain" and as "levelled".

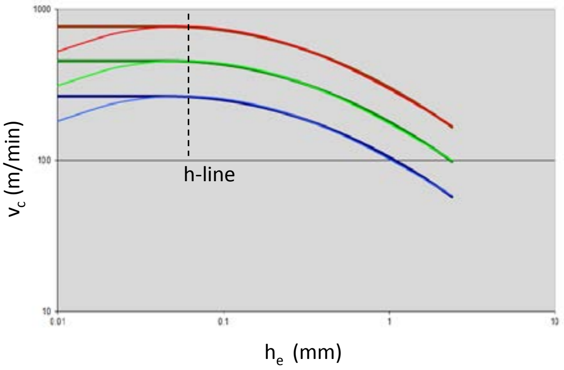

Fig. 2: *Example of the Coromant model "levelled" to the left of the h-line and the Colding model un-modified, "plain", plotted for the same set of cutting data.*

4. Results

Table 3: *The resulting error for each tool life model, work material and tool grade combination where green represents the lowest error, light green the second lowest and yellow the third lowest error.*

Grade	Workpiece	ISO	Colding		Coromant Turning ver. 1			Taylor		
			h_e (eq. 9)		f (eq. 5)	h_e (eq. 7)	h_m (eq. 6)	N/A (eq. 1)	a_p, f (eq. 2)	h_e (eq. 3)
			Plain	Levelled	Levelled	Levelled	Levelled		Levelled	Levelled
A	235JRG2	P	4.4 %	6.9 %	7.5 %	7.5 %	7.5 %	18.2 %	11.6 %	12.6 %
A	16 MnCr 5	P	2.2 %	3.9 %	3.9 %	3.9 %	3.9 %	19.0 %	9.3 %	10.8 %
A	C 45E	P	4.7 %	4.7 %	4.5 %	4.8 %	4.5 %	20.4 %	5.9 %	5.7 %
B	C 45E	P	5.1 %	5.1 %	5.2 %	5.2 %	5.2 %	25.2 %	5.7 %	6.2 %
C	C 45E	P	2.5 %	2.6 %	2.4 %	2.6 %	2.4 %	18.2 %	21.3 %	7.8 %
A	42 CrMo 4	P	3.1 %	6.1 %	7.5 %	7.5 %	7.5 %	18.9 %	11.8 %	12.8 %
B	42 CrMo 4	P	5.4 %	5.8 %	6.1 %	6.1 %	6.1 %	17.8 %	9.1 %	10.1 %
C	42 CrMo 4	P	5.6 %	10.6 %	11.7 %	11.2 %	11.7 %	18.8 %	16.8 %	16.2 %
A	100 Cr 6	P	4.7 %	9.5 %	10.1 %	9.7 %	10.1 %	15.6 %	13.4 %	14.2 %
A	X5 CrNi 18 9	M	3.9 %	11.8 %	12.6 %	12.0 %	12.6 %	15.9 %	19.8 %	15.8 %
A	EN-GJS-500-7	K	2.6 %	2.7 %	3.1 %	3.0 %	3.1 %	8.5 %	6.7 %	7.3 %
	Average		**4.0 %**	**6.3 %**	**6.8 %**	**6.7 %**	**6.8 %**	**17.9 %**	**11.9 %**	**10.8 %**

Table 3: shows the model error for each material and tool life model combination. Also the average error for each model is presented. The best performing model in nine out of eleven materials is the plain Colding model (9) that has not been levelled. The model has an average error of 4.0 % and the highest error for a specific material is 5.6 %. The standard Taylor model (1) is the model with the highest average model error of 17.9 %, as expected as it has only two model constants and does not include the theoretical chip geometry. The highest model error is found for the Taylor model modelling tool life for EN C45E with an error of 25.2 %.

It can be noted that the extended Taylor (2, 3) and the Coromant turning model version 1 (5, 6, 7) both performs best in this test when using Woxén's equivalent chip thickness h_e as base. The extended Taylor equation based on a_p and f (2) has 4 constants and the extended Taylor equation based on h_e (3) has 3 constants and still performs better; 11.9 % resp. 10.8 % average error.

By introducing a levelled Colding model the error increases for these specific sets of data by 2.3 % and for the M2 stainless steel material the error is almost 3 times higher than for the un-modified plain Colding model.

Table 4: shows how the standard Taylor (1) and the two extended Taylor models (2, 3) performs if the more extreme data points are excluded and the span of h_e is decreased. The model error is decreased, as can be expected for the models with fewer model constants. It can be noted that the two extended models (2, 3) performs identical when the error is presented with only one decimal.

Table 4: *The resulting error for Taylor and extended Taylor when only modelling on the mid-range data points.*

Grade	Workpiece	ISO	Taylor (mid-range)		
			N/A (eq. 1)	a_p, f (eq. 2)	h_e (eq. 3)
A	235JRG2	P	13.5 %	0.6 %	0.6 %
A	16 MnCr 5	P	10.4 %	2.7 %	2.7 %
A	C 45E	P	15.0 %	4.9 %	4.9 %
B	C 45E	P	17.3 %	6.2 %	6.2 %
C	C 45E	P	13.2 %	2.4 %	2.4 %
A	42 CrMo 4	P	14.1 %	2.9 %	2.9 %
B	42 CrMo 4	P	11.6 %	6.5 %	6.5 %
C	42 CrMo 4	P	11.1 %	6.6 %	6.6 %
A	100 Cr 6	P	6.6 %	5.1 %	5.1 %
A	X5 CrNi 18 9	M	8.7 %	2.6 %	2.6 %
A	EN-GJS-500-7	K	2.7 %	2.0 %	2.0 %
	Average		**11.3 %**	**3.9%**	**3.9%**

5. Discussion

Modelling this collected data for a wide range of different work piece materials using different published tool life models gives a clear indication of the models performance and reliability when compared. The Colding model (9) gave the smallest average model error of 4.0 %, which can be regarded as very good considering that the data was collected in an industrial environment using optical microscopy to measure the developed tool wear. The limitations with both the standard Taylor equation (1) and the extended versions (2, 3) are shown quite clearly in ***Table 3***. The standard Taylor can only model the data with an average error of 17.9 % and the extended version 11.9 % and 10.8 % respectively. ***Table 4*** shows how dependent the Taylor models are of a limited range in cutting depth and feed. When the range is decreased the standard Taylor model error in this tests are 11.3 % and for the extended versions 3.9 %, a decrease of approximately 6 % each. To improve the cutting data selection incrementally for an existing production process as suggested by Schultheiss et al. [13] the standard Taylor model (1) may very well be a good tool life model as the potential change in chip thickness is small and limited by the type of operation and pre-defined tool selection. The number of data points needed to create the model is 2-4 defined by the number of model constants. To limit the number of tests needed is important as it adds a cost of work material, tool material, machine time and operator time to create the data for the tool life model, thus making both the standard Taylor (1) and extended Taylor models (2, 3) feasible. It should be noted that the extended Taylor with h_e (3) as base only requires a minimum of three data points and still preforms better than the extended Tylor based on a_p and f (2). The Woxén equivalent chip thickness manages to take the energy balance of a_p and f in to account in one variable and thereby reduces the number of model constants.

As for a tool maker creating tool life models for different combinations of work piece material and tool material as well as tool geometry and setup it is of great importance that the model can handle a large range of h_e to limit the number of tests and models. A normal range of h_e can be of the magnitude of 10 times the smallest h_e when covering ruffing to fine finishing operations. In this type of applications the Coromant model and the Colding model outperforms the more traditional Taylor models. It should also be noted that for this set of data, and in particular for the high alloy steels and the stainless steels, the plain Colding model outperformed the rest. The levelled Colding model also fails in modelling high alloy steels and stainless steel compared to the plain Colding. If the user chooses to extrapolate the result as straight lines to the left of the h-line as in ***Fig. 2*** one should be very careful publishing cutting data for fine finishing operations with smaller chip thicknesses. One possible reason for the models preforming less well in high alloy steels and stainless steel is the possible increase of work hardening on the surface from the previous cut which would have a bigger relative impact when machining with small h_e and then be compensated in only the plain Colding model. High alloy steels and stainless steels have been noted to have a bigger tendency to be affected of the previous machining, thus leaving a work hardened surface [14].

The collected data being used in this work was not primarily collected to evaluate different tool life models but was collected when evaluating new types of tool material. The ratio between the tool nose radius and depth of cut was held constant throughout the testing which might not be optimal when evaluating tool models. It is possible that the Colding model in particular, but also all tool life models based on Woxén equivalent chip thickness, would perform even better than the other tool life models as Woxén equivalent chip thickness is designed to handle different theoretical chip geometry from a tool wear and energy prospective.

6. Conclusions

- Wear test in eleven different work material and tool grade combinations with cemented carbide tools when turning was successfully preformed. The collected data was used to evaluate the accuracy of the most commonly used tool life models such as the standard Taylor model, the extended Taylor model, the Coromant model and the Colding tool life model.
- The different Taylor models are relatively accurate when used with caution and in smaller ranges of selected chip thickness.
- All models preform most accurate when using the Woxén equivalent chip thickness as base for the tool life model. When extended Taylor is used, it produces more accurate results when based on feed and depth of cut for seven out of the eleven tests compared to the model based on equivalent chip thickness. The average error for all eleven tests was lower when using equivalent chip thickness compared to the model based on feed and depth of cut even though a forth constant is introduced in the latter.
- The best preforming model is the Colding model which is most accurate in nine out of eleven combinations and has the lowest model error. The model that is not levelled left of the h-line is the most accurate.
- High alloy steels and stainless steels are most affected when using levelled models. This might be an effect of work surface hardening, which is greater in the previously cut surface for this materials.

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