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.

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.

\[
h_e = \frac{a_p f}{\frac{a_p - r(1 - \cos \kappa)}{\sin \kappa} + k r + \frac{f}{2}}
\]  

(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, $\kappa$. 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 $K$, $H$, $M$, $N_0$ 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.

$$v_c = e^{K-(\frac{(\ln(h_e)-H)^2}{4M}-(N_0-L\cdot\ln(h_e))-\ln(T))}$$  \hspace{1cm} (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, $\kappa$ 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

$$0 < a_p \leq \frac{d}{2}$$  \hspace{1cm} (3)

$$0 < f \leq 2 \cdot \sqrt{a_p \cdot (d-a_p)}$$  \hspace{1cm} (4)

$$h_e = \frac{a_p f - \frac{d}{2} \left[ f - \frac{f}{2} \sqrt{1-\left(\frac{a_p}{d}\right)^2} - \frac{d}{2} \sin\left(\frac{\pi}{2}\right)\right]}{4\left[\frac{d}{2} \cos\left(\frac{d-2a_p}{2}\right) + \sin\left(\frac{\pi}{2}\right)\right]}$$  \hspace{1cm} (5)

$$\kappa = \sin\left(\frac{a_p}{r}\right)$$  \hspace{1cm} (6)

$S_A$ case 1, $S'A$ case B for pointed inserts

$$\kappa \geq \kappa_b$$  \hspace{1cm} (7)

$$a_p > r \cdot \left(1 - \cos(\kappa)\right)$$  \hspace{1cm} (8)

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

$$\varphi' = \frac{1 - \frac{f}{r} \cdot \sin(\kappa_b)}{\sin(\kappa_b)}$$  \hspace{1cm} (10)

$$h_e = \frac{a_p f - r f \left(1 - \cos(\pi)\right) + \frac{f^2}{2} \sin\left(\frac{\pi}{2}\right) - \left(\kappa_b + \varphi\right)}{\cos(\kappa_b)}$$  \hspace{1cm} (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 $h_e$. 

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_p )</td>
<td>Cutting depth</td>
<td>mm</td>
</tr>
<tr>
<td>( d )</td>
<td>Nose diameter</td>
<td>mm</td>
</tr>
<tr>
<td>( f )</td>
<td>Feed</td>
<td>mm/rev</td>
</tr>
<tr>
<td>( h_e )</td>
<td>Equivalent chip thickness</td>
<td>mm</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Major cutting edge angle</td>
<td>° or radians</td>
</tr>
<tr>
<td>( \kappa_b )</td>
<td>Minor cutting edge angle</td>
<td>° or radians</td>
</tr>
<tr>
<td>( r )</td>
<td>Nose radius</td>
<td>mm</td>
</tr>
<tr>
<td>( T )</td>
<td>Tool life</td>
<td>min</td>
</tr>
<tr>
<td>( VB )</td>
<td>Flank wear</td>
<td>mm</td>
</tr>
<tr>
<td>( v_c )</td>
<td>Cutting speed</td>
<td>m/min</td>
</tr>
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</table>

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, \( \kappa \) 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 \( VB_{\text{max}} = 0.3 \) 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.

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

Work piece material used was the low alloy steel SS2541 (34 CrNiMo6), rods 1000 mm long, machined from a diameter 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. $\kappa$ 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 $28.95 \pm 22.8 \%$ 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 $a_p/f$ for case 1, $h_e = 0.12$ mm.](image)

Fig. 2 presents the relationship between $T$ and $a_p/f$ for case 2. The mean tool life for this data set was $12.7 \pm 55.2 \%$ 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.

![Graph](image)

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

<table>
<thead>
<tr>
<th>$h_e$ (mm)</th>
<th>Mean tool life (min) for all data</th>
<th>Relative standard deviation</th>
<th>Mean tool life (min) for center points</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>28.95</td>
<td>22.8 %</td>
<td>31.65</td>
<td>15.4 %</td>
</tr>
<tr>
<td>0.26</td>
<td>12.7</td>
<td>55.2 %</td>
<td>10.45</td>
<td>8.8 %</td>
</tr>
</tbody>
</table>

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 \( V_{B_{\text{max}}} \) 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 \( V_{B_B} \). 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 \( V_{B_{\text{max}}} \) located in \( V_{B_B} \) 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 \( \kappa \) 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 \( a_p \) 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.
Acknowledgements

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References