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Equivalent Chip Thickness and its Influence on Tool Life

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Abstract

This paper investigates the accuracy of using the Woxén equivalent chip thickness to represent feed, depth of cut, nose radius and major cutting angle in tool life modeling of machining low alloy steel in longitudinal turning. Hägglund's way of calculating the equivalent chip thickness has been used and compared to the Woxén equation. The equivalent chip thickness was held constant as the tool life was recorded for varied feeds and depths of cut. The results show that the tool life decreases for an increase of depth of cut and a decrease of feed, using the same equivalent chip thickness.

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1. Introduction

When machining, cutting data is generally optimized for maximizing the depth of cut, feed and optimizing the cutting speed considering physical constraints. Commonly, the cutting data is provided by the tool manufacturer, in different web applications. The suggested cutting data can be calculated using tool life models such as the Taylor equation, the extended Taylor equation or the Colding tool life equation [1-3]. Johansson et al. has shown that the Colding model is a well-functioning tool life model in metal cutting [4].

The Colding equation uses the Woxén equivalent chip thickness [5] to describe the theoretical chip thickness of the process, presented in eq. 1.

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

The Woxén equivalent chip thickness h_e is based on feed, f, depth of cut, a_p, nose radius, r, and the major cutting edge angle, κ. This relation allows for the geometrical entities to be represented by one entity in the Colding equation, eq. 2. The entities are h_e, tool life, T, cutting speed, v_c, and the model constants K, H, M, N0 and L. When calculating T as a function of h_e and v_c, the model will give a specific T for the selected cutting data. As h_e is based on both f and a_p, therefore the same tool life is expected for a high f and a low a_p, as for a low f and high a_p, given that h_e is held constant.

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

Hägglund presents a way of calculating h_e for rounded and pointed inserts. Hägglund's h_e for S_A case 2, S'_A case A for rounded inserts is presented in eq. 5 and the constraints in eq. 3 and eq. 4. Hägglund's h_e for S_A case 1, S'_A case B for pointed inserts is presented in eq. 11, and eq. 10 is needed to calculate h_e for this case. The constraints for this case is presented in eq. 7, eq. 8 and eq. 9. When the insert is considered round, according to the constraint in eq. 3 and eq. 4, κ is calculated using eq. 6 [6].

Hägglund's way of calculating h_e is based on the same variables as Woxén, but also counts for the minor cutting edge angle.

S_A case 2, S'_A case A for rounded inserts

$$0 < a_p \leq \frac{d}{2} \tag{3}$$

$$0 < f \leq 2 \cdot \sqrt{a_p \cdot (d - a_p)} \tag{4}$$

$$h_e = \frac{a_p \cdot f - \frac{d}{2} \cdot \left[f - \frac{f}{2} \cdot \sqrt{1 - \left(\frac{f}{d}\right)^2} - \frac{d}{2} \cdot \text{asin}\left(\frac{f}{d}\right)\right]}{\frac{d}{2} \cdot \left[acos\left(\frac{d - 2 \cdot a_p}{d}\right) + asin\left(\frac{f}{d}\right)\right]} \tag{5}$$

$$\kappa = \text{asin}\left(\frac{a_p}{r}\right) \tag{6}$$

S_A case 1, S'_A case B for pointed inserts

$$\kappa \geq \kappa_b \tag{7}$$

$$a_p > r \cdot (1 - cos(\kappa)) \tag{8}$$

$$2 \cdot r \cdot sin(\kappa_b) < f \leq \frac{r \cdot (1 - cos(\kappa + \kappa_b))}{sin(\kappa_b)} \tag{9}$$

$$\varphi' = acos\left(1 - \frac{f}{r} \cdot sin(\kappa_b)\right) - \kappa_b \tag{10}$$

$$h_e = \frac{a_p \cdot f - r \cdot f \cdot \left(1 - \frac{cos(\kappa_b) + cos(\varphi')}{2}\right) + \frac{r^2}{2} \cdot \left[sin(\kappa_b + \varphi') - (\kappa_b + \varphi')\right]}{\frac{a_p - r \cdot (1 - cos(\kappa))}{sin(\kappa)} + r \cdot (\kappa + \kappa_b) + \frac{f - r \cdot \left(sin(\kappa_b) + sin(\varphi')\right)}{cos(\kappa_b)}} \tag{11}$$

The purpose of the study is to analyze how the tool life corresponds to variances in a_p and f for a constant value of h_e.

Nomenclature		
a_p	Cutting depth	mm
d	Nose diameter	mm
f	Feed	mm/rev
h_e	Equivalent chip thickness	mm
κ	Major cutting edge angle	° or radians
κ_b	Minor cutting edge angle	° or radians
r	Nose radius	mm
T	Tool life	min
VB	Flank wear	mm
v_c	Cutting speed	m/min

2. Experimental setup and calculations

2.1. Experimental setup

The testing was done by longitudinal turning using coated CNMG120408 inserts, with r = 0.8 mm. Tool holder DGLN3232P12-M with 50 mm tool overhang, and $\kappa = 95^{\circ}$ was used. When the constraints in eq. 3 and eq. 4 for rounded inserts are fulfilled, κ changes to 30° respectively 45° depending on a_p, although the holder was always installed in the same position. The machining was done in dry conditions. The machine, used for the data collection, was an SMT SAJO 500 Swedturn, NC-turning machine. The cutting forces were recorded in three different directions (main cutting, passive, and feed force) by a Kistler piezo-electric 3-components measuring system, type 9129A.

Tool wear was measured with an Olympus SZX7 stereo microscope. The tool life criterion was selected to flank wear $VB_{max} = 0.3$ mm. The tested cases are presented in Table 1. For $h_e = 0.12$ mm (case 1) a medium fine chip breaker was used, and for $h_e = 0.26$ mm (case 2) a medium chip breaker was used.

Table 1. Cutting data tested.

Case	h_e (mm)	v_c (m/min)	a_p (mm)	f (mm/rev)	κ	a_p /f	Woxén h_e (mm)
1	0.12	300	0.4	0.30	30°	1.3	0.119
			0.8	0.20	45°	4.0	0.118
			1.2	0.18	95°	6.7	0.124
			1.6	0.16	95°	10.0	0.120
2	0.26	230	0.8	0.50	45°	1.6	0.266
			2.0	0.35	95°	5.7	0.266
			3.0	0.32	95°	9.4	0.265
			4.0	0.30	95°	13.3	0.260

Work piece material used was the low alloy steel SS2541 (34 CrNiMo6), rods 1000 mm long, machined from a dimeter of 220 mm to 80 mm.

2.2. Calculations

Two out of seven cases for calculating the equivalent chip thickness according to Hägglund has been used for rounded and pointed inserts, eq. 5 and eq. 10. For low ratios of r/f, the uncut material needs to be considered when calculating the true area being cut by the tool, and this area is always smaller compared to when calculating the area using the traditional Woxén chip thickness [6].

Woxén's way of calculating the equivalent chip thickness has not been used when calculating the corresponding feed for a given h_e and a_p. In Table 1 the Woxén h_e is presented using eq. 1. κ in eq. 11 for when the tool is considered as round, when $a_p \leq r$, is not used when calculating the Woxén h_e.

3. Result and discussion

In Fig. 1, the relation between T and a_p/f for case 1 is presented. The mean tool life of this data set with relative standard deviation is 28.95 ± 22.8 % min. The longest tool life is achieved when the ratio of $a_p/f = 4$. When a_p is increased over this point, the tool life is decreasing.

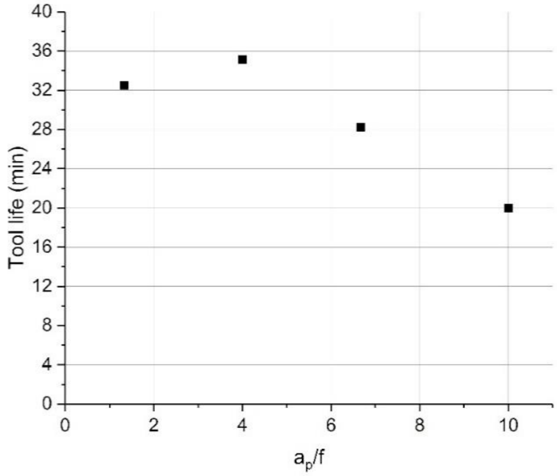

Fig. 1. The tool life as a function of ap/f for case 1, $h_e = 0.12$ mm.

Fig. 2 presents the relationship between T and a_p/f for case 2. The mean tool life for this data set was 12.7 ± 55.2 % min. It should be noted that the tool life at $a_p = 0.8$ mm and $f = 0.5$ mm/rev, with a ratio of $a_p/f = 1.6$, is considerably longer (22.9 min) than the other tested data points.

The ratio of a_p/f for case 1 was 1.3-10.0 and the ratio of a_p/f for case 2 was 1.6-13.3, as presented in Table 1. This can be considered rather large and the expected use of the tool would be within a smaller range. Hence, the relative variation for the data when removing the outer points was calculated, see Table 2.

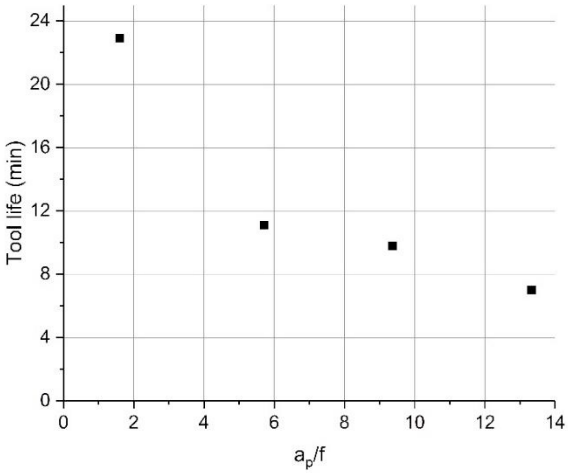

Fig. 2. The tool life as a function of ap/f for case 2, h_e = 0.26 mm.

Table 2. Mean tool life and relative standard deviation.

h_e (mm)	Mean tool life (min) for all data	Relative standard deviation	Mean tool life (min) for center points	Relative standard deviation
0.12	28.95	22.8 %	31.65	15.4 %
0.26	12.7	55.2 %	10.45	8.8 %

When studying the collected data, it can be concluded that the Woxén chip thickness model does not accurately predict the expected tool life for large ratios of f and a_p when h_e is held constant. Still, the model shows a somewhat linear or exponential relationship, when a_p/f is increased, and T is reduced. This is not true for the data point a_p = 0.4 mm and f = 0.3 mm/rev, case 1. One possible explanation for this is that the tool was used outside of the designed cutting data range and the chip breaker was not properly used, or that the cutting data selected allowed for a tool protective layer build up, protecting the cutting tool as reported by Johansson et al [7].

Several studies show the accuracy of the Woxén equivalent chip thickness when modeling tool wear using the Colding tool life model [2-11]. This study shows that the tool life is not constant for a constant h_e, varying a_p and ratios of a_p/f ranging from 1.3 – 13.3. Nevertheless, the tool life accuracy is improved for smaller ranges of a_p/f. Further studies are needed based on cutting data tests using a smaller range of a_p/f, to find a proper correction factor of the influence when increasing a_p and decreasing f. Further, more tests should be performed in several of the commonly used work piece materials such as cast irons, steels and stainless steels.

If the presented phenomena is valid, the accuracy of the Colding model when based on h_e can be lower than expected. When predicting cutting data, the Colding model will be prone to suggest an inaccurately high a_p and low f, based on modeling error of the chip thickness model as the most optimal cutting data for a given machining operation.

The Woxén h_e, in Table 1, varies as the Hägglund h_e is held constant. When the ratio of a_p/f increases, the accuracy of the Woxén h_e increases. When using cutting data with lower ratios of a_p/f, attention must be paid to the true area being removed per revolution.

Hardness measurements of the surface has not been performed during the data collection. For further studies, this could be interesting in order to analyze the effects of strain hardening on the work piece material, since the tool life can be affected by strain hardening effects. Also, the hardness of the outer layer can affect the tool wear deterioration depending on the diameter of the work piece material. a_p is the parameter deciding if the strain hardened layer is cut through or not, hence affecting the wear mechanism of the tool. The wear on the tool caused by strain hardening are typically located in the end points of the wear of the tool, when a_p exceeds the deformed layer. However, the VB_{max} has during the tests always been located under the cut surface, not in the edges of the wear on the tool, corresponding to the area of VB_B. When a_p/f is at its lowest, the tool life is longer compared to higher values of a_p/f, with a_p closer to a potentially strain hardened layer. Hence, the wear might be caused by other effects, such as high temperatures in the edge. This could be an explanation of the VB_{max} located in VB_B area since the tests were performed during dry conditions.

Regarding cutting speeds in relation to the edge temperature, an increase in cutting speed can both higher and lower the cutting edge temperature depending on the thermal conductivity of the work piece material. If the cutting speed increases, the heat generated could be transported from the cutting edge by the removed material, or be concentrated in the cutting edge – depending on the thermal conductivity of the work piece material. For lower values of a_p/f , the area of material will be concentrated to the edge of the tool. Fig. 1 and Fig. 2 shows that for lower values of a_p/f the tool life is the second longest respectively the longest, indicating that the possible temperature increase might have been transported with the chips.

As tool wear progresses the ratio of a_p/f will vary. This has not been taken in to account and can have minor influence on the result. Also, to minimize the effect of the chip breaker and in some cases using the chip breaker outside of its designed cutting parameters it would be of interest to repeat these test with tools not having any chip breakers.

4. Conclusion

Hägglund’s way of calculating the equivalent chip thickness equation has been investigated when machining low alloy steel SS2541 (34 CrNiMo6) using coated CNMG120408 inserts in longitudinal turning. The influence on T when changing the ratio of a_p/f was recorded. The result shows a decrease in T when a_p is increased, keeping h_e constant, for all but one cutting test. This suggest that there is an inaccuracy when using Woxén chip thickness equation to represent f, a_p, r and κ in tool life modeling. Also, the fact that for smaller ratios of a_p/f the true area being removed is not considered when using the Woxén equation, which can result in suggestions not applicable for the case. This model inaccuracy will result in a tool life model being prone to suggest higher a a_p and a lower f for the same given T. When using Hägglund’s way of calculating the equivalent chip thickness, the tool life accuracy increases when the ration of a_p/f decreases. It is also shown that the accuracy of the Woxén chip thickness is improved when the ratio of a_p/f is increased regarding the true area removed per revolution. It is possible that this model error is negligible in industrial applications, when the suggested window of cutting data is small, and the tools are used in a correct application area. Nevertheless, this phenomenon needs to be further studied to investigate the effects of changes in the ratio of a_p/f, when using the Woxén chip thickness.

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