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COLDINGS TOOL LIFE MODEL APPLIED ON TOOL WEAR WHEN MACHINING THE MAXTHAL MATERIAL
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METAL CUTTING IN A HIGH TEMPERATURE INTERMETALLIC COMPOSITE MATERIAL

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Abstract: Coldings tool life equation for metal cutting tools has been modified to suit the difficult to machine material Maxthal. The dominant tool wear mechanisms during machining of Maxthal are abrasive and adhesive wear and a strongly temperature dependent chemical deterioration. The combination of these three mechanisms leads to a considerable variation in tool life, even when the cutting speed has been varied in a relatively close range. Metal cutting experiments has been carried out as straight turning, were the wear level of the tool has been monitored by cutting force measurement. Sample tests have been performed with 3 different insert types. The results show that the best cutting conditions are obtained with a cermet insert. The difference in tool life and total cutting capacity between the studied insert types is ca 10%. The experimental data has been adapted to Coldings tool life model. Within the cutting data interval $25<v_c<50$ m/min, Coldings model can suggest a cutting speed for a total tool life of 7 minutes with an average accuracy better than 10%. For carbide inserts, maximum chip volume flow is obtain for a fixed value of the equivalent chip thickness h_e, for a given tool life.

Keywords: Colding, metal cutting, tool wear, high temperature, intermetallic alloys.

1. INTRODUCTION

The established tool life models for cutting tools are substantially based on one wear criterion, such as flank wear, crater wear or other non-wear related changes of edge geometry. The validity of the models are governed by that a balance exists between the different tool wear mechanisms, within the entire scope of the model. During progressive wear this balance of wear types often shifts. This can for example be sudden geometry changes due to plastic deformation or a breakthrough from a crater wear at the minor cutting edge.

2. OBJECTIVES AND DELIMITATIONS

The main objective with this work is to investigate if Coldings tool life model can be applied and adapted to a complex tool wear process. Furthermore, optimal cutting data for machining of the intermetallic alloy Maxthal shall be determined, through straight turning experiments. The study has been limited to include only cutting tools available on the market.

3. LIST OF SYMBOLS

a_p	Depth-of-cut	mm
b	Active cutting edge length	mm
e_T	Tool engagement up to T	m
f	Feed	mm/varv
h_1	Theoretical chip thickness	mm
h_e	True equivalent chip thickness	mm
v_c	Cutting speed	m/min
r	Nose radius	mm
T	Tool life	min
V	Chip volume	cm^3
$\dot{V}$	Chip volume flow	cm^3min^{-1}
VB	Flank wear	mm
κ	Approach angle	°

K, H, M, N_0 and L are Colding constants. The letters A-G represents different types of inserts used in the experimental studies.

4. MAXTHAL AS A WORK MATERIAL

Maxthal is an intermetallic alloy based on Ti_3SiC_2 with smaller amounts of the abrasive carbide TiC. Round the grain boundaries a fusion product from the sintering process can appear, in the form of titanium silicide. When deformed, Maxthal has only one dominant slip plane. During separation, the Ti-Ti bonds will break, which can explain the chemically and thermally dependent reaction tendency.
Maxthal produces short chips, an can be compared to gray cast iron with respect to cutting resistance and chip formation.
Maxthal has however, during machining, an exceptional adhesion to alumina coatings, which causes drastically increased cutting forces at the time period when the coating is functional (ca 30 seconds)

(Ståhl J-E, Högrelius B. 2006). In straight turning Maxthal has a machinability that is 50-100 times lower than for a conventional steel and ca 5 times lower than for Inconel 718, with regard to total possible chip volume per tool.

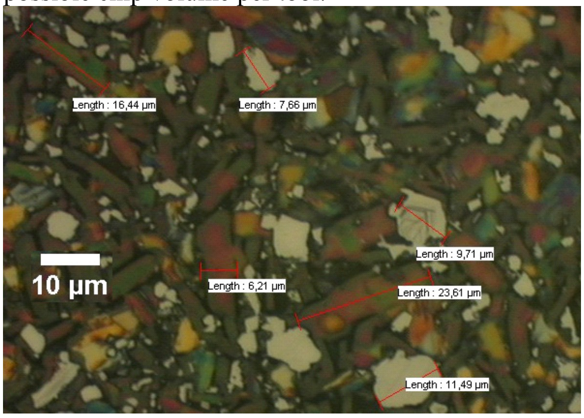


Figure 1. Etched surface showing the microstructure of Maxthal. The white grains are TiC. Ti_3SiC_2 appears as colourful, oblong grains. The black (etched away) areas around these grains has been titanium silicide.

5. THEORY AND REALIZATION

The choice of insert types and cutting data is of vital importance for the total tool life and therefore also decisive for the production cost. The tool life in the studied case is determined by the appearance of flank wear. When the flank wear has grown to a given value, the tool is considered to be worn out, because the workpiece doesn't meet the demands on tolerances or surface integrity. In the studied cases, the wear criterion VB_{max} = 1.0 mm has been used, according to **Figure 2**. Measurements of tool wear have been performed in a light microscope.

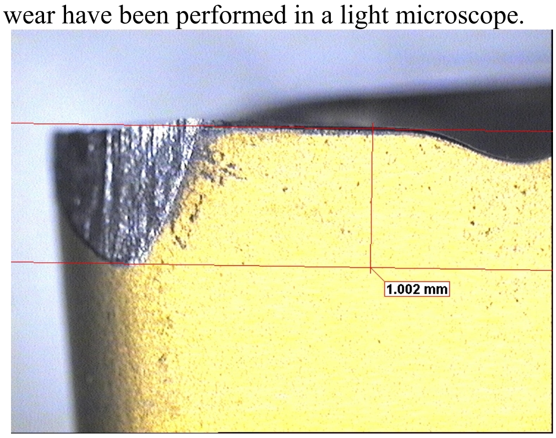


Figure 2. Cutting tool (A) having reached the wear criterion VB_{max} = 1.0 mm.

The two most important factors governing the wear-related tool life for a specific insert, are the choices of cutting speed v_c and feed f. When machining with an insert with a given nose radius, in this case r=0.8mm, the theoretical chip thickness will vary along the cutting edge. An equivalent chip thickness h_e can be calculated and be regarded as mean chip thickness with reference to the active cutting edge length. For known values of feed f, depth-of-cut a_p, approach angle κ and nose radius r, the equivalent chip thickness can be calculated (Ståhl J-E. et al, 2007). Calculated values of the equivalent chip thickness h_e are presented in Figure 3, Table 1 and Table 2. The equivalent chip thickness is precisely calculated and differs to some extent from the corresponding values derived from Woxéns equations (Woxén R. 1932).

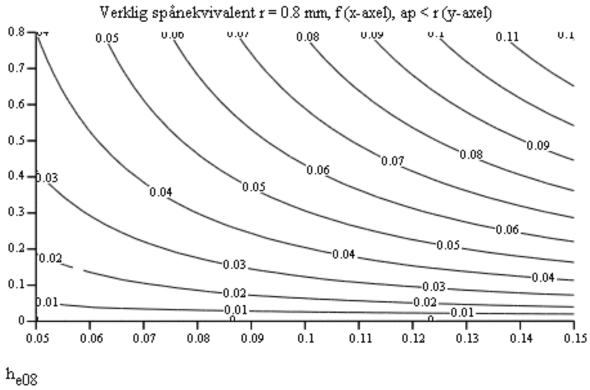


Figure 3. Equivalent chip thickness for different combinations of depth-of-cut a_p and feed f. Nose radius r=0.8mm and approach angle κ = 90˚.

Table 1. Calculated values of the equivalent chip thickness. Nose radius r=0.8mm and approach angle κ = 90˚.

Feed f (mm/rev)	Depth-of-cut a_p (mm)			
	0.5	**1.0**	**1.5**	**2.0**
0.050	0.033	0.041	0.044	0.046
0.075	0.049	0.062	0.065	0.069
0.100	0.064	0.083	0.087	0.092
0.125	0.080	0.104	0.109	0.114
0.150	0.095	0.125	0.131	0.137

Table 2. Calculated values of the equivalent chip thickness, a_p =1.2mm. Nose radius r=0.8mm and approach angle κ = 90˚.

f [mm/rev]	**h_e [mm]**
0.090	0.076
0.100	0.085
0.125	0.106
0.140	0.119
0.180	0.154

Equation 1 according to (Colding B. 1981) can for a given combination of cutting tool and workpiece, describe the relationship between tool life T, cutting speed v_c, and equivalent chip thickness h_e. The equation is valid mainly for wear related tool deterioration, where one single wear mechanism dominate the tool wear in the studied research setup.

If different mechanisms dominate depending of cutting data combinations the deviations between model and reality becomes to large and the model validity becomes limited.

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

The Colding equation contains 5 constants (K, H, M, N_0, L), which can be determined by at least 5 separate experiments with 5 different cutting data setups.

Based on experience, the setups should be chosen in 2 pairs, where each pair has the same equivalent chip thickness. Each pair should then be combined with different cutting speeds. The remaining setup can preferably be chosen in the middle of the presumed cutting data domain.

The method applied in this work, to decide the constants, has no limitations in the number of possible cutting data setups, above the 5 compulsory. Any extra experimental data only add to the accuracy of the predicted values, since the data processing is based on curve fitting.

The maximum possible chip volume that can be cut by a tool can be calculated as the product between cutting speed v_c, tool life T, and chip area A. see equation 2. The chip area A can be calculated as the product between equivalent chip thickness h_e and the active cutting edge length b, $A \approx h_e \cdot b$. In this study, b is set to unity, that is b=1mm. The reason for this is to facilitate comparable results.

$$V = v_c \cdot h_e \cdot b \cdot T \quad (2)$$

The total tool engagement distance up to a worn out tool can be calculated as.

$$e_T = v_c \cdot T \quad (3)$$

The chip volume flow is directly related to the production speed and can be calculated according to equation 4.

$$\dot{V} = v_c \cdot h_e \cdot b \quad (4)$$

Cutting forces have been measured during all of the experimental tests. The cutting forces displays a pronounced dynamic behaviour, due to a distinct formation of discontinuous chips.

In the presented analyses, the cutting forces are filtered through a moving average over 0.1 seconds. The cutting forces will change during the wear progress, up to the point where the tool is worn out, when VB_{max} = 1.0 mm. In order to ensure similar conditions in the experiments as in reality, all machining was performed uninterrupted. This in turn made it necessary to estimate when the tool life criterion was met, when VB_{max}=1.0mm. A successive wear always leads to an increasing force level. Therefore, the feed force level was used as an indicator when to stop the experiment. In Figure 4 it can be observed that after ca 250 seconds, the feed force has doubled its value. This is approximately the level where the tool wear criterion is met.

Sometimes an experiment was interrupted prematurely, before $VB=VB_{max}$. In these cases a linear wear progress has been assumed and the estimated tool life T at VB_{max}=1.0 mm has been calculated. The error due to this extrapolation is probably much smaller than the alternative result, where an almost worn out tool would be reheated on more time.

The reheating phase and its influence on the tool life cannot be neglected in theses cases. Repeated short tool engagements with the same cutting tool, often lead to a prolonged tool life, during a pure wear situation with small h_1.

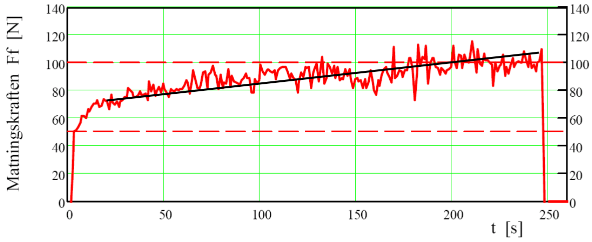


Figure 4. Filtered feed force F_f during wear progress up to the point when VB_{max} = 0.85 mm is reached. The increase of feed force is marked by two lines, at 50 N and 100 N. Insert type B.

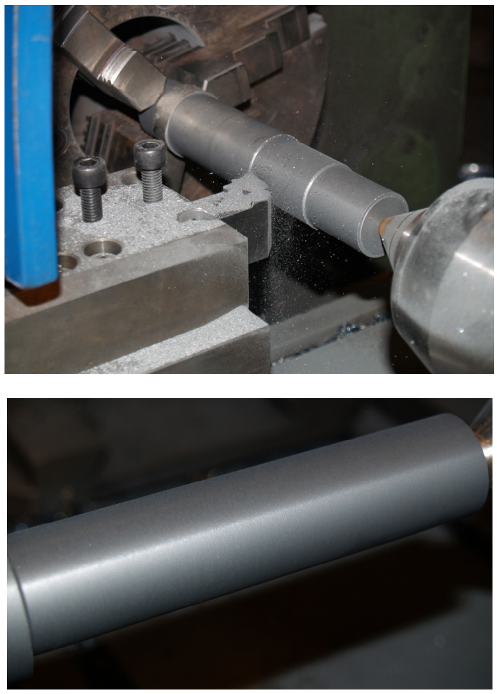


Figure 5. Machining of Maxthal (upper) and machined surface with a stable surface integrity during the whole tool life (lower).

6. EXPERIMENTALS

Tool wear tests in a lathe has been performed using insert types from 6 tool suppliers, see Table 3.

Table 3. Inserts types and description..

Type	Designation	Manufacturer	Grade
A	CNMG 120408-PF, GC4025	Sandvik Coromant	Carbide
B	CNMG 120408-PF, C5015	Sandvik Coromant	Cermet
C	CNMG 120408-MF2, TP2500	SECO TOOLS	Carbide
D	CNMG 120408-SH, NX1010	Mitsubishi Carbide	Cermet

E	CNMG 120408N-SU, T1200A	Sumitomo Electric	Cermet
F	CNMG 120408-ENBZ, F1T15	NTK Inserts	Cermet
G	CNMG 120408, CT320	TaeguTec	Cermet

Apart from the tools presented in Table 3, simplified tests have been performed using ca 10 other types of inserts. The results from these tests are not presented here. A number of diamond and CBN inserts have been tried out but with limited success. Initially, full scale wear tests were carried out with the insert types A and B (test nr 1-14). These results are presented in Table 4 and Table 5.

Table 4. Sandvik Coromant: CNMG 120408 PF, GC4025, A.

Nr	f	h_e	v_c	T
1	0.10	0.085	25	484
2	0.10		50	208
3	0.14	0.117	50	40
3b	0.14	0.119	50	46
4	0.14		25	210
5	0.125	0.106	25	300
6	0.09	0.076	25	557
7	0.09		50	259
15	0.10	0.085	25	487
19	0.10		35	329
25	0.10		35	329
31	0.125	0.106	35	175

Table 5. Sandvik Coromant: CNMG 120408-PF, C5015, B.

Nr	f	h_e	v_c	T
9	0.10	0.085	50	126
10	0.10		25	731
11	0.14	0.119	25	353
12	0.09	0.076	25	886
13	0.09		35	576
14	0.14	0.119	35	184
32	0.125	0.106	35	174

Table 6. Simplified tests with inserts from different tool suppliers.

Nr	f	h_e	v_c	T	Typ
16	0.10	0.085	35	129	D
17				137	E
18				242	F
19				329	A
20				223	G
23				227	C
24			25	239	C

Table 7. SECO TOOLS: CNMG 120408-MF2, TP2500, C.

Nr	f	h_e	v_c	T
26	0.10	0.085	35	317
27	0.10		50	473
28	0.125	0.106	25	381
29	0.125		35	222
30	0.14	0.119	35	165

After that, simplified test with fixed cuttings data were performed with the remaining insert types, C-G, results presented in Table 6. These results motivated a full test series with insert C, shown in Table **7**. All tests were performed without cutting fluids. The depth-of-cut a_p=1.2mm has been used throughout all experiments.

A balance factor B_f [1] was introduced to correct the error in tool life estimation caused by the spreading of machinability among the different work pieces used in the tests. This method of operation assumes that all tool are equally effected by the varying machinability.

7. CALCULATION OF COLDINGS CONSTANTS

Coldings constants are calculated using curve fitting and minimization of the errors to the measured point. The calculations are performed in the software Mathcad. In Figure 6, examples of input data for insert A are presented, based on tests nr 1, 4, 5, 6, 7, 15, 19, 25 och 31.

$$ap := \begin{pmatrix} 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \\ 1.2 \end{pmatrix} \quad fn := \begin{pmatrix} 0.10 \\ 0.14 \\ 0.125 \\ 0.09 \\ 0.09 \\ 0.10 \\ 0.10 \\ 0.10 \\ 0.125 \end{pmatrix} \quad vc := \begin{pmatrix} 25 \\ 25 \\ 25 \\ 25 \\ 50 \\ 25 \\ 35 \\ 35 \\ 35 \end{pmatrix} \quad T := \begin{pmatrix} 484 \\ 210 \\ 300 \\ 557 \\ 259 \\ 484. \\ 329 \\ 329 \\ 175 \end{pmatrix} \cdot \frac{1}{60} \quad re := \begin{pmatrix} 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \\ 0.8 \end{pmatrix} \quad he := \begin{pmatrix} 0.076 \\ 0.119 \\ 0.106 \\ 0.076 \\ 0.076 \\ 0.085 \\ 0.085 \\ 0.085 \\ 0.106 \end{pmatrix}$$

Figure 6. Input data for the modeling of tool life for insert type A.

The Mathcad models generate adapted Colding constants for the actual insert type. Calculated Colding constants for the insert types A, B och C are presented in Table 8 .

Table 8. Colding constants for inserts A, B and C.

	K	H	M	N_0	L
A	5.3741	-2.8473	0.1110	0.3820	0.2056
B	4.9262	-4.6480	1.4716	0.1732	0.0667
C	5.2754	-2.8709	0.1449	0.2952	0.2075

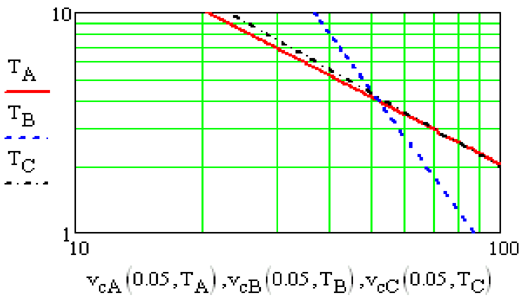
The model error can be expressed as a velocity error for a given tool life. This error can be calculated by studying the difference between the model cutting speed and the cutting speed used in the experiments ($\varepsilon = v_c - v_{cexp}$). In Figure 7 the model errors for inserts A,B and C are shown.

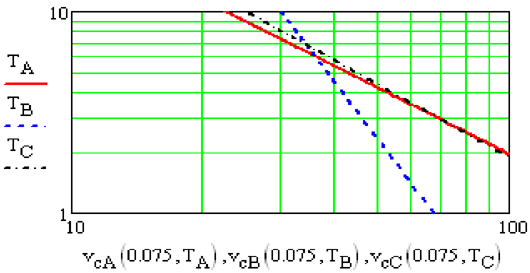
By inserting the Colding constants in equation 1, the relations between equivalent chip thickness h_e, cutting speed v_c and tool life T can be illustrated graphically. In Figure 8 traditional Taylor diagrams (Taylor F W. 1907) for 4 different values on the equivalent chip thickness, h_e = 0.05, 0.075, 0.10 och 0.125. In Figure 9 equation 1 is illustrated in the form of contour diagrams for inserts A, B och C with cutting speed as a parameter. The equivalent chip thickness h_e represented on the x-axis and tool life on the y-axis. The chip volume V that ca be machined with one cutting edge is given by equation 2. Figure 10 shows the cut chip volume up to the wear criterion VB=1mm is reached. The corresponding chip volume flows are presented in Figure 10.

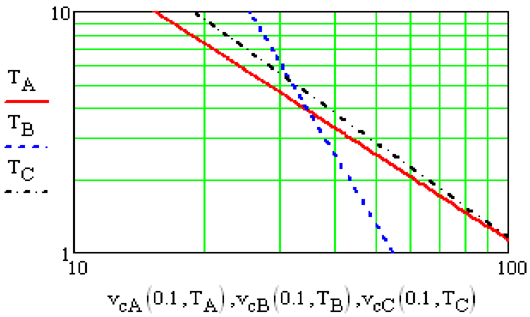
$$\varepsilon_A = \begin{pmatrix} -2.64 \\ 0.53 \\ 0.48 \\ 0.55 \\ 2.23 \\ 0.61 \\ 1.1 \\ 1.1 \\ -2.93 \end{pmatrix} \quad \varepsilon_{A\%} = \begin{pmatrix} -9.6 \\ 2.2 \\ 2 \\ 2.3 \\ 4.7 \\ 2.5 \\ 3.2 \\ 3.2 \\ -7.7 \end{pmatrix} \quad \varepsilon_B = \begin{pmatrix} 2.12 \\ -1.4 \\ -1.87 \\ -1.29 \\ 4.5 \\ 2.03 \\ -1.68 \end{pmatrix} \quad \varepsilon_{B\%} = \begin{pmatrix} 4.4 \\ -5.3 \\ -6.9 \\ -4.9 \\ 14.8 \\ 6.1 \\ -4.6 \end{pmatrix}$$

$$\varepsilon_C = \begin{pmatrix} -2.04 \\ 3.09 \\ -2.71 \\ 0.9 \\ 1.52 \end{pmatrix} \quad \varepsilon_{C\%} = \begin{pmatrix} -5.5 \\ 9.7 \\ -9.8 \\ 2.7 \\ 4.5 \end{pmatrix}$$

Figure 7. Modell errors, expressed as cutting speed errors [m/min] and in percentages. Insert types A, B, C.







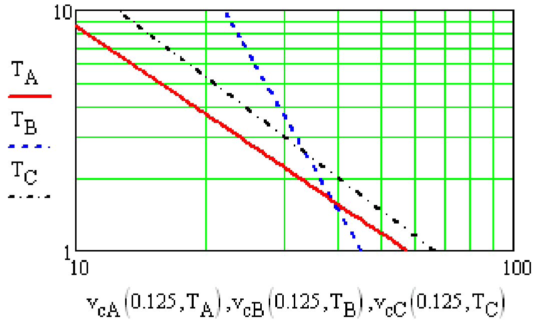
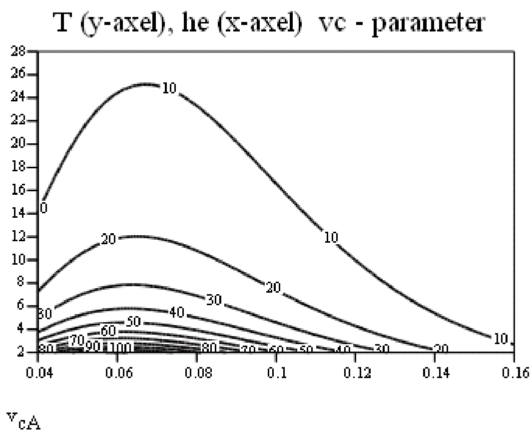
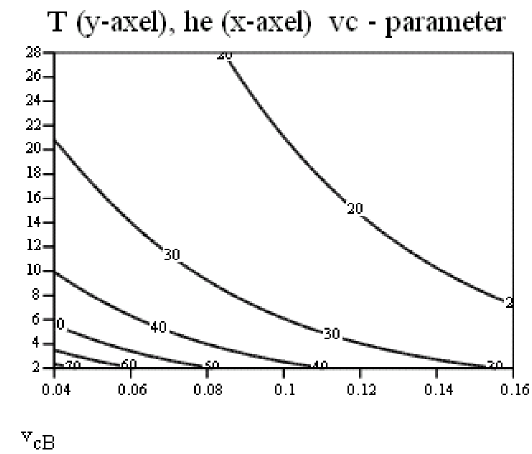


Figure 8. Taylor diagrams for the 3 different insert types A, B och C and for 4 different chip equivalents.

For a given life time, for example T=7 minutes, a maximum chip volume flow can be calculated, by seeking the he value for which the volume flow derivate is zero. The obtained equivalent chip thickness can be considered to be optimal, if no other aspects of the chip volume flow should be considered. A maximum for the total chip volume per cutting edge can be calculated in the same way. Figure 12 shows chip volume flow and its derivate for insert type A. Figure 13 shows the chip volume per insert for insert type A.





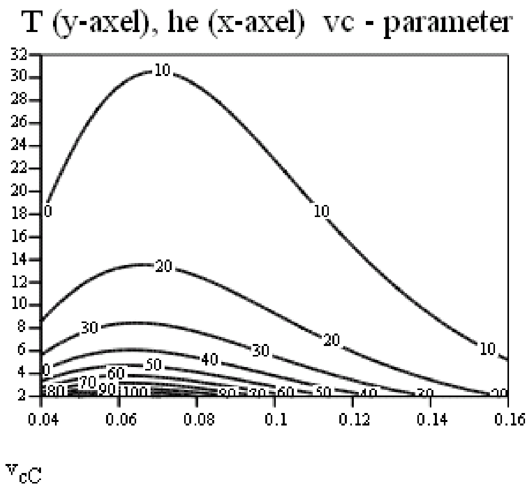
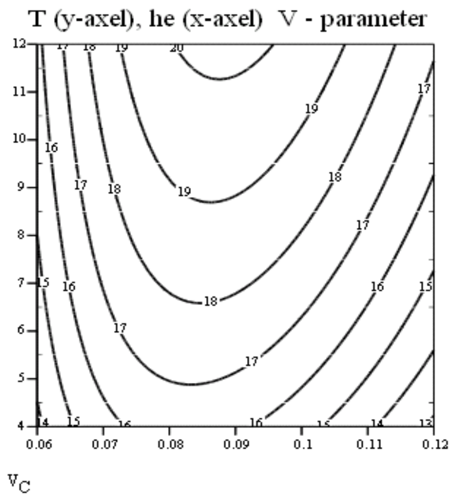
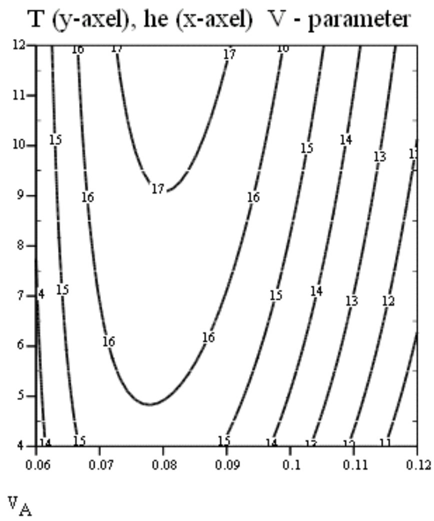


Figure 9. Tool life T [min] as a function of equivalent chip thickness h_e [mm] with cutting speed v_c [m/min] as parameter. Insert types A, B and *C.*





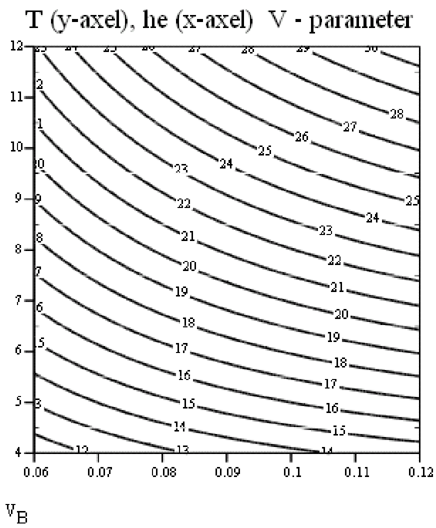
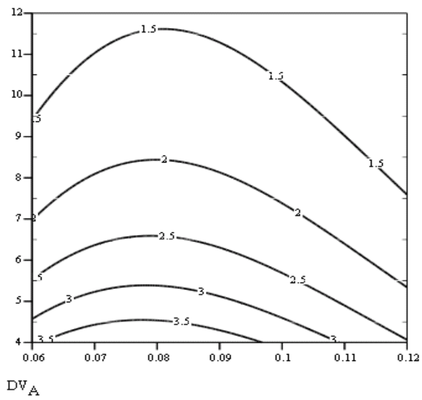
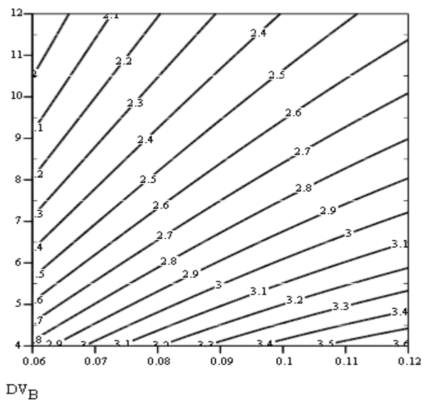


Figure 10. Tool life T [min] as a function of equivalent chip thickness h_e [mm] with chip volume V [cm^3] per edge as a parameter. Insert types A, B och C.

The h_e-value corresponding to the maximum changes very little when choosing different tool life T, that is the derivate is 0 for approximately a constant h_e-value. This fact is illustrated in Figure 14 in a contour diagrams for insert type A and C. In this case a maximum in chip volume and in chip volume flow is reached for the same h_e-value.





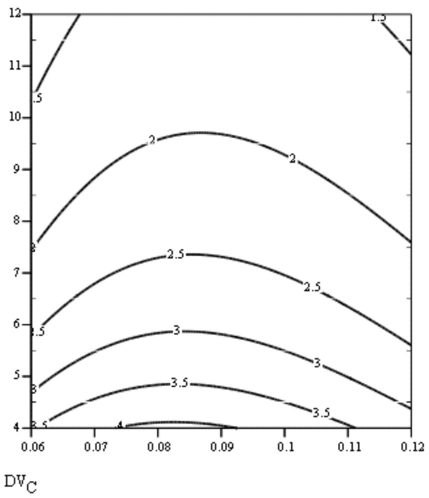


Figure 11. Tool life T [min] as a function of equivalent chip thickness h_e [mm] with chip volume flow V [cm^3/min] per edge as a parameter. Insert types A, B och C.

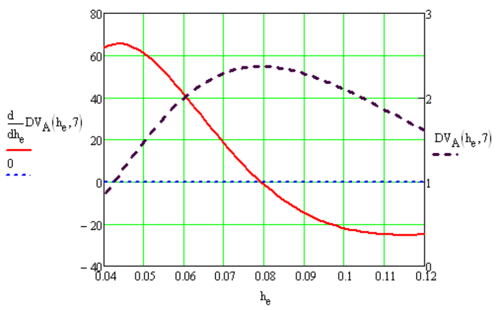


Figure 12. Chip volume flow (broken line) and its derivate (solid line) as a function of equivalent chip thickness h_e, insert type A.

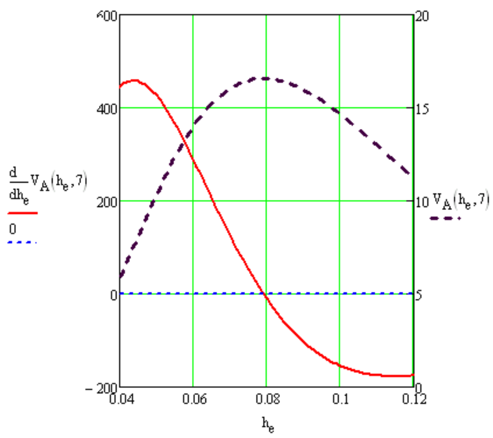


Figure 13. Chip volume per insert (broken line) and its derivate (solid line) as a function of h_e, insert type A.

8. RESULTS FROM TOOL LIFE TESTS

In Table 9 a compilation if the results form the tests with insert types A, B and C are presented. The tool life 7 minutes was chosen as a basis for the evaluation. Insert types A and C exhibits distinct maxima in chip volume flow at T=7 min, which is exemplified in Figure 12 and in Figure 13 for insert type A. Insert type B lacks the maximum for chip volume flow, which makes it difficult to determine an optimal h_e-value.

Table 9. Performance for insert types A, B and C. T=7 minutes.

Type	V [cm^3]	dV/dt [cm^3/min]	v_c [m/min]	h_e [mm]
A	16.6	2.4	29.6	0.080
B	18.0	2.6	34.2	0.075
C	18.2	2.6	30.6	0.085

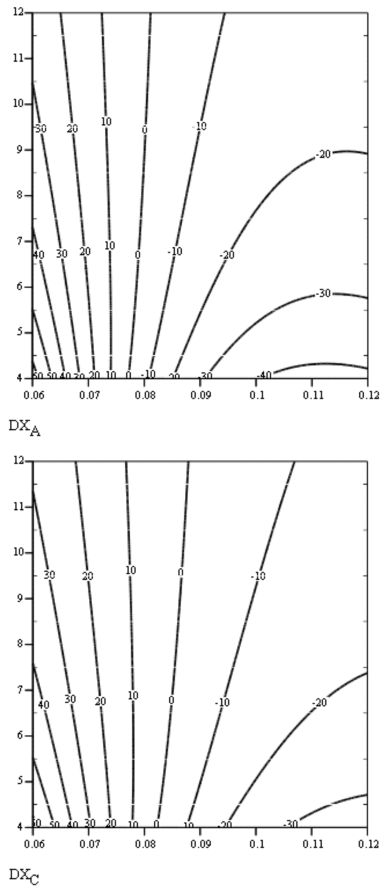


Figure 14. Tool life as a function of h_e, with chip volume per insert as parameter. Insert type A (upper) and insert type C (lower).

9. RESULTS AND DISCUSSION

Maxthal is a difficult to machine material, regarding tool wear and deterioration. By comparison with conventional steel, Maxthal is ca 400 times more wear aggressive. It should be observed, however, that no tool optimized for Maxthal exist on the market, but a large number of tools exist that has been optimized for machining of steels. The comparison is therefore not entirely true.

In the studied case, 2 base types if inserts have been tested, ceramic based and cermet based. The differences between these inserts are not especially large. The differences lies in the dominating wear mechanisms, which is evident from Coldings constants in Table 8 and the Taylor diagrams in Figure 8. The differences between the two carbide inserts are as expected,. Insert type C has a stronger micro geometry than insert type A, which allows for cutting with a slightly larger chip thickness. This fact is apparent by a comparison of optimal he-value, according to figure 14. The carbide inserts in the study are coated with aluminium oxide, which is not effective from a trobological perspective. The aluminium oxide reacts with the work material, with severe adhesion as consequence. An increased process temperature, through increased cutting data, will increase the adhesion and the cutting forces drastically. Titanium from the work material and aluminium from the tool material form new intermetallic alloys (Zwicker U. 1974). Combinations of Al, Ti and Si are inconvenient when it comes to machining and machinability. Ti also reacts with Co and can also form the intermetallics Ti_2O och TiO. These reactions induce an increased wear speed of the carbide tool, especially at increased cutting speeds and process temperatures. The aluminium oxide coating adds about 30 seconds to the tool life, compared to an uncoated WC-insert of the same grade (Ståhl J-E, Högrelius B. 2006). Considering the drastically increased cutting forces connected to the breakdown of the coating, there is an obvious risk that the dimensional accuracy of the work piece will be poor, see Figure 16. This fact confirms the use of cermet based tool when machining Maxthal. Additional to the chemical wear, wear related to the existence of TiC-particles in Maxthal also occurs.

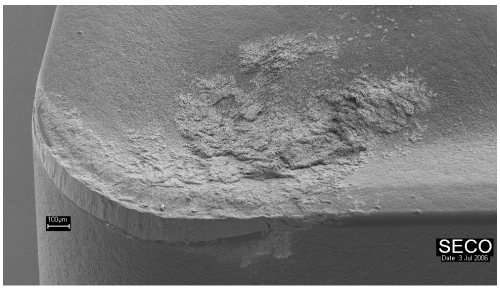


Figure 15. Insert type C after ca 25 seconds of engagement, showing adhesion of Ti_3SiC_2.

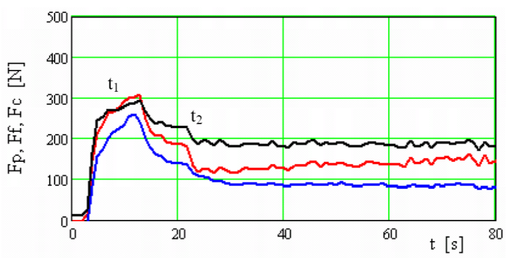


Figure 16. Cutting force build-up corresponding to insert types A and C, where t_1 indicates maximum adhesion and t_2 indicates a total breakthrough of the coating.

10. PROPOSED TOOL DEVELOPMENT

Tool materials based on cermet with a low content of binder should have the best potential for machining of Maxthal. However, the risk for chipping and flaking of the tool will increase. There were no signs of flaking visible on insert type B.

Coating of cermets with TiC, and tool geometry preparations similar to inserts for e.g. grey cast iron, should provide the best conditions for an improvement of machining and economy.

New test with a TiC-coated cermet should be performed. The increased edge radius produced by the coating (suggested 10-12 µm) will also improve the mechanical stability of the process.

11. RECOMMENDED CUTTING DATA AND TOOLS

Table 10 shows the recommended cutting data to reach a tool life of 7 minutes.

Table 10. Recommended cutting data for insert type B, when machining Maxthal.

Feed	Cutting speed	Depth-of-cut
f = 0.07 – 0.10 mm/rev	v_c = 25 – 35 m/min	a_p = 0.05 – 3 mm

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