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MATERIALS
ENGINEERING

Tool life in stainless steel AISI 304: applicability of Colding's tool life equation for varying tool coatings

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Abstract. The current paper investigates the applicability of Colding's equation for modelling tool life while turning stainless steel AISI 304. The turning inserts used in the study together with the work material displayed an irregular wear behaviour, thus making it impossible to use flank wear as the tool wear criterion. Failure of the tool tip was thus used as an alternative criterion. The obtained tool life model is shown to have some amount of extrapolative power and a potential for modelling tool behaviour outside the experimentally tested cutting parameter range by using the constant K to adjust Colding's model for different tool coatings. Solid carbide (WC–Co) inserts with constant cutting geometry and with five different PVD coatings were used in the machining trials. The results will help minimize the amount of work material and test time as well as tools needed to obtain reliable machining data.

Key words: longitudinal turning, stainless steel, tool life, Colding's equation, carbide inserts, PVD coatings.

1. INTRODUCTION

To be able to predict and describe the tool life and, as a result, determine optimal cutting data considering manufacturing costs in industrial production is of great importance. Cutting data commonly involve the cutting speed v_c, feed f, and depth of the cut a_p. The tool life T describes the length of the time the tool can be engaged with the workpiece without being worn out in respect to such parameters as for example risk of tool failure, deteriorated surface quality, or geometrical dimensions outside the given tolerances. A wear criterion is commonly decided with regard to factors such as the maximum allowed size of the flank wear, i.e. $VB < 0.3$ mm.

A wear model describes the relation between the engagement time t_i and the attained tool wear, such as flank wear VB, for varying cutting data or cutting conditions. Examples of previously published tool wear models include models published by Archard [1] and Usui and Shirakashi [2]. Tool life models have been published by several authors, among others by Taylor [3] and Colding [4]. Tool wear models such as those published by Archard [1] and Usui and Shirakashi [2] contain hard to determine constants that are established as results from mechanical, thermal, tribological, and chemical loads. Models describing the tool life as a function of cutting data according to Taylor [3] and Colding [4] require that tests should be made until the determined tool wear criterion is fully reached. The minimum number of trials that must be performed is determined by the number of constants included in the

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given model. Colding's equation has a good validity in many applications according to Hägglund [5]. Further studies show that under favourable conditions the cutting speed v_{c} can be modelled with less than 1% error for a given tool life by using Colding's equation [6].

The aim of the work reported in this article was to study the possibility of using Colding's tool life equation in evaluating different tool coatings and its performance for varying cutting data while longitudinally turning AISI 304 stainless steel. For this material, wear propagates rapidly after a given engagement time, often resulting in tool failure. Also, through using the constant *K* to adjust Colding's model for different tool coatings, the possibility of using a limited number of tests and its effect on the model error was studied.

2. COLDING'S MODEL

Colding's tool life equation is based on empirical curve adjustments made between tool life and cutting data. The equation can be regarded as a derivation of Taylor's well-known equation [3], which is clearly seen through Lindström's reformulation of Colding's equation [7].

The widely used generalized Taylor's equation contains two empirical constants. When using logarithmic scales, sets of straight, parallel lines are attained in the cutting speed–time (v_{c}–T) plane. Colding [4] noted that when this approach is used for a wide range of machining data, the accuracy of the tool life estimates is poor, except for the experimental cutting data on which the equation was based. An ideal polynomial relationship containing nine constants was proposed by Colding in 1959 [4]. Later, in 1981, Colding [8] presented a new equation containing five constants. The two described tool-life relationships with two and five constants are presented below (Eqs (1) and (2)). In the equations x is the theoretical chip thickness, y is the cutting speed, and z is the tool life, all in log–log scale, and b, c, d, h, and k are the model constants.

$$k+y+bx+cx^2+dz+hxz=0, \tag{1}$$

where $x=\ln h_e$, $y=\ln v_{\mathrm{c}}$, and $z=\ln T$,

$$k+y+bx+dz=0, \tag{2}$$

where $x=\ln h_e$, $y=\ln v_{\mathrm{c}}$, and $z=\ln T$.

Colding's equation can be rewritten in terms of a parabolic equation shown by Eq. (3). For a given combination of the cutting tool and workpiece, this equation describes the relationship between the tool life T of the cutting tool, the cutting speed v_{c}, and the equivalent chip thickness h_e with five constants K, H, M, N_0, and L. The equation is, according to Colding [9], based on curve fitting and adjusting on measurement points.

$$v_{\mathrm{c}}=e^{\left[K-\frac{(\ln(h_e)-H)^2}{4\cdot M}-(N_0-L\cdot\ln(h_e)\cdot\ln(T))\right]}. \tag{3}$$

Woxén [10] introduced an equivalent chip thickness h_e, Eq. (4), for turning operations with the purpose of using it as a characteristic parameter for describing the mean theoretical chip thickness along the tool nose.

$$h_e=\frac{A}{l_{\mathrm{c}}}\approx\frac{a_p\cdot f}{\dfrac{a_p-r(1-\cos\kappa)}{\sin\kappa}+\kappa\cdot r+\dfrac{f}{2}}, \tag{4}$$

where A is the chip area, l_{c} is the length of the portion of the edge line that is active in the cutting process, r is the nose radius, and κ is the major cutting edge angle.

Additional relationships for calculating the equivalent chip thickness have been published by several other authors including Bus et al. [11], Hodgson and Trendler [12], and Carlsson and Stjernstoft [13]. A more accurate model, which is valid also for finishing operations where the feed and depth of the cut can be of the same magnitude, was published by Ståhl and Schultheiss [14]. However, at cut depths larger than the tool nose radius their model provides almost identical results as compared to Woxén's model. This was the reason for choosing in this investigation the simplified definition according to Woxén.

Colding's equation should be used with considerable caution when extrapolating outside the cutting data interval where the measurement points were taken due to its generic, empirical construction. As Colding's equation contains five constants $C_i=(K,\ H,\ M,\ N_0,\ L)$, at least five separate experiments are required to determine their values. Colding's constants are preferably obtained through curve fitting onto empirical data while trying to minimize the model error as compared to empirical data. The use of Colding's equation and its adaptation to different machining operations were further investigated and evaluated by Hägglund [5], who illustrated the applicability of the equation in a wide range of different conditions.

3. EXPRIMENTS AND CALCULATION OF MODEL CONSTANTS

The experimental trials were conducted through longitudinal turning experiments while machining stainless steel AISI 304. Coated cemented carbide cutting inserts were used as study subjects. Cutting fluid was used constantly throughout the testing. A total of 13 full trials were carried out. Of these 13 trials, data from 7 attempts were used as the basis of the tool life modelling. To evaluate the other coated inserts, eight more tests were performed. In total five different coatings were evaluated: two commercially available and three experimental. Tool lives obtained in the initial tests and the respective information about the coatings are shown in Table 1.

Table 1. Measured tool life during the initial test with five different tools at $v_c = 250$ m/min, $f = 0.275$ mm/rev, and $a_p = 1.5$ mm

Tool	Tool life, min	Coating (PVD)	Coating thickness, µm	Adhesion**
A	9.8	P185	1.71	HF 3
B	7.07	P181	1.40	HF 3
C	4.67	Commercial		
D	2.44*	Commercial		
E	0.37*	P176	1.71	HF 3

* Excluded from further analysis.
** Daimler–Benz adhesion method.

The two excluded tool coatings either experienced large plastic deformation or a rapid tool failure at the chosen cutting data. Figure 1 shows the tip of the excluded tool E after tool failure.

During the conducted experiments, cutting force components were monitored in three directions and recorded with a Kistler piezo-electric cutting force measurement system. Cutting force components as functions of the engagement time T were monitored on-line during the experiments. In addition the cutting tools were depicted in 3D using an optical measurement system to ensure that no large plastic deformation had occurred. Set-up data for all tool life experiments are presented in Table 2. Figure 2 depicts the measured cutting forces for a selected test.

Evaluation of the model is based on the mean linear error ε_{err} (in % according to Eq. (5)) between the experimentally attained $v_{\text{c,exp}}$ and the modelled cutting speed $v_{\text{c,mod}}$ for each test.

$$\varepsilon_{\text{err}} = \frac{100}{n} \cdot \sum_{j=1}^{j=n} \left| \frac{v_{\text{c,exp}_j} - v_{\text{c,mod}_j}}{v_{\text{c,exp}_j}} \right|. \tag{5}$$

Colding's constants were determined using a least squares method through a built-in feature in the Mathcad 15 software. The cutting data and the corresponding tool life are presented in Table 3. Colding's constants were then calculated by minimizing the average error and keeping the error smaller than 4% for the two last sets of cutting data. These two cutting data points were then used to extrapolate and verify Colding's constants for tools B and C by shifting the constant K.

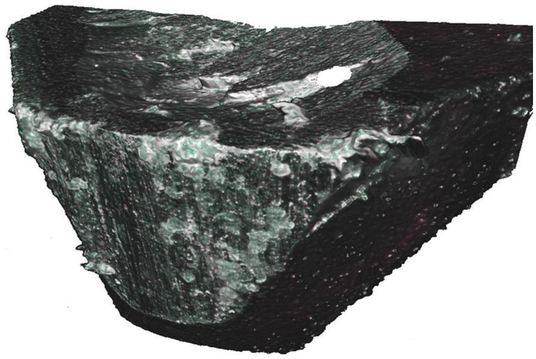

Fig. 1. Micrograph of tool D after 0.37 min of machining.

Table 2. Data on the set-up used in the experiments

Workpiece material:	AISI 304
Workpiece geometry:	Length: 500 mm
Tool, insert:	Cemented carbide, insert code key CNMG431MJ
Lathe:	SMT 500
Condition:	Cutting with cutting fluid
Tool edge radius:	$r_\beta = 20$–25 µm
Clearance angle:	$\alpha = 6°$
Reference wear:	$VB = 0.30$ mm, or tool failure

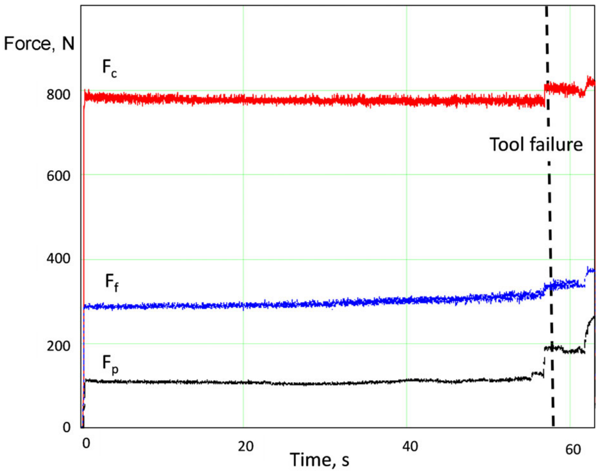

Fig. 2. Development of the cutting force components: tangential (F_c), axial (F_f), and radial (F_p) forces prior to and after tool failure for one test.

Tool life tests were performed with tools B and C for the two last cutting data points, which had previously been tested with tool A. While keeping the constants H, M, N_0, and L fixed and solving for a new

Table 3. Input data to calculate Colding's model constants, obtained using tool type A

Test	T, min	v_c, m/min	a_p, mm	f, mm/rev	h_e, mm
1	10.03	350	1	0.150	0.115
2	1.27	350	1	0.300	0.217
3	19.7	250	1	0.225	0.168
4	2.91	250	2	0.300	0.252
5	14.43	200	2	0.300	0.252
6	9.8	250	1.5	0.275	0.221
7	5.14	275	1.5	0.250	0.202

constant K using only one cutting data point ($v_c = 250$ m/min, $a_p = 1.5$ mm, $f = 0.275$ mm/rev) new extrapolated tool life models were created for tool types B and C. The second cutting data point ($v_c = 275$ m/min, $a_p = 1.5$ mm, $f = 0.250$ mm/rev) was then used to evaluate the new models for tools B and C.

4. RESULTS AND DISCUSSION

The error of the modelled values for each measurement used for creating a Colding's model for tool type A as compared to empirical results is shown in Table 4. It can be seen that the highest individual error is 7.7%. The model error was the smallest, only 0.5%, in test number 5. The mean error is below 4%.

Table 5 shows the new Colding's constants for tool types A, B, and C where the constant K has been adjusted to fit the new tool life time in test point 6 for tools B and C. Figure 3 depicts modelled data for tools A, B, and C plotted for a tool life of 9.8 min together with the experimental data point for tool A.

To evaluate the new models of tool types B and C, a secondary test point, test 7, was chosen. The results are presented in Table 6. In tool type B the new model was able to predict the cutting speed for a chosen tool life with a relative error of 6.8%. When the original model error of 3.1% was added, the total error in this test point is 9.9%. In tool type C the total model error was 3.7% for test point 7 and the relative error was 0.6%. It would be possible to force Colding's model by using the constant K to allow for no error in test point 6. However, this would most likely only distort the error for all other possible cutting data combinations.

The new models are plotted for cutting speed v_c as a function of chip thickness h_e in log–log scale for three tool lives (1, 5, and 20 min) in Fig. 4. It is evident that the constant K has some capability of capturing the influence of different coatings on the tool life behaviour.

Table 4. Individual and mean error of Colding's model as compared to experimental data for tool A

Test	$v_{c,exp}$, m/min	$v_{c,mod}$, m/min	Error, %
1	350	343.052	2
2	350	338.826	3.3
3	250	268.938	−7
4	250	270.954	−7.7
5	200	201.016	−0.5
6	250	241.277	3.6
7	275	283.703	−3.1
		Mean error	3.88

Table 5. Colding's model constants for tools A, B, and C

Tool type	K	H	M	N_0	L	Mean error, %
A	5.955	−2.0166	0.6591	0.4316	−0.1776	3.88
B	5.902	−2.0166	0.6591	0.4316	−0.1776	N/A
C	5.836	−2.0166	0.6591	0.4316	−0.1776	N/A

N/A – not applicable.

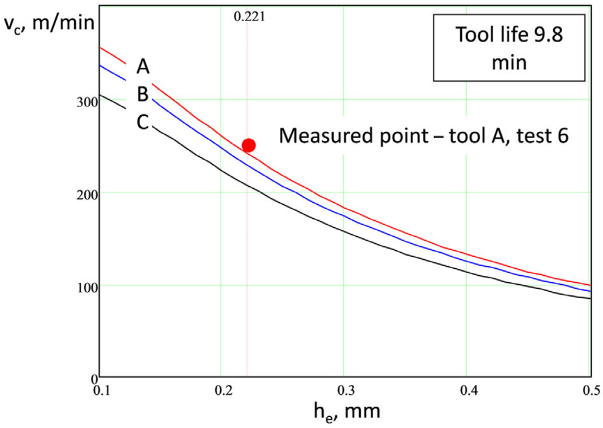

Fig. 3. Cutting speed as a function of different chip thicknesses for a tool life of 9.8 min.

Table 6. Model error for tools A, B, and C in test 6 with $v_c = 250$ m/min and reference test 7 with $v_c = 275$ m/min

Tool type	$v_{c,exp}$, m/min	$v_{c,mod}$, m/min	Error, %	$v_{c,exp}$, m/min	$v_{c,mod}$, m/min	Error, %
A	250	241	3.6	275	284	−3.1
B	250	241	3.6	275	302	−9.9
C	250	241	3.6	275	296	−0.6

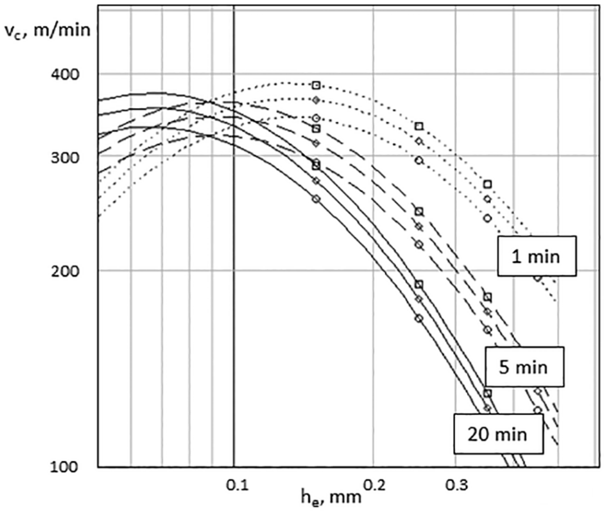

Fig. 4. Cutting speed v_c as a function of equivalent chip thickness h_e for different tool lives T in log–log scale. Tool A (□), Tool B (◊) and Tool C (○).

5. CONCLUSIONS AND FURTHER WORK

Colding's tool life equation is a well-functioning model for describing the tool detrition for different machining processes. The disadvantage of the model is that it requires at least five separate experimental trials where the full wear criterion is reached. This research shows how the five constants and the model error change for different tool coatings and the possibility for using the constant K to adjust the model for varying process conditions. Future work will include an effort on evaluating the validity of this approach varying different process conditions.

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Kõvapinnete mõju treitera teriku püsivusajale roostevaba terase AISI 304 töötlemisel, katsetulemuste kasutatavus Coldingu mudelis

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Käesolevas töös uuriti erinevate kõvapinnetega kaetud treitera terikute püsivusaega ja selle modelleerimise võimalusi vastavalt Coldingu püsivusaja mudelile. Töödeldavaks materjaliks valiti roostevaba teras AISI 304, töö eksperimentaalne osa teostati välistreimisega piki toorikut. Katsete käigus täheldati terikute kulumisprotsessi erinevust klassikalistest, standarditega kirjeldatud kulumiskriteeriumidest: nimelt ei olnud võimalik registreerida ajas püsivalt süvenevat ja ennustatavalt progresseeruvat teriku kulumist. Katsetes täheldatud teriku kulumise lõppfaas arenes väga kiiresti lõikeserva plastse deformatsiooni toimel. Artiklis on analüüsitud täheldatud plastse deformatsiooni kui ühe võimaliku kulumiskriteeriumi kasutamise võimalust teriku püsivusaja modelleerimiseks Coldingu mudeli abil.

Saadud tulemustest on võimalik järeldada, et plastsest deformatsioonist tingitud teriku hävimise nähtust on teatud tingimustel võimalik kasutada teriku kulumiskriteeriumina teriku püsivusaja modelleerimisel. On põhjust arvata, et Coldingu mudel võimaldab ekstrapoleerimise abil modelleerida erinevate kõvapinnetega terikute püsivusaega. Ühtlasi on näidatud, et pinnatud lõikeinstrumentide kasutamisel saab kõvapinde kui protsessi ühe sisendparameetri mõju kirjeldada ühena viiest Coldingu mudeli sisendparameetrist.