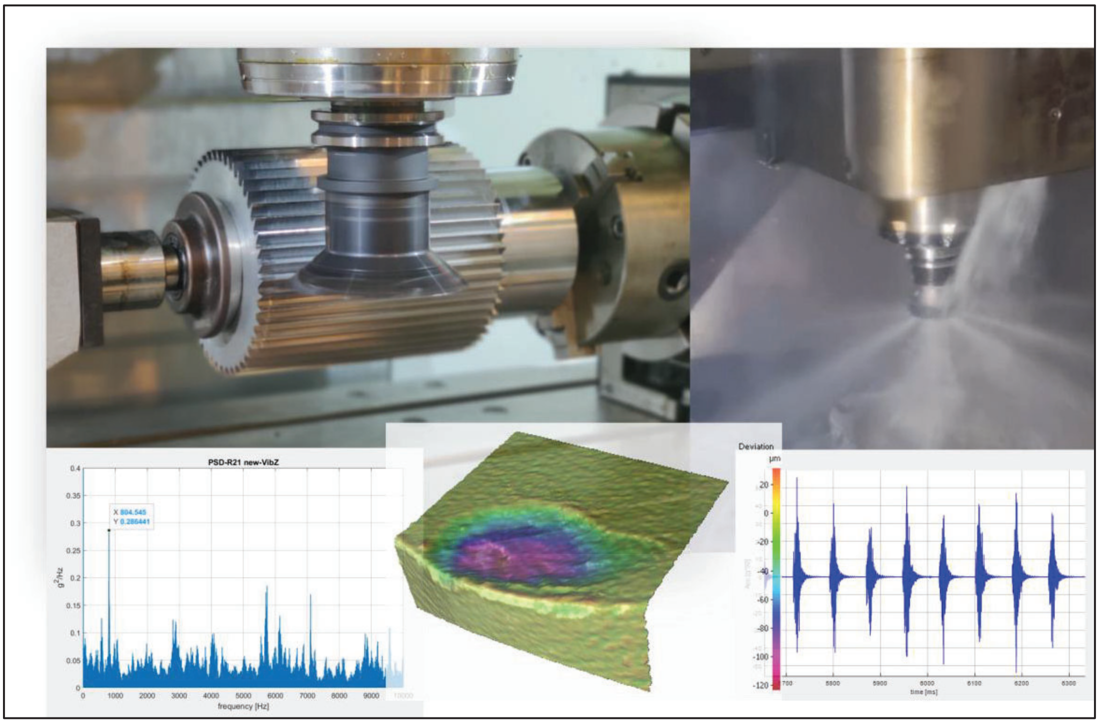
SiTCoM

Public report



Project within FFI

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Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1 Summary

In this project a test method for evaluating wear of HSS cutting tools in gear manufacturing processes has been developed. The test method is subsequently used to study the wear of several HSS tool materials with Cobalt contents from 0 to 8.5 % and one extreme at 29%.

The main effect of Cobalt in the HSS material is to increase hot hardness, enabling the use of higher cutting speeds. However, the element is associated with problems regarding availability, unstable prices, environmental issues and working conditions during the mining step. The second project aim was to find Cobalt free replacement HSS materials to reduce the use of Cobalt in the automotive industry.

The test method uses standard machine tools and tool holders, a normal 3 axis milling machine and a standard off the shelf tool holder suitable for axial grooving which is the selected method. The only unique part is the HSS cutting edge to be tested. This must be manufactured specifically for the test. In these tests five different HSS materials and four different work materials in the form of thick walled tubes were used.

The tests showed that the Co free tool ASP2062 performed equally well as the standard 8% Co alloyed HSS material ASP2052 at normal gear cutting data. These results were confirmed by industrial tests in hobbing and skiving. It was not until speeds and feeds were increased substantially that the Co alloyed materials performed better in the test method.

In fact, hot hardness seemed not to be relevant at skiving since chipping was the dominant wear mechanism in our industrial case. The ASP2062 with its higher toughness showed more stable wear results than the Co containing materials in skiving.

The tests are more relevant for hobbing than skiving where the wear is associated with some vibrations and thus shows chipping related damages that we do not find in the test method results.

2 Sammanfattning på svenska

I projektet har en testmetod utvecklats för utvärdering av olika faktorers inverkan på verktygsslitaget vid kuggtillverkning. Axiell spårfräsning är den valda processen utförs på en vanlig treaxlig fräsmaskin med en standardhållare för spårfräsning med 11 positioner för hårdmetallplattor. Bara en av positionerna används medan övriga skyddas av blindskär.

Fem olika HSS material med varierande koboltinnehåll levererades av Erasteel och plattor specialtillverkades för verktygshållaren av Specialverktyg i Norrköping. Huvudmaterialen som ingick i alla tester var ASP2052 (8% Co) och ASP2062 (inget Co). Plattorna belades av Ionbond med en AlCrN PVD beläggning, Crosscut Plus.

Fem olika varianter av två sätthärdningsstål, 20MnCr5 och 19MnVS6 har använts som arbetsmaterial i testerna. Arbetsmaterialet levererades av Ovako och utgjordes av tjockväggiga rör som bearbetades ner till ämnen där 140 mm långa spår frästes. Varje spår blev 6 mm djupt efter 6 eller 12 passeringar. På ett ämne gjordes 48 spår och målet var att ett resultat skulle kunna avläsas efter två ämnen, 96 spår.

Viktiga faktorer i testen är den vinkel med vilket verktyget matas in för varje ny passering, skärhastigheten och matningen per tand. Genom att variera dessa parametrar kan slitagets typ, grop- eller flankförslitning, och position på skäret kontrolleras. Med en kombination kan man få båda slitagetyperna att uppträda med små variationer i skärhastigheten.

Testmetoden är mycket känslig för vilket arbetsmaterial som används och ett typiskt sätthärdningsstål för kuggtillverkning, 20MnCr5 gav goda resultat medan renare material medförde mycket låg förslitningshastighet och orimligt långa testtider.

För att validera testresultaten utfördes industriella försök hos Scania i Södertälje och hos Leax fabriker i Köping och i Rezekne, Lettland. Kuggfräsar och skivingverktyg tillverkades av Star SU i Italien och av Sandvik Coromant i Tyskland. Även dessa belades av Ionbond.

Testmetodens resultat visade att det koboltfria ASP2062 väl klarade att matcha ASP2052 upp till relativt höga skärhastigheter och tandmatningar. Över en viss gräns så presterar koboltmaterialen bättre. Slitagetyperna i testerna var gropförslitning eller fasförslitning medan urflisningar inte uppträdde, troligen på grund av den relativt stabila uppställningen som inte medförde stora vibrationer,

Valideringsförsök vid kuggfräsning visar att man vid produktionsdata inte ser någon skillnad mellan ASP2052 och ASP2062. Vi förhöjd matning slits ASP2062 något snabbare men inte nämnvärt. Slitaget förekom som grop.

Valideringsförsöken vid skiving innehöll ännu ett material, ASP2190 med 29% kobolt. Detta testades vid förhöjd skärhastighet mot ASP2052 som då gav längre livslängder med färre tandskador. Den ökade varmhårdheten hos ASP2190 var av mindre betydelse här än den minskade slagsegheten och förslitningen uppträdde huvudsakligen som urflisningar.

Skivingförsök två jämförde ASP2052 mot ASP2062. Här är urflisning den huvudsakliga förslitningsmekanismen. ASP2062 uppvisade här små urflisningar runt eggen som ökade kontinuerligt i antal men som sammantaget inte når upp till det slitage som skulle medföra omslipning. ASP 2052 får till en början inga skador men så småningom uppkommer betydligt större urflisningar med ett mer sprött utseende och som direkt skulle leda till omslipning av verktyget. Verktygslivslängden blir här bättre för ASP2062.

Tydligen har det koboltfria materialet egenskaper som vid normal kuggbearbetning ger en tillräckligt bra varmhårdhet för att klara mjuknande och gropförslitning kombinerat med en tillräckligt bra slagseghet för att motverka urflisningar. En kartläggning av exakt vad som behövs och en optimering av denna kombination av egenskaper skulle ytterligare kunna öka de koboltfria materialen konkurrenskraft.

Testmetoden fungerade väl för att rangordna HSS med avseende på förslitningsmotstånd vid kuggbearbetning. Det koboltfria materialet visade lika bra eller bättre förslitningsmotstånd i testmetoden och detta kunde valideras med industriella försök för både kuggfräsning och skiving.

3 Background

The standard HSS tool materials for gear manufacturing today includes up to 8% Cobalt. The Cobalt increases hardness both at room temperature and at elevated temperatures and increases wear resistance and enables higher cutting speeds to be used. However, the cutting processes used during gear manufacturing such as hobbing and skiving and the machine tools and geometries of the gears may not make such high speeds attainable. In addition, generous amounts of cutting fluids used to facilitate chip removal also result in lower tool temperatures. Therefore Cobalt free tools could be a valid alternative in many cases.

Testing of new tool materials in the manufacturing industry is often a lengthy process and a conservative attitude is motivated by the high cost of tool failures in the production line. Machine tools may also be tied up in production and not available for testing purposes. Moreover, in the manufacturing of the cutting tools themselves, it may not be easy to introduce new materials for the same reasons.

The aim of our project was to develop and use a simple test methodology that enables comparative studies in cutting situations similar to gear manufacturing but without the complicated and costly gear manufacturing machines. The method could be used in the whole production chain by companies specialising in the manufacturing of tool materials, coating technologies or the gear materials. In our project we have focussed on wear of the tools and the influence of Cobalt on the tool life.

4 Purpose, research questions and method

The project purpose is twofold, developing the test method and using it to evaluate different high speed tool materials with the final aim of finding competitive Co free HSS tool materials.

The test method was developed and used at two sites, at Swerim in Kista and at Erasteel in Söderfors on 3 axis milling machines.

The test method results were then validated in industrial production situations at the Leax factories in Köping and Rezekne, Latvia and at Scania in Södertälje for skiving and hobbing respectively.

4.1 Test method description

The purpose of the test method is that it should enable ranking of different alternatives in the gear manufacturing process with regard to wear and tool life and to do so in an ordinary three axis milling machine. Axial slot milling was chosen as the method to use as a simple operation that resembles gear manufacturing. The tool holder for the test is shown in Figure 1. Using such a tool holder makes it possible to use small replaceable HSS inserts as test tools rather than massive milling tools that must be regrinded thus saving time.

The tool holder is designed for hard metal inserts HM 176M40-N100608E-PM 1130. In this project we manufacture geometric copies in our HSS test materials. The tool holder has 11 positions of which we only use one to create tool wear quicker. The remaining 10 positions are protected against wear at a possible fracture of the test insert with standard hard metal inserts that have been grinded down 0.2 mm. This ensures that they don't engage with the work piece even at the highest feed rates.

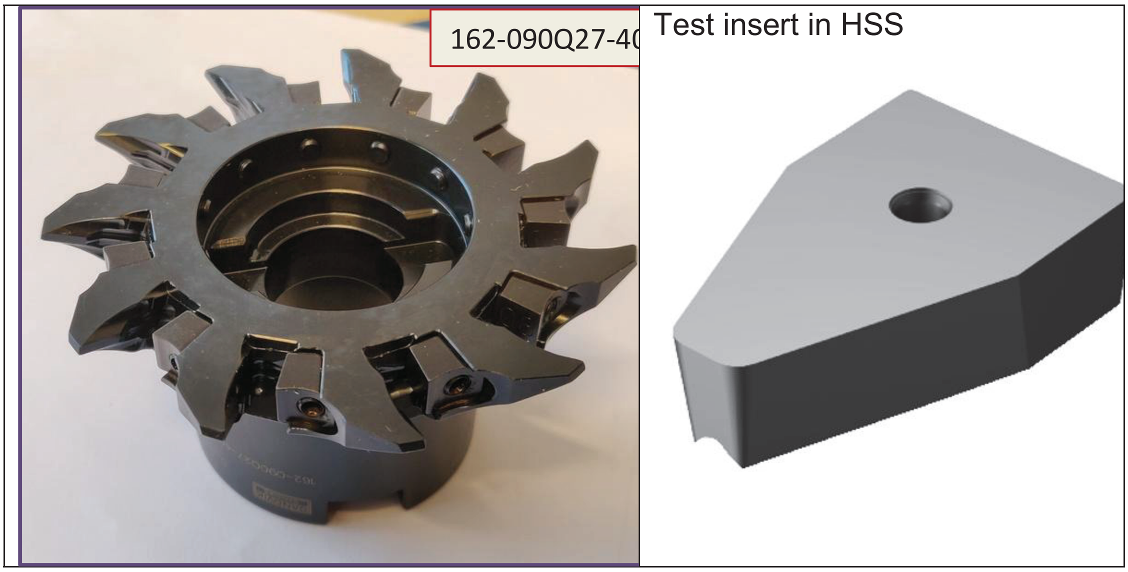


Figure 1   Sandvik Coromant tool holder for axial slot milling and custom made HSS test insert.

The inserts have been grinded to shape at specialverktyg in Norrköping. Each insert has been delivered as blanks from Erasteel in Söderfors, sent to Specialverktyg for grinding, hardened and tempered at Erasteel and sent back for final precision grinding. Ionbond has then prepared the edges and applied a PVD coating (crosscut plus) on the insert.
The work piece material for the test method was delivered as thick-walled tubes from Ovako Steel. In all 5 work piece materials were tested.
The tubes are turned into blanks with a shape that makes it possible for the tool holder to fit between the blank and the chuck at the start of each groove without coming into contact. Down milling is used with maximum chip thickness at the start of each tool engagement. The cutting speeds are adapted to actual production speeds between 160 and 280 m/min and the feed per tooth is varied between 0.08 and 0.3 mm/rev. The tool will make a 6 mm deep groove by travelling 6 or 12 times along the test piece using a cutting depth of 1 or 0.5 mm. The spindle cannot be tilted so in order to get a symmetric groove the first pass will start above the center line and the next passes will start at lower positions. This creates a symmetrical groove when using a 20º in feed angle, IFA where each part of the edge line cuts an equal amount. The IFA controls how much each flank of the insert will cut and how the wear is distributed on the tool and was varied between 0 and 30° during the tests.

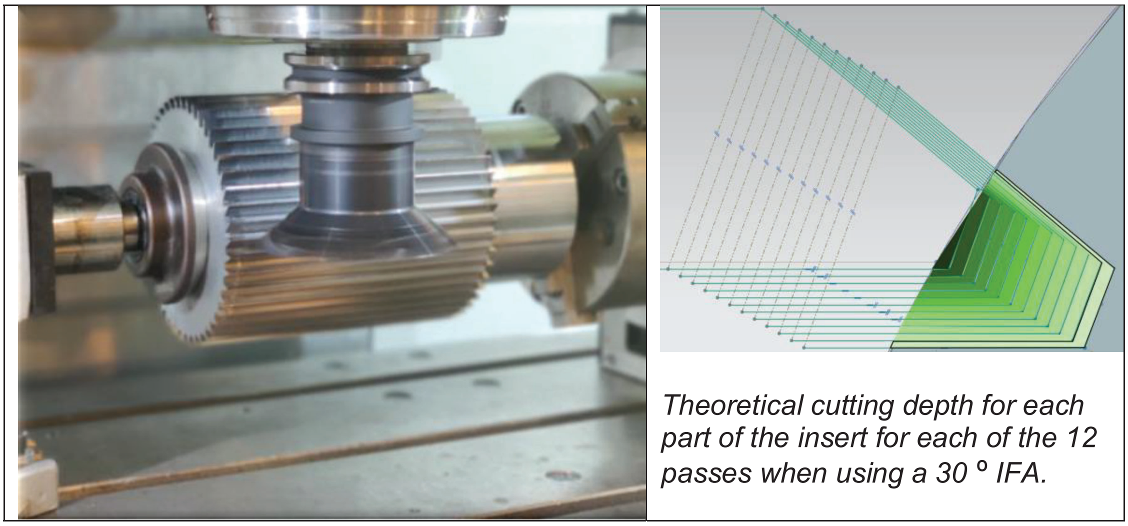


Figure 2 Tool holder and blank, mounted in a pneumatic doll bolted to the milling table.

For each new groove the work piece is rotated 7.5 degrees which gives 48 grooves in total for each work piece. At Erasteel this is done by hand but at Swerim a programmable pneumatic chuck is used which saves a lot of time. The aim was to find relevant production related test data that gives tool lives of 96 grooves, two test pieces, which would match normal tool lives per tooth in skiving and hobbing. The inserts are inspected with 5 to 20 grooves interval, more frequently when wear rates are increased.

The wear of the inserts in the test method is compared with wear appearance from the industrial hobbing and skiving tests and from literature. The crater wear from the test method is very similar to the one seen on the gear hobbing and skiving tools while the chipping that is associated with some skiving cases rarely is seen in our tests, Figure 3. The u shaped chip is created here as well as in skiving, Figure 4.

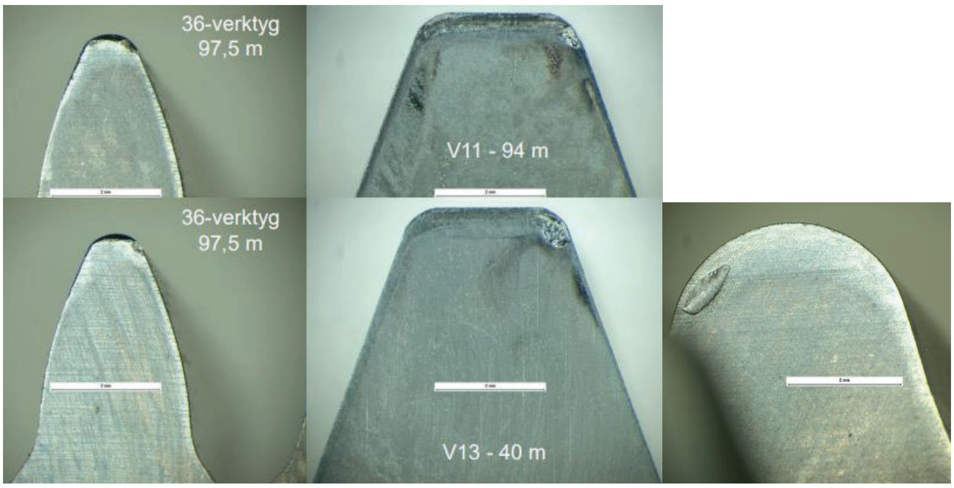


Figure 3 Crater wear during skiving (left), test method (middle) and on a Scania hob (right)

Figure 4 Skiving chips (Leax) och chips from the test method.

4.2 Cutting tool materials

Five high-speed steel (HSS) grades from Erasteel Kloster's ASP® series, ASP®2190, ASP®2052, ASP®2023, ASP®2030, and ASP®2062 were evaluated. These grades are commonly used in industry for coated cutting tools. To investigate the effect of cobalt content on tool wear resistance, the selected grades span a wide range of cobalt levels, including high, medium, and zero cobalt content, Table 1. These inserts were manufactured by Specialverktyg through a multi-step process involving rough grinding, hardening, tempering (the hardening and tempering was performed by Erasteel) and fine grinding. Final edge preparation, and PVD coating was done by Ionbond, applying AlCrN-based Crosscut™ Plus via advanced arc physical vapor deposition (PVD) technology. The coating thickness ranged from 2 to 4 µm.

ASP®2190: A super high-Co grade (29%) designed for maximum hot hardness. It represents the extreme end of the cobalt spectrum.
ASP®2052: A widely used high-performance grade with 8% Co, serving as a reference material for gear hobbing and skiving applications.
ASP®2062: A non-Co grade specifically designed to maximize hot hardness through high Mo and W content. It offers the highest hardenability (67 HRC) among the non-Co grades and is a promising candidate for cobalt-free cutting tools.
ASP®2030: A classic 8.5% Co grade with historical relevance in hobbing and moderate use in skiving applications.
ASP®2023: The non-Co counterpart to ASP®2030, commonly used in shaper cutters but less so in modern hobbing.

Table 1 Chemical composition, hardness, and impact toughness of ASP® inserts

HSS grade	C	Cr	Mo	W	Co	V	Nb	HRC	IT(J)
ASP®2190	0,78	4,2	2,9	2.99	29	1,1	1,1	69	12
ASP®2052	1,67	4,8	2,0	10,5	8	4,9	-	69	15
ASP®2062	1,30	3,8	10,5	6,3	-	2,0	-	67	17
ASP®2030	1,28	4,2	5,0	6,4	8,5	3,1	-	67	22
ASP®2023	1,28	4,0	5,0	6,4	-	3,1	-	66	34

The hardening and tempering parameters were chosen to achieve maximum hardness to toughness ratio possible for the grades. ASP®2030 was hardened both to 67 and 66 HRC to have the same hardness as ASP®2023 at 66 HRC, to evaluate the influence of cobalt and the hardness on the performance of these grades that have the same chemical composition except for the cobalt addition.

The main type of primary carbides in HSS cutting tools are MC and M_6C carbides, see Table 2 for the carbide contents of the grades. These carbides are critical in determining the tools hardness, wear resistance and overall durability during cutting operations. The MC carbides are typically composed of vanadium and/or niobium. Their high hardness and thermal stability make them highly effective in resisting abrasive wear, especially under high-speed and dry cutting conditions. A fine and uniform distribution of MC carbides throughout the steel matrix enhances the cutting-edge retention and contributes significantly to the tools wear resistance. M_6C carbides on the other hand has a slightly lower hardness compared to MC carbides and is rich in molybdenum or tungsten and may contain moderate amounts of chromium or vanadium. M_6C carbides offer good thermal fatigue resistance and contribute to the overall toughness of the steel and are particularly beneficial in applications where resistance to cracking and chipping is essential. The presence of both these carbide types in HSS, provide synergistic effects that enhances the tool performance. MC carbides offering superior hardness and abrasion resistance, while M_6C carbides contributes to the toughness and thermal stability.

HSS grade	Total carbide content (%)	MC carbide content (%)	M6C carbide content (%)
ASP®2190	5	3	2
ASP®2052	13,7	8,7	5
ASP®2062	19,5	1,2	18,3
ASP®2030 (at 66 HRC)	13,9	5,5	8,4
ASP®2030 (at 67 HRC)	13,3	5,3	8
ASP®2023	12,5	4,7	7,8

Table 2   Carbide content at maximum heat treatment temperature (maximum hardness)

4.3 Cutting tool coating

All tools manufactured for the test method and the gear hobbing and power skiving tests have been edge conditioned and coated by Ionbond. Ionbond has also been acting as a quality control of the grinding steps on all tools and provided some measurements for the worn hobs. The coating used is the AlCrN PVD coating Crosscut Plus.
The thickness of the coating is ~4 µm and it has a microhardness of 3200 HV0.02.
The coating is recommended for cutting tool applications for

- Low to high tensile steels, cast irons, tool steels
- Medium to high-speed, high-feed machining:
- Milling, hobbing and skiving
- Minimal or low lubrication and cooling
- High mechanical loads – High toughness
- Difficult to machine materials, Stainless Steels, Ni alloys

The flow for our tools arriving at Ionbond is:
Incoming inspection –decoating – cleaning – deburring - pre treatment / edge radii – cleaning - PVD coating – post treatment – adhesion tests on coupons.

The final step is done to check how well the coating is bonded to the tool surface.

4.4 Workpiece materials

The workpiece material in the tests are different variants of standard case hardening steels commonly used for gears and axles. The material variants used in the project are Ovako 236 in three different variants (Z, F and Q) and Ovako 280 in two variants (T and X).

The materials for the single insert milling trials were delivered in the form of thick-walled tubes supplied by Ovako. The tubes are turned into workpieces designed to allow each slot to start close to the chuck without interference.

Ovako also provided blanks for the skiving tests in material 236Z, 236F and 236Q.

20MnCr5 (the 236 variants) is a case-hardening steel with low carbon content but good hardenability, reaching good wear resistance due to high surface hardness after hardening. The small grain size results in good ductility and fatigue strength. The material is suitable for gearboxes and axle gears.
Ovako 236Z is standard variant, 236F has controlled sulphur content for consistent machining properties. Ovako 236Q is an IQ variant, an isotropic quality ultra clean steel optimized for high fatigue strength under multi axial loading.

19MnVS6 EN10267 (Ovako 280T/X) may with its generous chemical analysis and moderate mechanical requirements host a number of grades. All variants are micro-alloyed with vanadium which gives a fine grain size and a good start for excellent toughness.

A heat-treatment will naturally affect the mechanical properties. The Ovako program starts with a yield strength of minimum 400 MPa and finishes at minimum 520 MPa where each variant is carefully balanced to give the desired properties without a wasteful addition of alloying elements. Weldability goes from excellent to good with increasing alloying content and yield strength.

Chemical composition of all the variants including 236F, 236Q, 236S, 280X and 280T is summarized in .

Table 3 Chemical composition of Ovako materials used in the workpieces

Steel	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al	Ti	Ca	O	N
236Z	0.19	0.33	1.19	0.012	0.041	1.19	0.24	0.07	0.219	0.007	0.026	34	8	19.5	136
236F	0.19	0.25	1.17	0.012	0.022	1.16	0.13	0.04	0.237	0.007	0.029	5	1	6.5	107
236Q	0.21	0.14	1.15	0.005	0.0008	1.14	0.15	0.06	0.172	0.005	0.097	10	20	3.2	80
280X	0.18	0.31	1.51	0.006	0.026	0.08	0.12	0.03	0.074	0.08	0.012	8	20	14.4	185
280T	0.18	0.33	1.51	0.011	0.028	0.24	0.15	0.05	0.074	0.096	0.033	9	2	5	107

The main material delivery for this project was the 280T variant (and a few pieces of 280X). A brief inclusion study was performed for these variants, specifically aimed at the oxides.

A surface of 350-400 mm2 is analysed for each sample. Settings are used to avoid sulphides and concentrate on oxides so that the smallest detectable particle has a 9µm equivalent circle diameter (ECD) and a smallest width of around 2 µm. The ternary diagrams show different types of oxides in the 280T and 280X, Figure 5. Its also clear that there are a lot fewer particles in 280T and that they are slightly smaller, Figure 6.

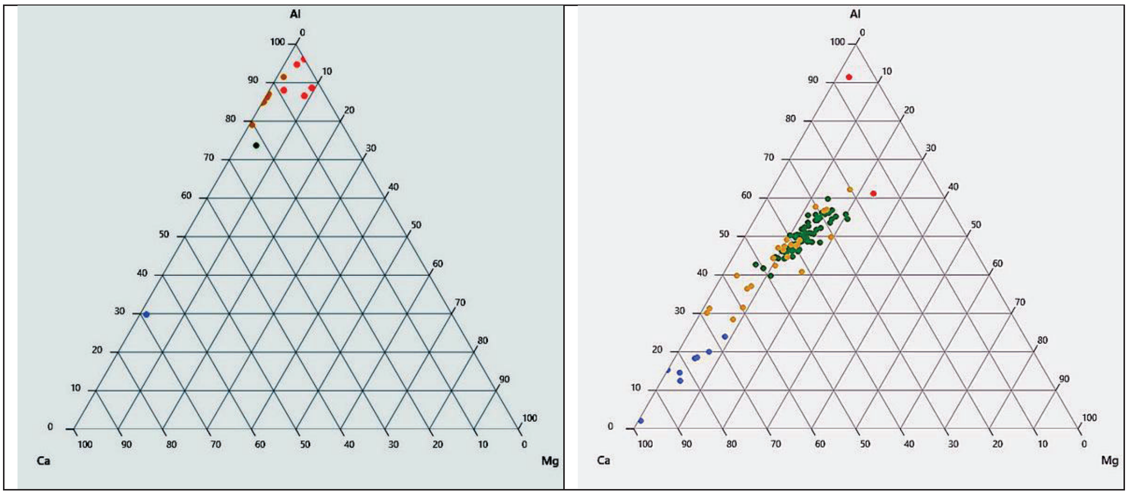


Figure 5   Oxide types for 280T (left) and 280X (right).   280T: 5 Oxides (red), 1 CaAl (green), 7 Oxysulphides (brown), 1 Calcium sulphide (blue), 9 MnS (magenta), 3 non classified (light green). 280X: 2 Oxides (red), 71 CaAl (green), 24 Oxysulphides (brown), 8 CaSulphide (blue), 3 MnS (magenta)

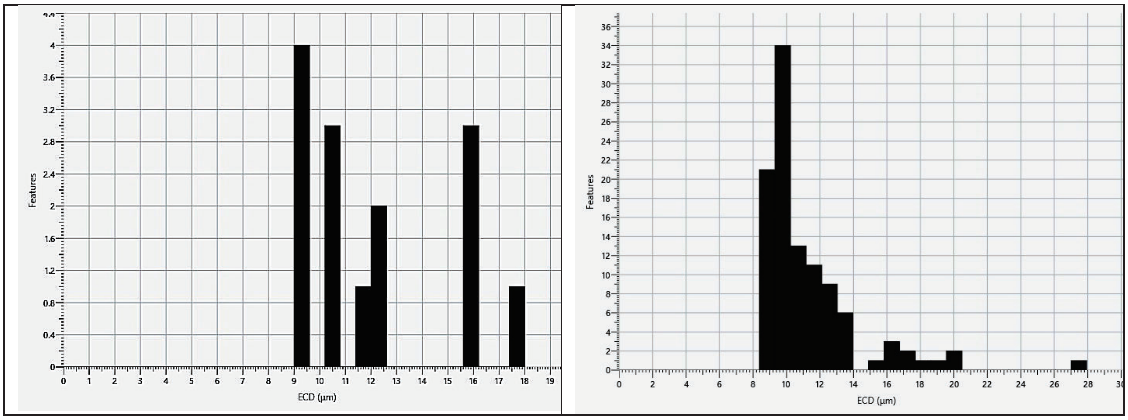


Figure 6   Size distribution of the detected oxides show smaller, fewer oxides in 280T (right).

4.5 Industrial test1 - Hobbing

Gear hobbing tests have been carried out in the production line at Scania in Södertälje. Tools made from the Cobalt free steel ASP2062 has been compared with tools made from the standard material ASP2052.

Star-SU manufactured the ASP®2062 hobs for the project. The material for the ASP®2062 was supplied by Erasteel with grinding instructions. Both ASP®2062 and the reference ASP®2052 hobs were resharpened at Scania and coated by Ionbond (AlCrN) between each trial. The hardness of the tools was 66 HRC for ASP2052 and 67 HRC for ASP2062.

The test was made for a layshaft gear with following gear data:
Z=38, α=20°, ß=+24°, da=171, b=41,5.
The work piece material was a case hardening steel.

The reference tool ASP2052 was tested 6 times with resharpening and coating between each test. An increasing amount of details was produced in each test.

The cutting speed used was kept constant at 190 m/min. The dimensions of the hob and limitations of the machine spindle rotation made higher cutting speeds impossible. The axial feed was set to 4.4mm/rev in the first five tests and increased to 4.9 mm/rev in the final test. This will lead to an equivalent max chip thickness hex of 0.198 and 0.209 mm respectively, as calculated using the Hoffmeister equation.

The Cobalt free ASP2062 was tested 3 times with resharpening and coating between each test. Two tests were run at production data 190 m/min and 4.4 mm/rev and the last one with increased axial feed, 4.9 mm/rev.

Table 4 Test details for the gear hobbing tests at Scania

ASP2052 test no	1	2	3	4	5	6
# details/feed	250/4.4	300/4.4	350/4.4	450/4.4	450/4.4	450/4.9
ASP 2062 test no	1	2	3			
# details/feed	450/4.4	450/4.4	450/4.9			

4.6 Industrial test 2 - Skiving tests

Skiving, the second industrial validation test , was performed on two sites, at Leax in Köping and in the Leax facilities in Rezekne, Latvia. The dedicated skiving machine Gleason 300 PS in Latvia was not available for a major part of the project so the first tests were made in the smaller 5 axis DMG Mori DMU 60 Evo milling machine in Köping fitted with special software for skiving.

The process used is soft skiving and the tests have been made at production data on a commercial product, a ring wheel for the automotive industry, (Øy= 217 mm, Øi=193 mm, B=32 mm, with 113 inner cogs, Figure 7. The workpiece material is 20MnCr5 (Ovako 236) in the unhardened state, a material commonly used for gears. The material used is mainly production material but some material (236Z, 236F and 236Q) was also provided by Ovako. The blanks are produced by Leax with internal and external turning

The original tool geometry used in production has an outside diameter of 118 mm and has 69 teeth. For this project, smaller tools were made with just 36 teeth to increase the wear rate of the tool. Tool lives in the tests could be reduced by a factor 2.

Figure 7 Left: Produced ring wheel. Right: The bigger production tool and our test tool

Sandvik Coromant manufactured the 36-teeth tools used in the project in Zell, Germany and also made two unique tool holders to fit the new tool in both machines.
Erasteel provided material with very different Cobalt content for the tools (29%, 8% and 0%). The three materials tested were ASP2190, ASP2052 and ASP2062. The measured hardnesses of the tools used are shown in Table 5 together with the general impact toughness values.

Table 5 Measured hardness for the skiving tools

HSS grade	HRC	IT(J)
ASP®2190	68.7	12
ASP®2052	68	15
ASP®2062	67.5	17

Four tools of each material was produced by Coromant. The tools were regrinded between tests at Leax in Köping and sent to Ionbond for inspection, edge preparation and coating with their Cross Cut Plus PVD coating.
The wear is measured at regular intervals, here about every 10 details produced. The limit between regrinding for these tools is normally around 0.2 mm and to follow the progressing wear and document it an Alicona Infinite Focus SL instrument was used, Figure 8. The wear levels are often too small for normal light optical microscopes. The instrument makes a three dimensional image of the tooth nose that can be further studied later. The measurements can thus be made fast and the tool returned to the machine for further cutting after ten minutes of measurements.
Initially 6 of the teeth were measured at each stop but at more recent test series all teeth were given a quick inspection and measured if anything out of the ordinary was detected. Fixtures were made where the tool could be rotated and the next tooth quickly positioned for measuring and to get the same view of all measured teeth. All tools were documented prior to cutting to ensure that no damage was present from production and handling.

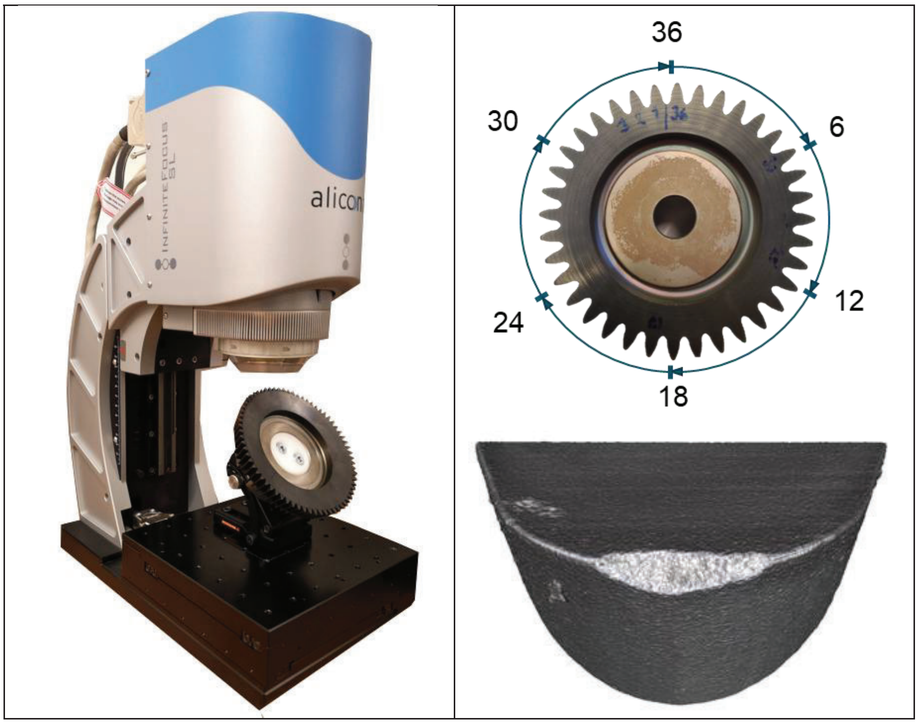


Figure 8 Measuring setup with the Infinite focus SL instrument , fixture and tool, the measured teeth and a typical wear appearance.

Initially the edge master program was used to measure various values of flank and crater wear. As the project developed a more simple way of manually determining when the tool had reached its tool life was instead used, when a large enough number of teeth has reached a maximum wear limit of around 0.25 mm. Running the tools longer than that could lead to difficulties in regrinding the tool to perfect geometry. As production of the detail was cancelled towards the end of the project, a lack of work material rings made us instead stop after a fixed number of produced details and compare the wear at that point.

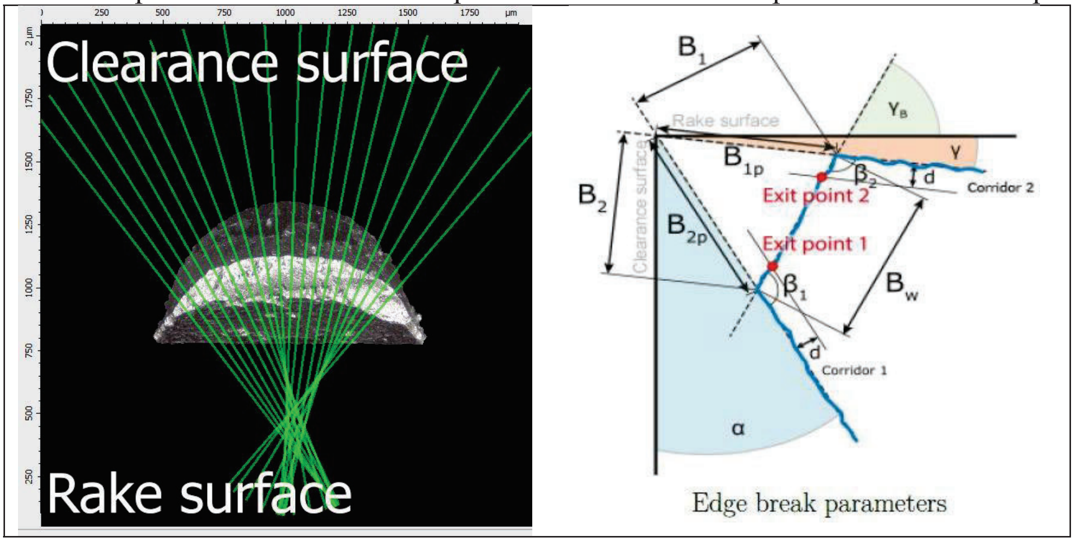


Figure 9 Automatic evaluation of flank wear, parameter B2, using edge master.

The wear studies were focussed on the nose area of the teeth where the most cutting is done and where from experience the wear is concentrated.

4.7 Test method studies

Force measurements at KTH

The purpose of the force measurements was to learn more about the test method details and evaluate the effect on cutting forces of different test parameters such as feed per tooth hex, cutting speed v, infeed angle IFA, work material and wear pattern and amount of wear on the tool. The force measurements and the vibration measurements show in detail what happens during each spindle revolution. Moreover, monitoring forces during the test and knowing when and why forces increase could potentially be a way to define a stop criterion for the test.

The trials were performed in the Hermle milling machine at KTH. A rotating cutting force dynamometer was used and mounted in the spindle. The equipment had not been used in this way before so new adapters and fixtures had to be devised and data acquisition parameters set. Test pieces from the wear trials were used and the fixture from the Erasteel workshop test set up was borrowed for the tests, Figure 10.

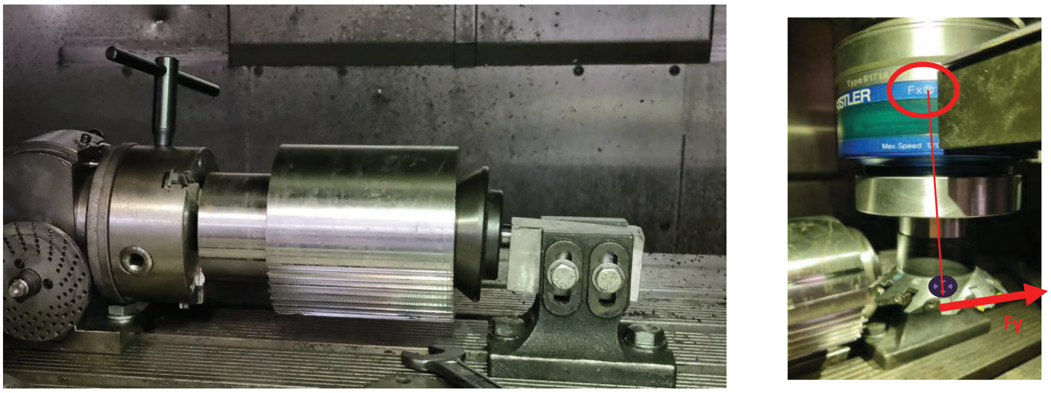
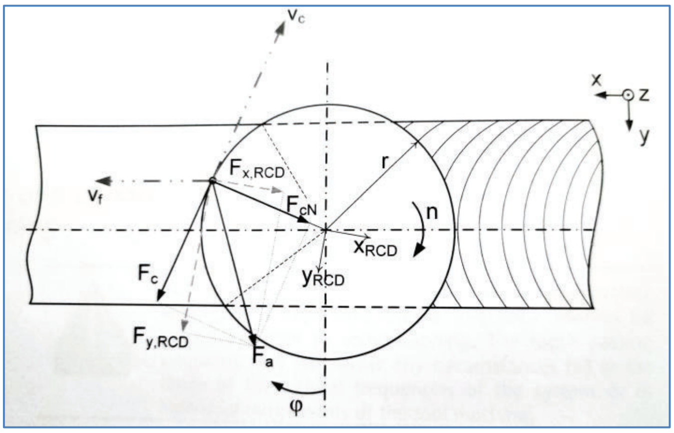


Figure 10 Fixture with workpiece (left) and dynamometer with tool (right)

We use the dynamometer signals to calculate Fc and FcN and the “active force” Fa, Figure 11. Reliable comparisons between the test cases are made by evaluating the active force, Fa and the torque, Mz.



$$F_a = \sqrt{F_{x,RCD}^{\;2} + F_{y,RCD}^{\;2}} = \sqrt{F_c^{\;2} + F_{cN}^{\;2}}$$

$$F_c = \frac{M_z}{r}$$

$$F_{cN} = \sqrt{F_a^{\;2} - F_c^{\;2}}$$

Figure 11 Force components from the rotating dynamometer

Vibration measurements

Vibration measurements were carried out on the test method setup at Swerim and at Erasteel. A Dytran 3313, a miniature triaxial IEPE accelerometer with a built-in amplifier and incorporating quartz shear sensing elements is used, Figure 12.
This type of sensor is best suited for high frequency vibrations and cannot measure static acceleration (0 g) or speed or position, that is how much a component is moving.

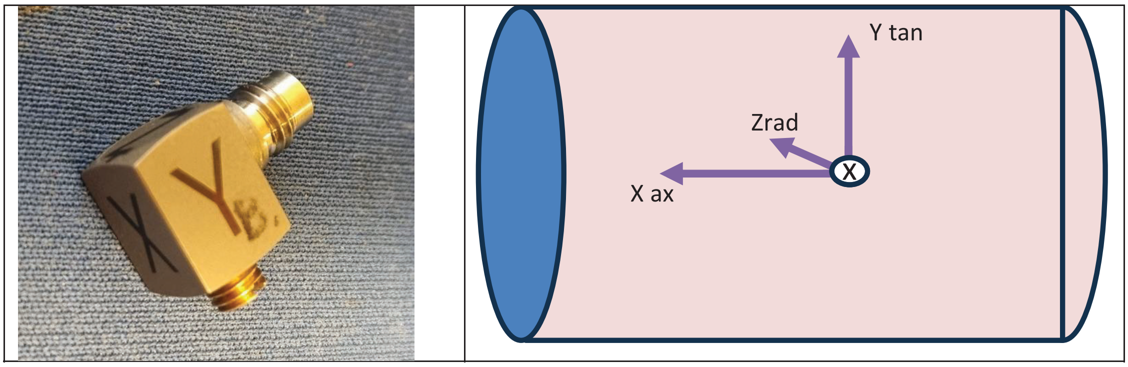


Figure 12   Accelerometer Dytran 3313A3H and orientation of the components.

The accelerometer is attached to the work piece using a threaded hole drilled into the work piece close to the test groove, Figure 13. In this way the vibrations are transferred very well to the sensor. Also shown in the image is the bigger wireless triaxial accelerometer Wiser 3x that Leax uses.

Figure 13 Setup at the accelerometer trials

With the accelerometer mounted as in Figure 13 and with down milling, close to the groove the accelerometer will show the highest vibrations and energy in the radial Z direction because of the tool entry direction. The Vy component will be linked with the infeed angle and the Vx direction will be the smallest component as it is measured perpendicular to the tool entry direction. As the work piece is rotated away from the accelerometer position for the next groove, the vibration components are changed slightly. The evaluations are made using inhouse matlab routines and routines taken from endaq web page, https://blog.endaq.com/vibration-analysis-fft-psd-and-spectrogram.

Temperature measurements

A short attempt was made at comparing the impact of different parameters on the cutting temperature of the test method. With a heat camera only comparative measurements between different cases can be made. If real cutting temperatures, generated between the chip and tool on the rake face could be measured it would be possible to estimate the hot hardness required for the gear machining. However it is almost impossible to see the interesting area in machining and extra difficult in such a constrained area as when creating gears.

The test was made at Swerim , using a FLIR A50 51º R&D heat camera recently acquired by KTH, Figure 14. It has 2 temperature ranges, -20 to +175 ºC and 175 to 1000ºC. The analysis of the measurements was made using FLIR Research studio.

Figure 14   FLIR A50 51° R&D camera

The camera is pointed at the tool rake face as it exits the work.
The setup is shown in Figure 15.

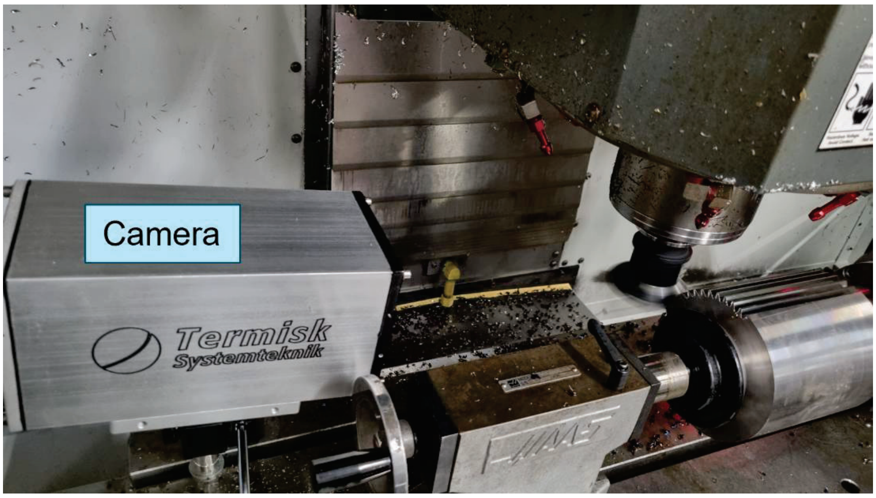


Figure 15 Heat camera mounted with the test setup which is rotated 180 degrees.

5 Results

5.1 Wear testing using the single insert test method.

Test site 1 - Erasteel

These tests were performed at Erasteel, more test results and detailed analysis can be found in the thesis work done at Erasteel by Andrea Roa (Roa, 2022).
To determine the influence of cutting parameters, the inserts were continuously analysed at regular intervals by LOM to record the wear progression until the wear out criteria were met. The wear-out criterion, and thus the end of tool life was defined as the point at which either crater wear on the rake face reached and damaged the cutting edge, and/or the flank or nose wear exceeded 200 µm.
The influence of cutting speed on crater wear progression for the grades ASP®2052 (8% Co) and ASP®2190 (29% Co) is shown in Figure 16 (Hex =0,18 mm) , Figure 17 (Hex=0,20 mm) and Figure 18 (Hex =0,22 mm). There is a clear correlation between the cutting speed and how fast the crater wear appears and progresses. ASP®2190 outperforms ASP®2052 in all these trials.
For the chip thickness 0,18 mm, Figure 16, the dominant wear type is crater wear for all types except for ASP®2190 with the speed 220m/min which had to be stopped due to flank wear criteria being met at 6 meters of slot cut. The tool life for ASP®2052 was very short when applying the cutting speed of 280 m/min.
Crater wear was the dominant wear type for the trials with the chip thicknesses 0,20 mm and 0,22 mm, Figure 17 and Figure 18. As chip thickness increases the craters get larger in size and appears earlier. For the higher chip thickness 0,22 mm The tool life for ASP®2052 was very short when applying the cutting speeds of 250 and 280 m/min.
It can be concluded from these tests that ASP®2052 has a very short tool life at cutting speeds above 220 m/min, while for ASP®2190, the start of the formation of crater wear is influenced by the cutting speed, it can withstand much higher speeds.
The cobalt free grades ASP®2023 and ASP®2062 were also tested with the same cutting parameters at a cutting speed of 220 m/minutes at a later time. However, these inserts would not wear out even after 8 meters of gear slot produced and no crater wear was formed, indicating some fault with the test-setup at that time.

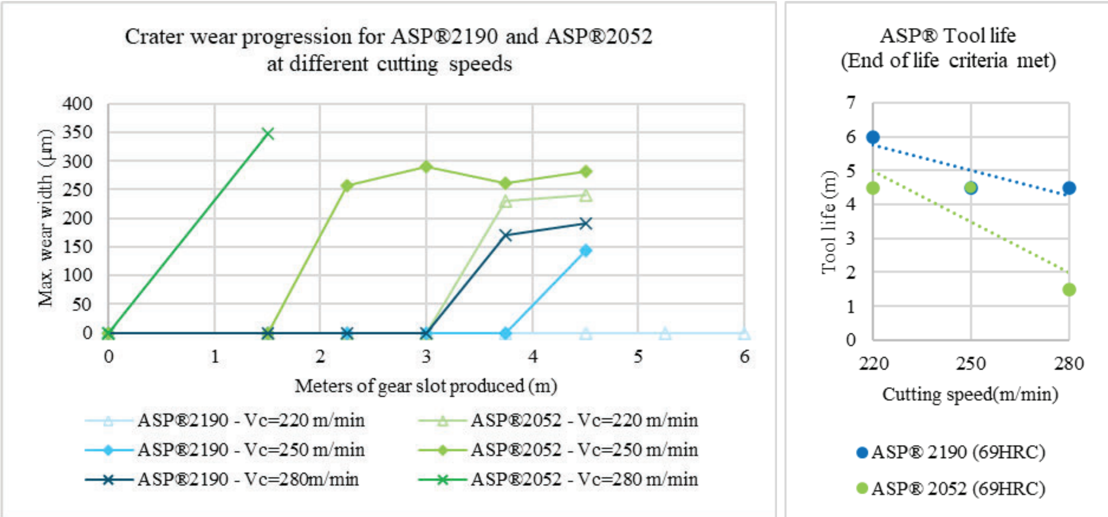


Figure 16 Comparison of the performance of ASP®2052 and ASP®2190 at different cutting speeds, work material Ovako 236F. Hex 0.18, In-feed angle 20 degrees. Crater wear (left) and tool life (right) for the same samples.

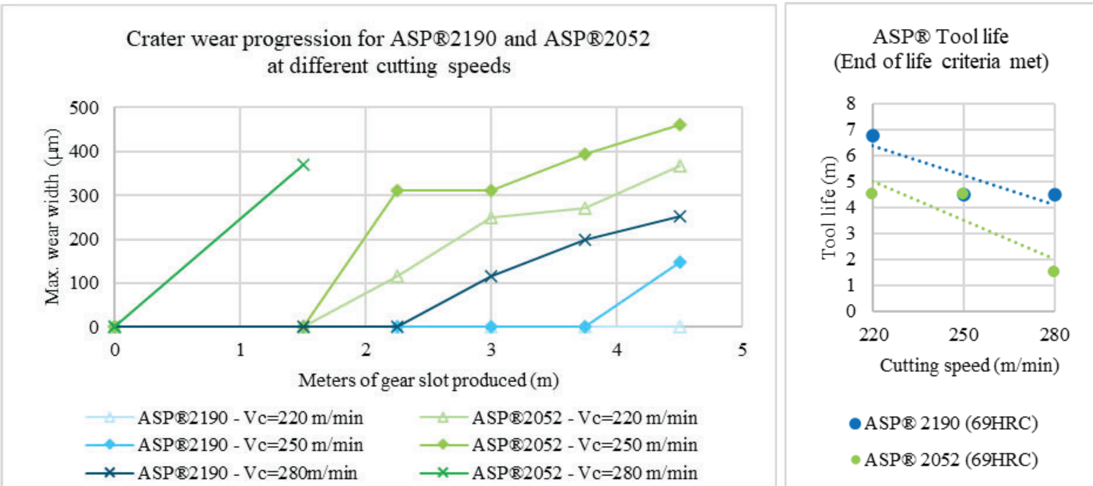


Figure 17 Comparison of the performance of ASP®2052 and ASP®2190 at different cutting speeds, work material Ovako 236F. Hex 0.20, In-feed angle 20 degrees. Crater wear (left) and tool life (right) for the same samples.

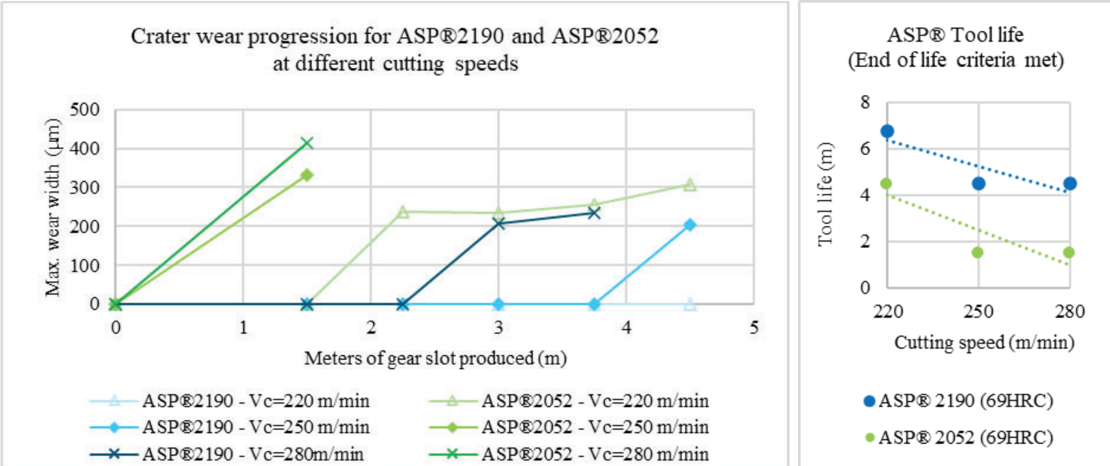


Figure 18 Comparison of the performance of ASP®2052 and ASP®2190 at different cutting speeds, work material Ovako 236F. Hex 0.22, In-feed angle 20 degrees. Crater wear (left) and tool life (right) for the same samples.

The cutting performance of the grades ASP®2023 (no Co), ASP®2062 (no Co), ASP®2052 (8% Co) and ASP®2030 (8,5% Co - with two different hardnesses) was evaluated at a cutting speed of 180 m/minute with otherwise same cutting conditions, Figure 19. Flank wear was the dominant wear type at this lower speed when a 20 degree in-feed angle was used. Flank wear typically progresses through three stages: an initial phase characterized by edge damage such as chipping; a steady wear phase caused by friction and abrasion between the workpiece and the tool's flank face; and finally, a stage of accelerated flank wear. The wear appears first in ASP®2023, followed by ASP®2030 (67HRC), ASP®2062 and lastly in ASP®2030(66HRC) and ASP®2052. The Flank wear then increases at a steady, linear pace in all 5 samples until rapid accelerated wear takes over. Wear out criteria is reached in ASP®2023 first, followed by ASP®2030(66HRC) and ASP®2062 and lastly in ASP®2052 and ASP®2030(67HRC).

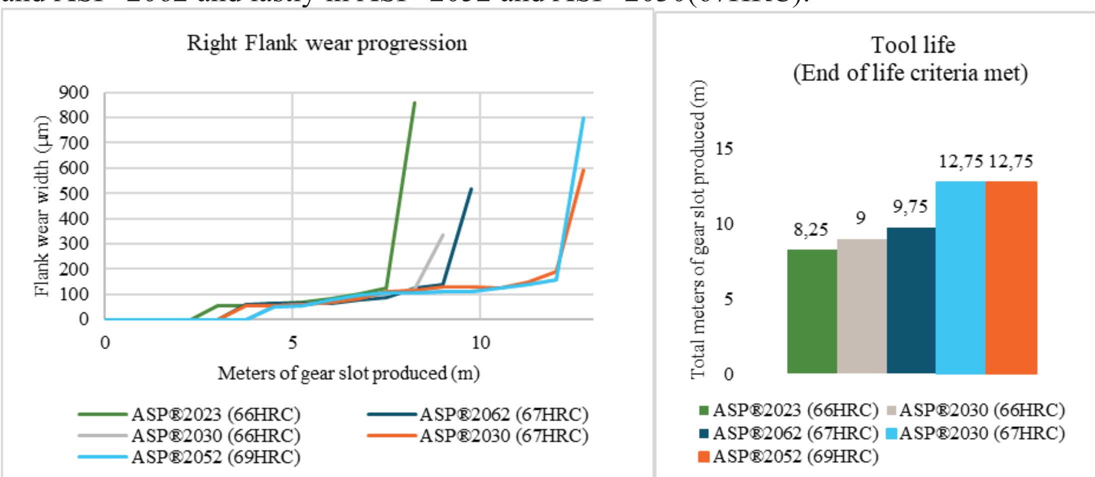


Figure 19 Performance of ASP®2023, ASP®2062, ASP®2052 and ASP®2030 with different hardness. Work material Ovako 236F. Vc=180m/min, Hex=0,22mm, In-feed angle=20 degrees. Right flank wear progression (right) and Tool life (right) for the same samples.

The influence of different work materials on the cutting performance of ASP®2052 can be seen in Figure 20. Crater wear develops at approximately the same cutting length when machining 236F and 280X materials. However, in 280T, crater wear begins to form significantly later, in fact the tool lasts more than twice as long.

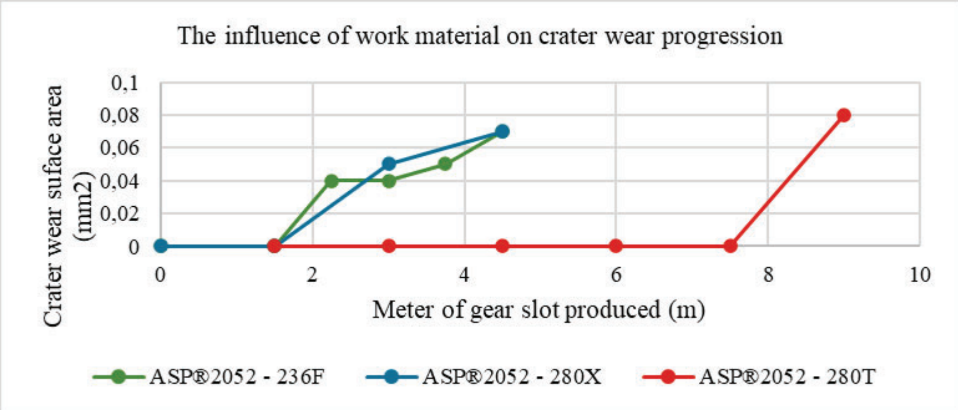


Figure 20 The performance of ASP®2052 when cutting in the work materials 236F, 280T and 280X. Vc=220m/min, Hex 0.22, In-feed angle 20 degrees.

In addition to the 20 degree in-feed angle used in the tests above, two more angles were tested at 0 and 30 degrees, Figure 21 and Figure 22 .
Left flank wear is promoted at a 0 degree in-feed angle and the wear appears more or less at the same time (3-4,5 meters) and the wear progresses at a steady until accelerated wear mechanisms take over. ASP®2023 and ASP®2030 with same harness (66HRC) are the first to reach wear out criteria, followed by ASP®2062 and ASP®2030 with the same hardness (67HRC).

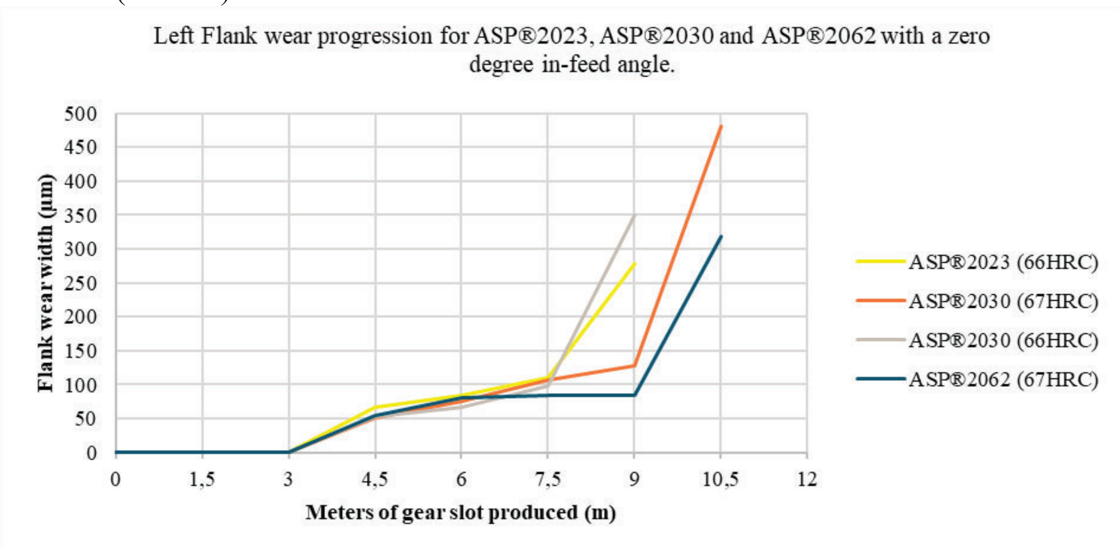


Figure 21 The performance of ASP®2023, ASP®2030 at two different hardnesses and ASP®2062, when applying a 0-degree infeed angle. Work material Ovako 236F. Vc=250m/min Hex=0.08 mm.

Crater wear is promoted at 30 degrees in-feed angle similarly to the 20 degrees angle, however it is seen for these cutting conditions that the speed of 250 m/min is too harsh on inserts, reaching the edge after only 1,5 meters cut. At 220 m/min cutting speed the crater is located further from the edge and grows slowly. The cobalt free inserts ASP®2023 and ASP®2062 are the first to reach the edge at 3,75 and 4,5 meters of cutting and the two ASP®2030 inserts reach wear out criteria at the 6-meter mark, with slightly bigger crater for the insert with 1 HRC lower hardness. LOM images of the difference in crater wear size can be seen in Figure 23. The thermal softening measured by means of Vickers Hardness (HV) profiles, in the cross section of the crates wear can be seen in Figure 24. The thermal softening seems to be going as deep as approximately up to 300 µm depth. A representative LOM image of one of these measured cross sections can be seen, in Figure 25 , revealing the heat affected zone underneath the surface of the crater as well as the absence of coating in the crater and cutting edge.

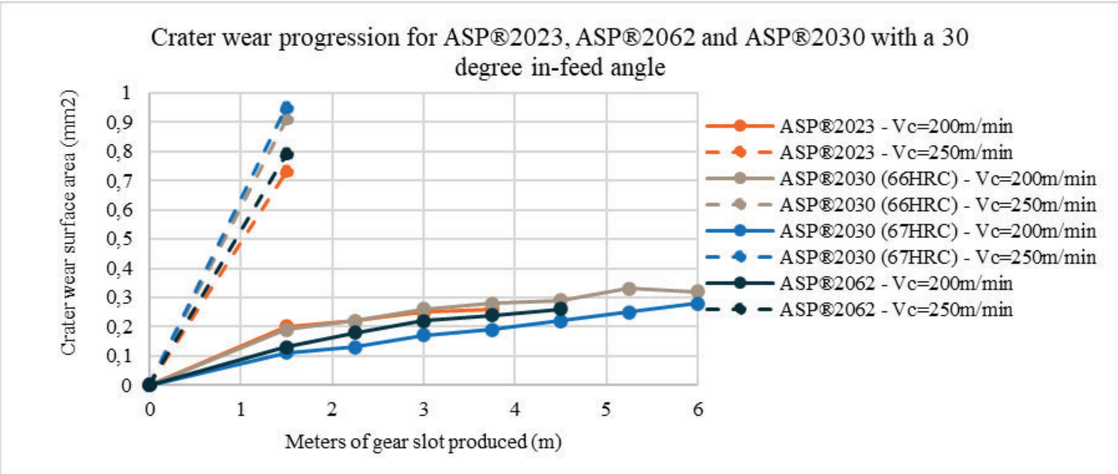


Figure 22 The performance of ASP®2023, ASP®2062 and ASP®2030 at two different hardnesses, when applying a 30-degree infeed angle. Work material Ovako 236F, Hex=0.25 mm.

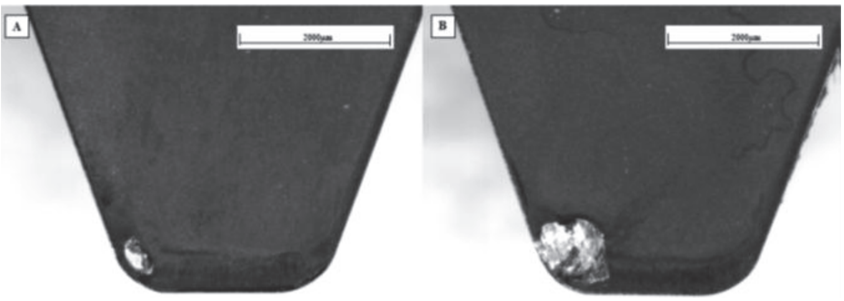


Figure 23 LOM image of the crate wear seen on ASP®2062 at 1,5 meters of cutting with a cutting speed of 200 m/min (A) and at 250 m/min (B) when applying an in-feed angle of 30 degrees and a chip thickness of 0.25 mm.

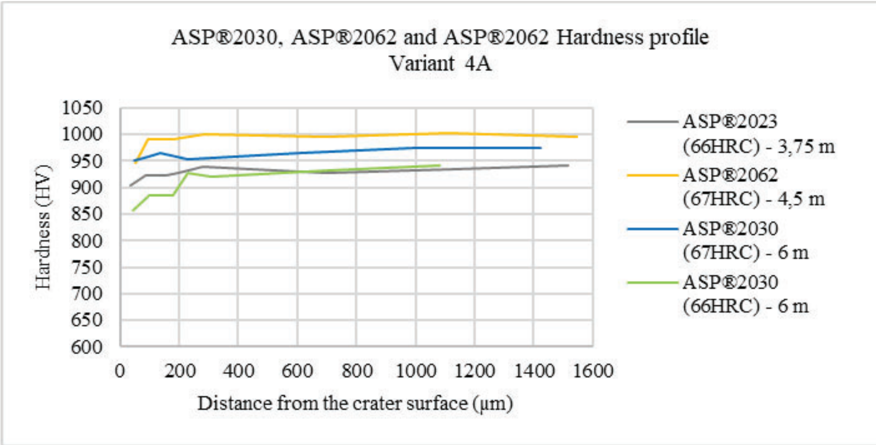


Figure 24 Thermal softening of ASP®2023, ASP®2062 and ASP®2030 at two different hardnesses, when applying an in-feed angle of 30 degrees, a cutting speed of 250 m/min and a chip thickness of 0.25 mm.

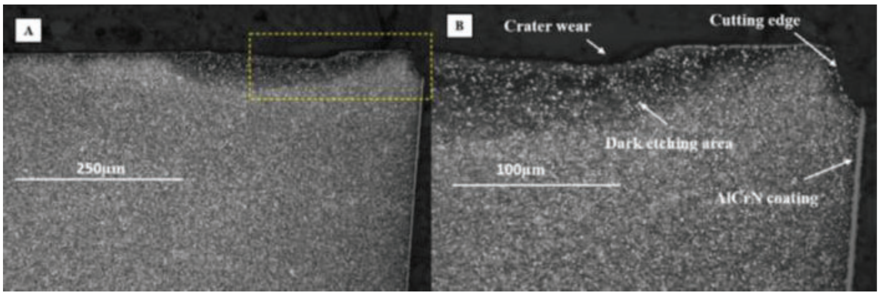


Figure 25 Etched cross-section in LOM, of a representative worn cutting insert showing (A) the heat affected zone and (B) Magnification of the area pointed in (A) where complete detachment of the coating layer on the crater surface and cutting edge can be seen. The rake face is the upper horizontal side.

Test site 2 - Swerim

A great number of test inserts have been run at Swerim to study the method itself and how the setup should be used. One problem with the test is to find a good tool life limit criterion that gives a well defined tool life value and is relevant to the process.
Initial tests showed that four factors are really important in controlling the wear type and appearance, the distribution on the edge and the wear rate during the test. They are in feed angle (influences how the groove is cut by which part of the insert nose), the feed rate and cutting speed and the work material.
Other factors that are important is the stability of the machine tool and fixtures and the tool material. In the project we made life difficult by using five work materials, five tool materials and two test sites. We also aimed at finding test data to promote both flank wear and crater wear. It was nearly impossible to get enough points to cover all variants.
Early tests at Swerim when the range of test data was determined were made using the 236Z work material. The tests showed clear results indicating that a combination of low infeed angle (0-10º) and low feed rate (hex=0.08 mm/r) promoted flank wear on the upper corner of the tool nose, Figure 26.

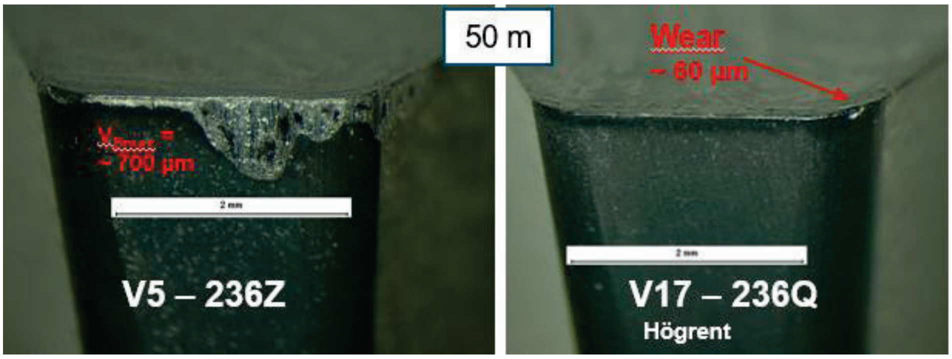


Figure 26 Low feed hex 0.08mm/r and

To promote crater wear a higher infeed angle (30º) should be used and a higher feed rate, hex~0.30 mm, resulting in a crater on the lower corner of the tool nose, Figure 27. The cutting speed used was around 250 m/min.

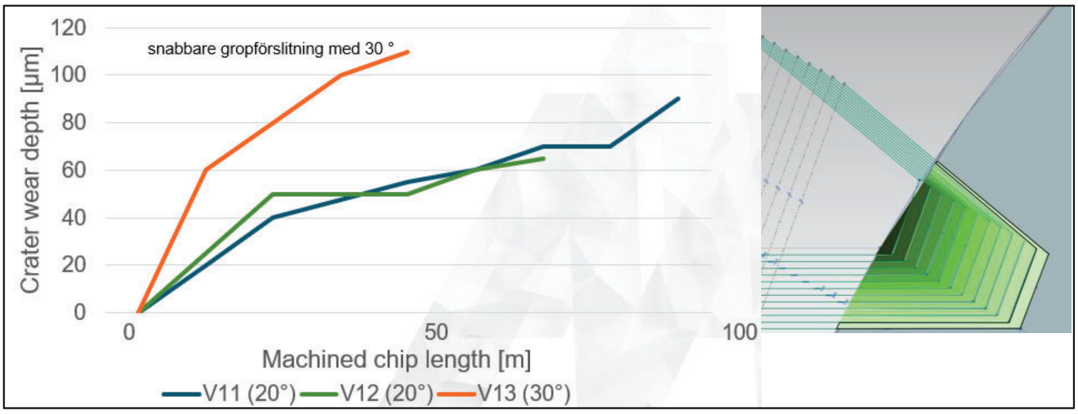


Figure 27 Higher infeed angle promotes crater wear.

When applied at Erasteel, these data gave tool lives too short for comparisons between tool materials. So a more moderate mid point, the new reference data was developed, with a cutting speed of 220 m/min, an IFA of 20º and a hex of 0.22 mm.
The new work piece material 280T also caused some problems in that it wore the tools so slow that testing times were getting very long. In order to get good tests comparisons between ASP2052 (8%Co) and ASP2062 (0% Co) 236Z blanks were used. This again led to clear results.

At data considered high (v250/hex0.25/IFA30) the ASP2052 clearly outperforms the Co free ASP2062 that shows a huge crater across the whole nose after only 4 grooves. The ASP2052 survives 36 passes around 5 m cut but with a big crater, Figure 28 and Figure 29.

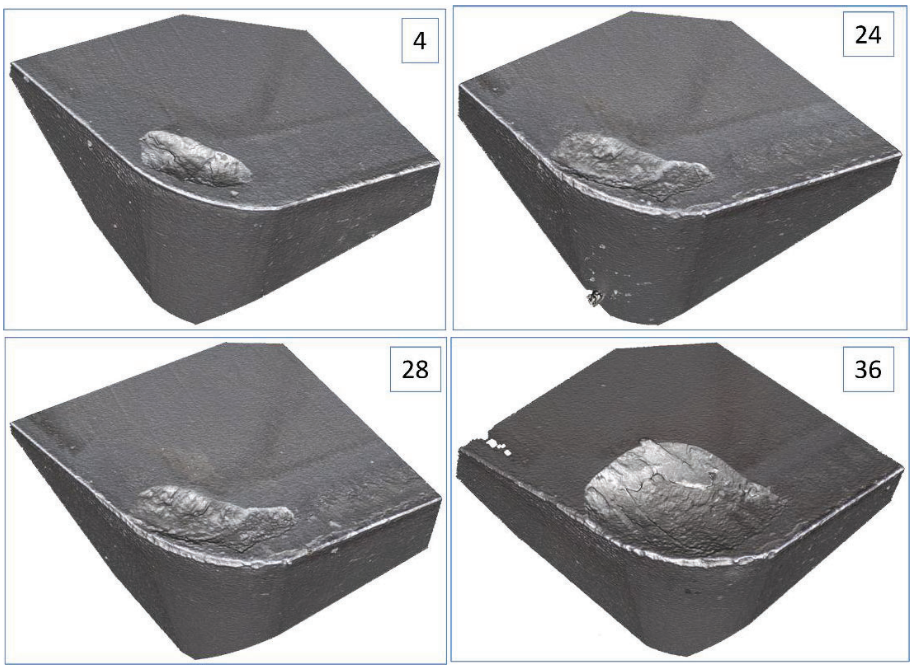


Figure 28 ASP2052 at extreme data, v=250m/min, hex=0.25mm and IFA=30.

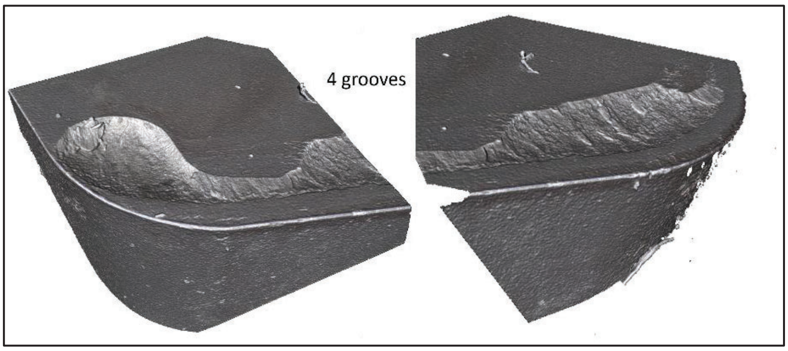


Figure 29   ASP2062 after only four grooves at v=250m/min, hex=0.25mm and IFA=30.

This is a very high speed not reachable in many gear manufacturing situations.
A relatively small lowering of speed and feed and a change in feed angle (v220/hex0.22/IFA20) reduces the wear considerably and also promotes some flank wear. It also reduces the difference in wear between the tool steels, showing that at moderate data ASP2062 is more competitive and actually runs up to 60 full grooves with very moderate wear, whereas the R35 insert (ASP2052) performs well up to 54 grooves where it fails completely.

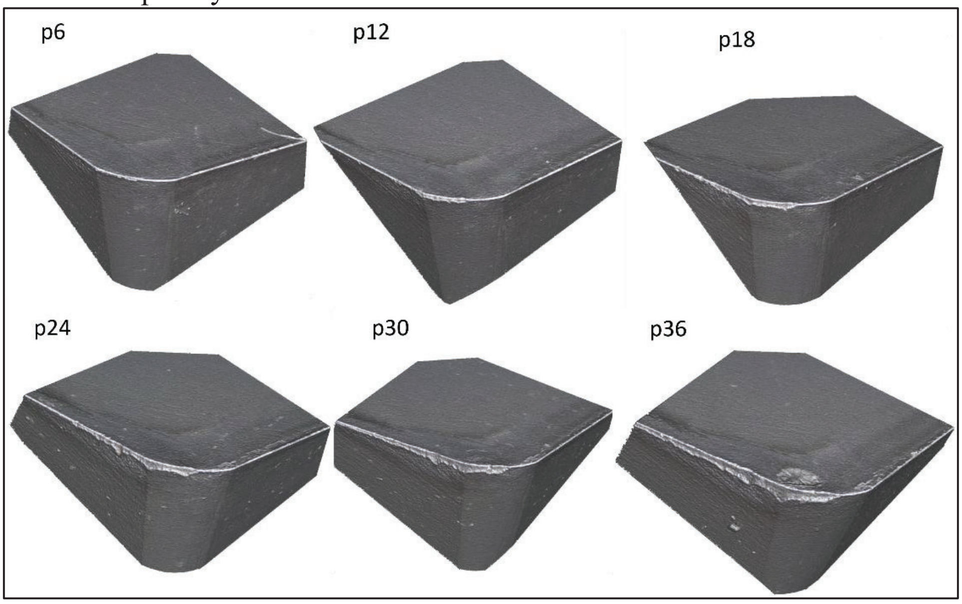


Figure 30 ASP2052 (R35) at moderate data, v=220m/min, hex=0.22mm and IFA=20.

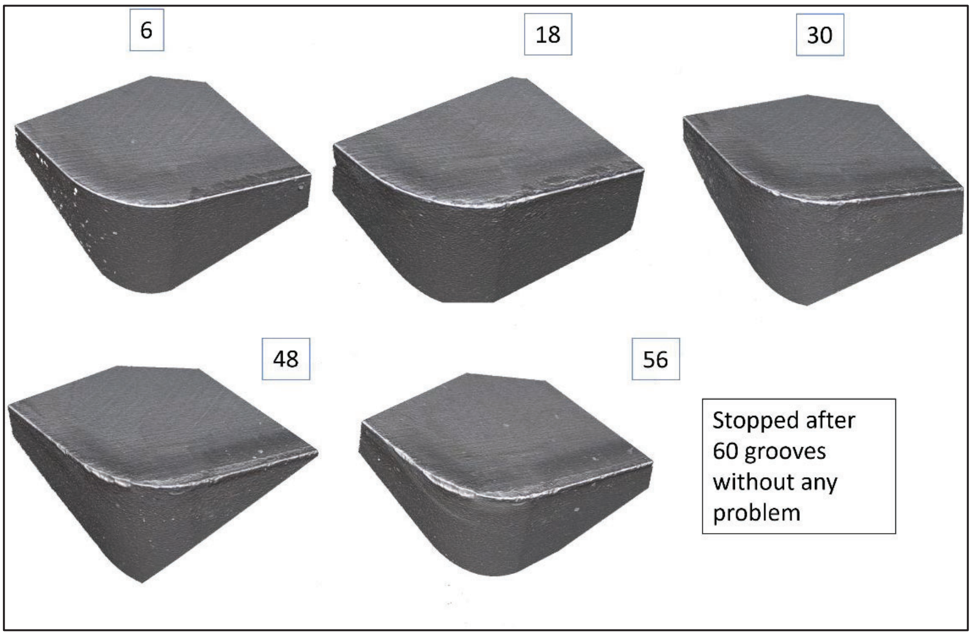


Figure 31 ASP2062 (62034) shows very little wear, life>60 at v220/0.22/20

The tests showed clear results for a few more cases such as that the more unclean variant 280X gave more wear than 280T in the tests. In most cases it was not possible to get any differences between the tool materials when cutting 280T. A crater would start to form but the growth would be very, very slow despite that the coating is removed. For reasonable test times to be achieved a more standard work material as the 236Z must be used.

Summary of test results – both sites

The single insert milling test conducted on a three-axis milling machine effectively replicated the wear mechanisms observed in actual gear hobbing operations, as documented in previous literature and confirmed through hobbing trials. The testing has provided a comprehensive evaluation of the cutting performance of various ASP® tool grades under different machining conditions. The results clearly demonstrate the significant influence of cutting speed, in-feed angle, work material, and cobalt content on both crater and flank wear progression.
Both abrasive and adhesive wear were consistently identified on the rake face, flank face, and cutting edge of the tools. Among the various wear types, crater wear emerged as the most dominant when applying high cutting speeds, developing within relatively short machining times and often surpassing the wear-out criteria across most test variants.

This crater wear is primarily attributed to thermal softening of the high-speed steel substrate. Its progression was found to be highly sensitive to increased cutting speed and feed rate that accelerated crater wear and consequently reduced tool life. Conversely, lower values for these parameters tended to promote flank wear, associated with less efficient chip removal and friction between the tool's flank face and the machined surface.

The study also demonstrated that by adjusting the in-feed angle and feed rate, it is possible to influence the dominant wear mechanism.

Furthermore, the type and composition of the tool material played a significant role in wear resistance. ASP®2190, with its higher cobalt content (29wt% Co), consistently outperformed ASP®2052 (8.5 wt% Co) across all cutting speeds, showing greater resistance to crater wear. Among the other tested grades, ASP®2030 (8wt% Co) delivered the best performance, followed by ASP®2062 and ASP®2023, both of which are cobalt-free.

The influence of cobalt was particularly evident when comparing ASP®2030 and ASP®2023, which share similar hardness and alloying elements aside from cobalt. Despite these similarities, ASP®2030 exhibited significantly better cutting performance, underscoring the beneficial effect of cobalt in enhancing wear resistance.

In-feed angle variations further highlighted wear behaviour differences. A 0° angle promoted flank wear, with ASP®2023 and ASP®2030 (66 HRC) wearing out earliest. At 30°, crater wear was accelerated, particularly at 250 m/min, where inserts failed rapidly. Thermal softening and coating detachment were observed in cross-sectional analyses, confirming the severity of thermal effects at high cutting loads.
Overall, the study underscores the importance of optimizing cutting parameters and material selection to enhance tool life and performance in gear slot machining.
The influence of work material was also evident, with ASP®2052 lasting significantly longer in Ovako 280T compared to 236F and 280X.

5.2 Validation trials 1 – Hobbing

All teeth on the hob are not worn equally much so the wear reported here is concentrated to the most worn teeth. The gear hobbing test wear results are summarized in Table 6. The wear level is estimated on a 6 degree scale with 5 being severely worn and 0 not worn at all.
The reference tool shows very little wear on both the rake and flank face in the first 2 trials, up to 300 details produced.
After 350 details, very small fragments are removed from the edge line leading to maximum flank wear levels of around 50µm. After 450 details, there is a clear crater on the edge line on the rake face reaching 0.12-0.13 mm in from the edge line. The identical test, no 5, showed the exact same appearance.
At trial 6, the increased axial feed did not increase the wear level (still a rake face crater around 0.125 mm wide) but made it a little more well-defined. In addition to the crater, the hob teeth also showed some very small chippings. The wear level reached may motivate sending the hob for resharpening but it could possibly be run for 50-100 details more.

Table 6 No of details and feed at each test. Also an estimated wear index

ASP2052 test no	1	2	3	4	5	6
# details/feed	250/4.4	300/4.4	350/4.4	450/4.4	450/4.4	450/4.9
Wear level	small, 1	small, 1	small, 2	medium 3	medium 3	medium 3
ASP 2062 test no				1	2	3
# details/feed				450/4.4	450/4.4	450/4.9
Wear level				medium 3	medium 3	medium 3.5

For the ASP2062 the wear looks the same as for the reference at the low feed, both in appearance and size, a small crater at the edge line with around 75 µm depth. At the higher feed the crater gets a little bigger for ASP2062 but the wear level is not critical and the level is within the limits for resharpening.

The appearance of the wear is shown in Figure 32 with the reference to the left and the Cobalt free ASP2062 to the right. Thus, at these cutting data ASP2062 is a valid alternative material.

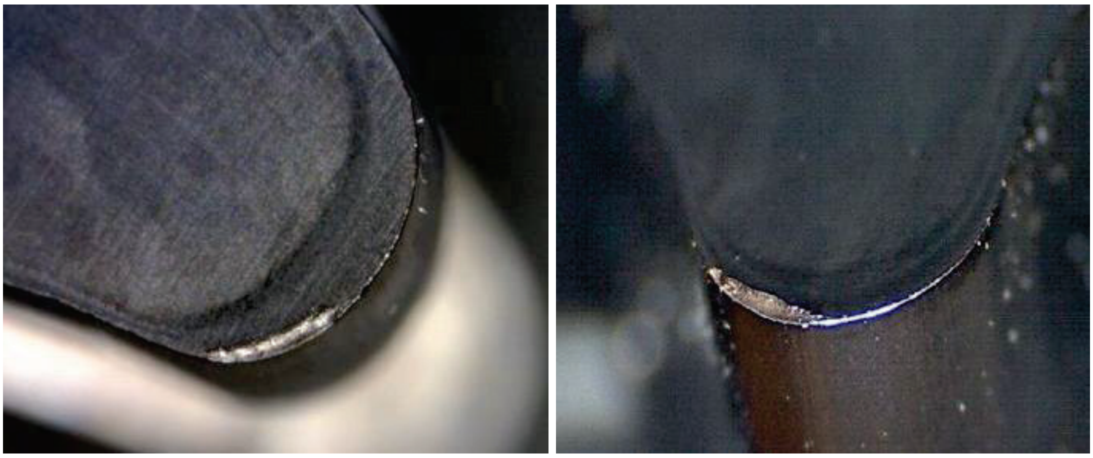


Figure 32 Max wear at 4.9 mm/rev. left: ASP2052, crater depth 50µm, right: ASP2062 75µm.

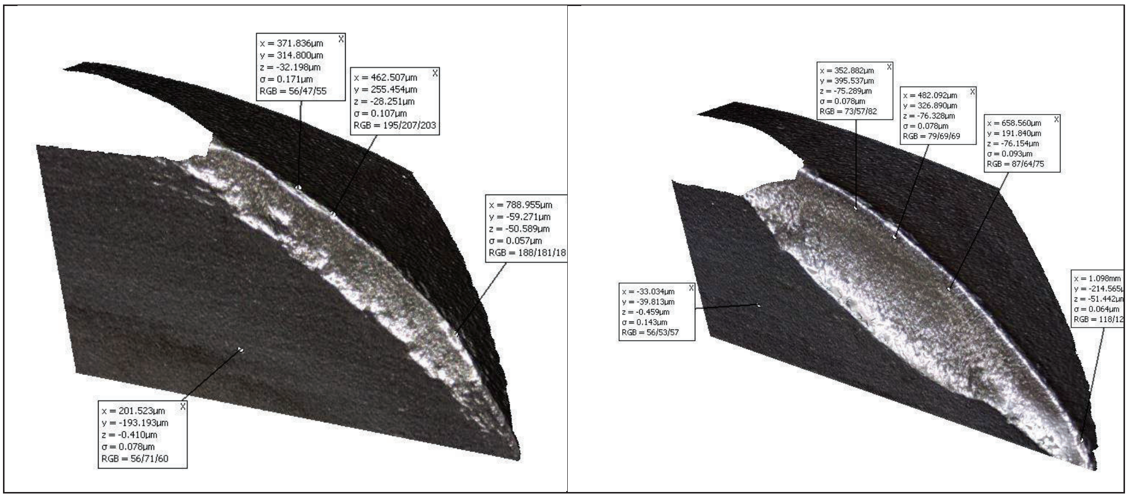


Figure 33 Tool ASP2052 left and ASP2062 right. Worst worn teeth at feed=0.49 mm /rev

5.3 Validation trials 2 – Power skiving

ASP2190 vs ASP2052

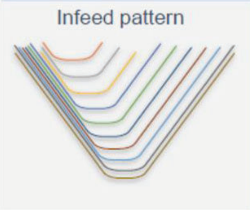
In these trials ASP2190, a material with 26% Co, is compared with the reference ASP2052. The tests took place in Köping on the DMG Moori machine and ring blanks from a previous project was used as work material. The details produced here would not be sold so there was some room for expanding the range of cutting data. The aim was to see if the ASP2190 would give good results at higher cutting speeds thanks to the materials increased hot hardness. The test method results from Erasteel showed that the ASP2190 outperformed the ASP2052 at high speeds.
Three tools of ASP2190 were available, named X1, X2 and X3 as well as two tools of ASP2052 named P1 and P2. All tools were inspected before the tests and in addition the 7 teeth to be measured at each stop were measured.
The amount of blanks were limited. A mix of different test materials 236Q, 236F and production material was available as well as some discarded pieces arriving from Rezekne. Therefore the materials were mixed so that all tools were run with the same number of each work piece material.
The new speed was set to 175 m/min equalling 827 rpm for the work piece and 1704 rpm on the tool. This is 52% faster than our original skiving tests. The hex on the nose of the tool teeth is set to 0.25 mm and the radial feed is slightly reduced. The total cutting depth is 4.475 mm in 10 steps from 0.56 to 0.34 and 0.25 in the last fine step where the hex is as low as 0.062. The tests are run with full flow on the cutting fluid. In our setup the cutting fluid is vital for removal of the chips. The cutting data is summarized in Table 7.

Table 7 Cutting data for each pass of the skiving operation

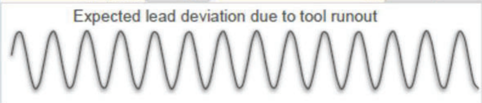
Part data				Tool data			Setting data		
Tip diameter	193,25	mm		Tool tip dia.	62,8	mm	Total feed length	41	mm
Nr of teeth	113			# of teeth	36		Overtravel start	7	mm
Module	1,64	mm		Helix angle	0	deg.	Overtravel end	2	mm
Root diameter	202,2	mm		Face width	4,4	mm	Radial clearance	1	mm
Gear width	32	mm		Tool life	10	m/tooth	Radial feed	0,5	mm/rev
Pressure angle	19	deg.		Tool material	S390		Machining angle	-20	deg.
Helix angle	20	deg.		Coating	Alcrona		Max table speed	826	RPM
Material/Mpa	20MnCr5	700-750		Condition	wet		Max tool speed	2593	RPM

Process data

	Vc	Tool	Part	Feed	Cut Depth	Acc depth	Chip thickness	Flank infeed	Feed time	
Pass	m/min	RPM	RPM	mm/rev	mm	mm	µm	mm	sec	Pass
1	175	2593,4	826,2	0,443	0,605	0,605	243,6	-0,842	6,7	1
2	175	2593,4	826,2	0,455	0,56	1,165	241,5	-0,713	6,5	2
3	175	2593,4	826,2	0,466	0,54	1,705	243,2	-0,588	6,4	3
4	175	2593,4	826,2	0,478	0,5	2,205	240,8	-0,473	6,2	4
5	175	2593,4	826,2	0,492	0,47	2,675	240,8	-0,364	6,1	5
6	175	2593,4	826,2	0,507	0,44	3,115	240,6	-0,263	5,9	6
7	175	2593,4	826,2	0,524	0,4	3,515	237,8	-0,170	5,7	7
8	175	2593,4	826,2	0,543	0,37	3,885	237,5	-0,085	5,5	8
9	175	2593,4	826,2	0,565	0,34	4,225	237,4	-0,006	5,3	9
10	175	2593,4	826,2	0,2	0,25	4,475	72,5	0,000	14,9	10



Nr of impacts per tooth	2732	Axial feed time	69,1	sec.	
		Total cycle time	100,0	sec.	
Meter/tooth	4,68	Total cycle time	1,67	min.	
Nr of resharpening	4	Calc by	AB		
Parts per resharp	76	Drawing nr	0		
Parts per tool	304	Issue	0		



Template 1.00

The first two tools, X1 and P1, were run for 100 details. The skiving went very well, the rings were within specification and nothing indicated any problem during cutting. The appearance of the tools however were very different,Figure 34 and Figure 35.

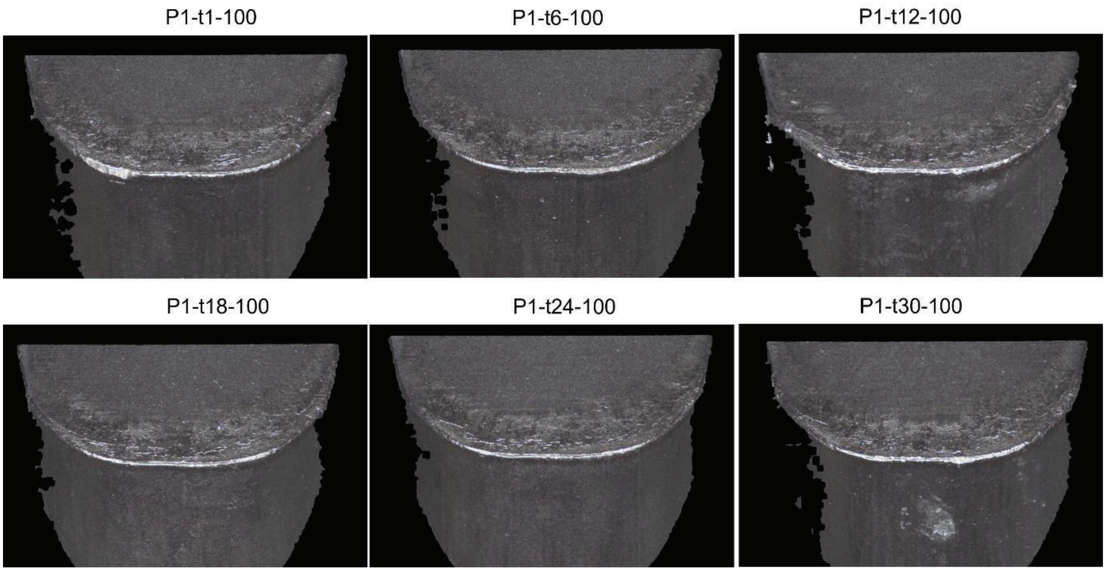


Figure 34 The appearance of the ASP2052 after 100 rings produced.

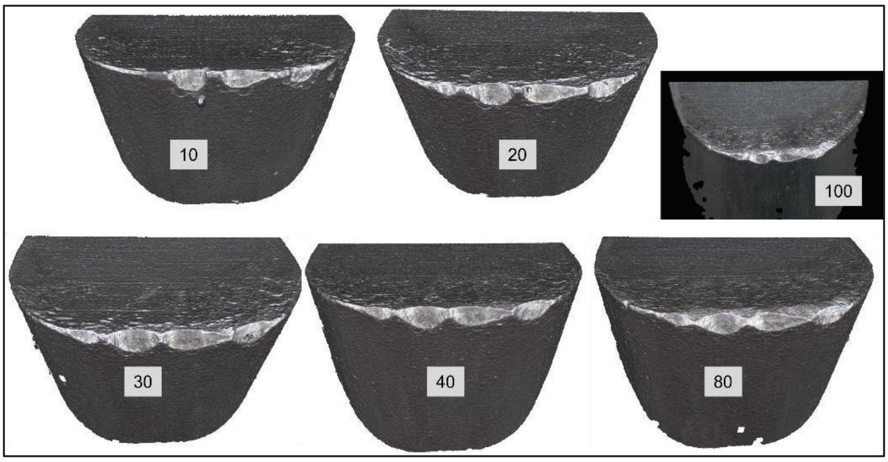


Figure 35 Wear development on ASP2190.

The ASP2052 was almost unworn the ASP2190 showed a lot of chipping that started to occur quite early after only 20-30 rings.

One more ASP2190 tool was run. Here the cutting was stopped after 70 details since 17 out of 36 teeth were chipped and the amount of big chippings was increasing fast

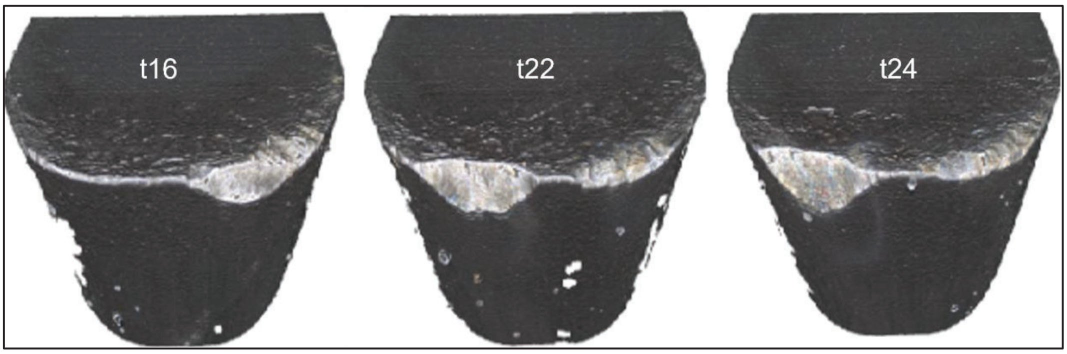


Figure 36 Example of chipped ASP2190 tool teeth.

From Table 7 we can see that the number of impacts per tooth after 100 rings is calculated to 237200 which is ample time for fatigue effects to occur.

- New software and a more conservative feed schedule in the program makes it possible for the ASP2052 material to perform at a considerably higher speed (+50%) than at previous trials.
- We do not detect any increase in tool life for the ASP2190 material in these tests. On the contrary, ASP2190 starts to show chippings earlier and gets a shorter tool life.
- The increased speed, closer to the limit for synchronization possibly increases the instability and vibrations associated with skiving and puts more demand on the tool toughness than on the hot hardness.

ASP2052 vs ASP2062

The ASP2062 trials took place in Rezekne, Latvia on the Gleason machine. These last trials were conducted here because of some trouble with failed test runs in Köping, probably related to fixture issues or in some way related to the machine stability. For these two trials, rings had to be purchased and only 120 rings remained for this test.

The Gleason is a much more stable machine than the DMG Mori and it was now available. The software on this particular machine is a little more limited so the number of passes had to be reduced from 10 to 8. To compensate for this, the final 8th pass was not a finishing stage but had the same feed as all other passes. The total cutting depth is the same as in previous tests. The cutting speed was set at 150 m/min, relatively high for our trials.

The cutting fluid delivery is much greater here compared with the DMG Mori machine and the fluid used is pure oil not an oil-water emulsion. The cutting data for each pass is shown in table YY. The chip thickness is around 0.24 mm as before. Another difference between test run 1 in Köping is that there is no flank infeed here so the cutting is not concentrated on one flank but completely symmetrical.

Table 8 Cutting data in Rezekne, Gleason machine.

Process data											
	Vc	Tool	Part	Feed	Cut Depth	Acc depth	Chip thickness	Flank infeed	Feed time	
Pass	m/min	RPM	RPM	mm/rev	mm	mm	µm	deg	sec	Pass
1	150	2223,0	708,2	0,38	0,827	0,827	240,2	0,000	9,1	1
2	150	2223,0	708,2	0,398	0,744	1,571	240,1	0,000	8,7	2
3	150	2223,0	708,2	0,419	0,664	2,235	240,3	0,000	8,3	3
4	150	2223,0	708,2	0,438	0,599	2,834	239,7	0,000	7,9	4
5	150	2223,0	708,2	0,465	0,528	3,362	240,2	0,000	7,5	5
6	150	2223,0	708,2	0,497	0,456	3,818	239,8	0,000	7,0	6
7	150	2223,0	708,2	0,525	0,407	4,225	240,2	0,000	6,6	7
8	150	2223,0	708,2	0,565	0,25	4,475	204,9	0,000	6,1	8

The tools were removed and measured every 5 or 10 rings. They are worn in very different ways. The ASP2062 gets small chippings after very few rings produced and the chipping continues to occur as the cutting time is increased but it is a stable process that does not exceed the wear level required for resharpening.

The ASP 2052 on the other hand looks very good without any damages up to 30 produced details. At that point chipping starts and these chippings look much more a result of brittleness. They are bigger and extend 0.25 to 0.4 mm down on the clearance face rendering the affected tooth useless and requiring a lot more material removal during resharpening to get back to the ideal geometry. Typical wear appearances are shown in the following 4 figures

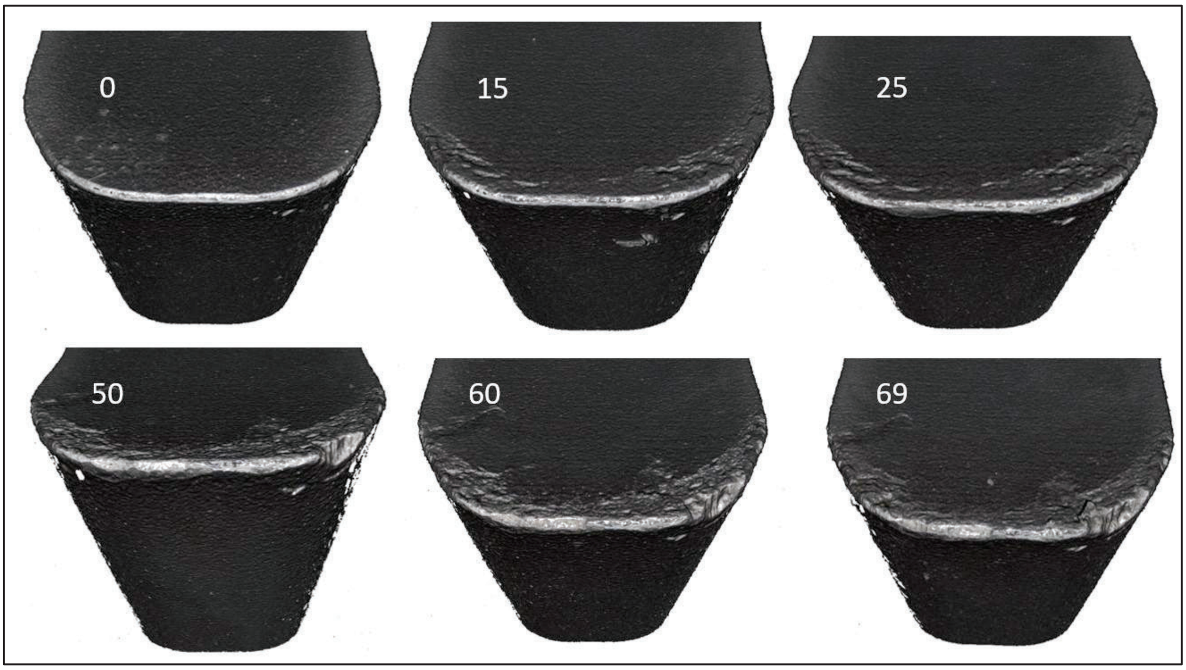


Figure 37 Typical appearance of ASP2062 tool with many small chippings

The ASP2062 tool is run for 69 rings and no tooth has reached tool life criterion at that point.
The ASP2052 tool is stopped after 50 rings since the number of chippings is increasing quickly and are at a high level already. Previous trials would have been stopped at this point to avoid massive damages to the tool.
Apparently there is a similar effect of hardness vs impact toughness here where the ASP2062 shows a tougher behaviour to better deal with vibrations and the increased hot hardness of ASP2052 is less effective due to the relatively low cutting speed.

Thus it seems that for this product, at these cutting conditions, the ASP2062 is a viable alternative to the Co containing tool materials.

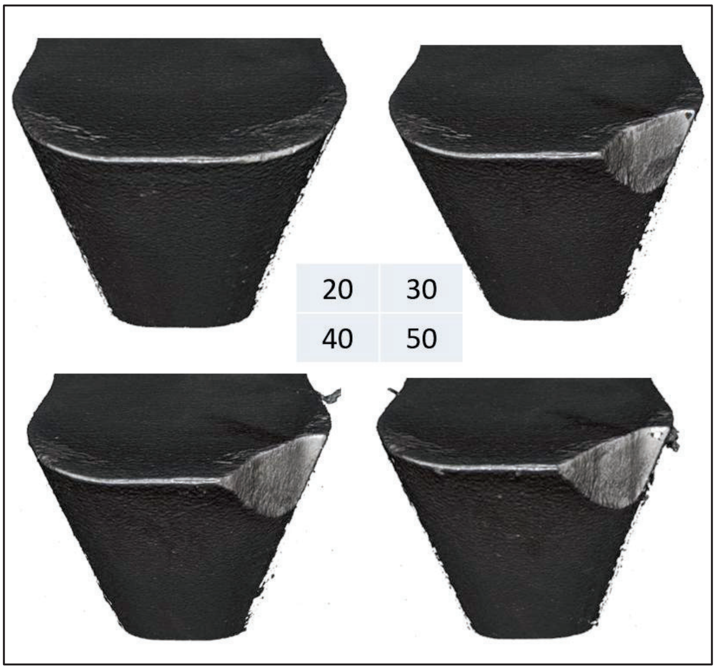


Figure 38 Typical appearance of early chipping in ASP2052. No growth after first appearance.

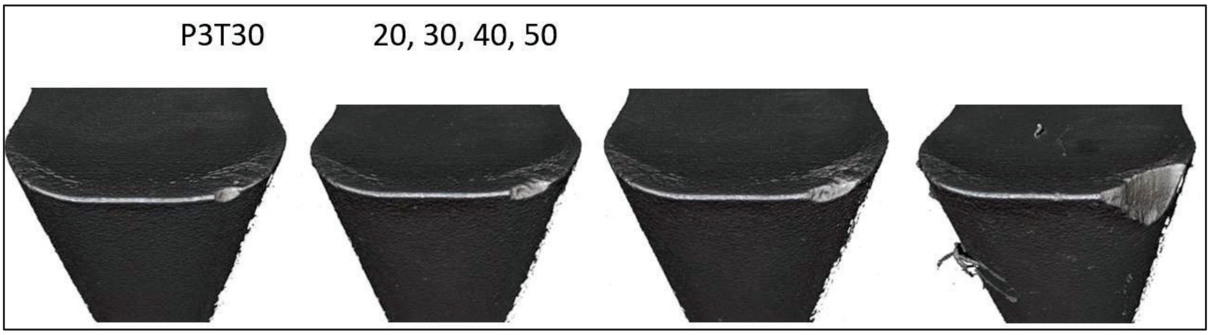


Figure 39 ASP2052. Rare case where a gradual wear has occurred with the same final result.

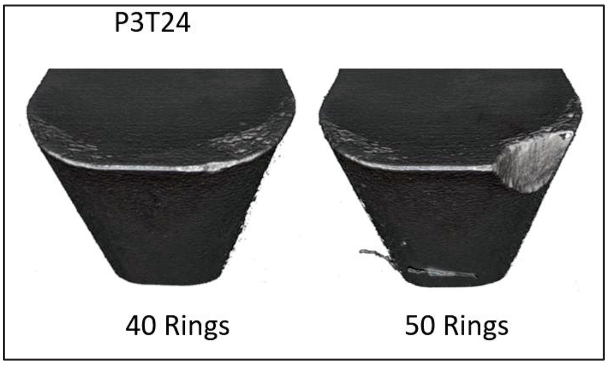


Figure 40 After 50 rings, so many big chippings are present that tool life is judged to be reached.

5.4 Test method detailed studies

Cutting force results

The standard center point was material 280T at v=220 m/min, hex=0.22 mm/r and infeed angle 20 degrees. Around this point some other combinations were tested including:
3 cutting speeds v, 180, 220 and 250 m/min,
2 feed levels hex, 0.08 and 0.22 mm/r,
3 infeed angles IFA, 0, 20 and 30 degrees,
3 work piece materials, 280X, 236F and 236Z.

General results - force measurements

For the cutting data mid point in the tests, there will be approximately 109 tool engagements per axial pass along the work piece. The theoretical time lap between entries is 77.1 ms. The tool actively cuts between 1.8 ms and 6.4 ms depending on the cutting depth since the tool is widening the groove, not just deepening it. Thus, there is a lot of idle time when the insert goes through air. The dynamometer vibrates for around 30 ms after impact, Figure 41.

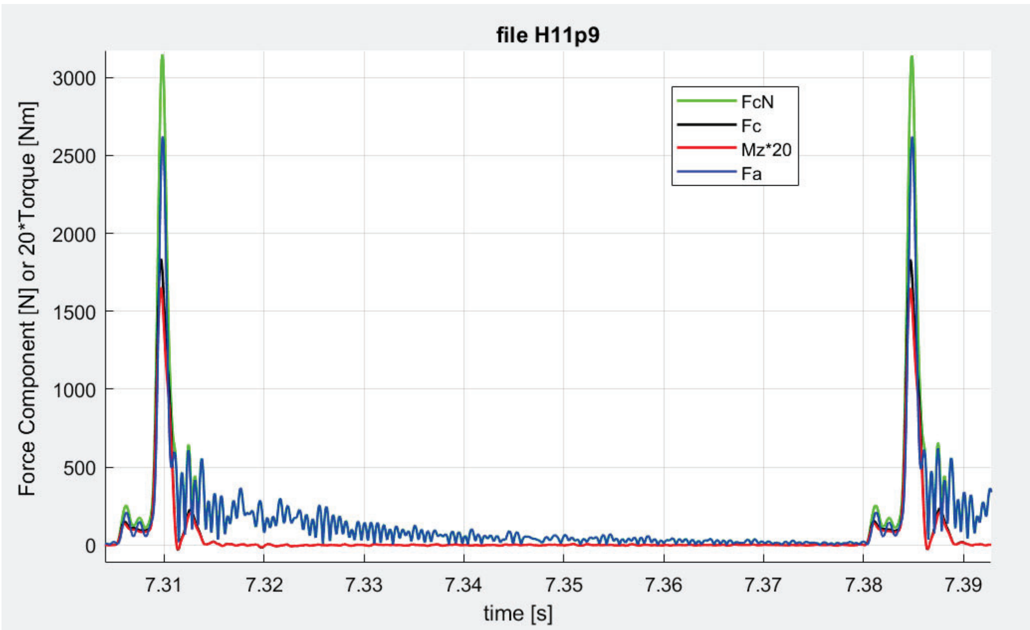


Figure 41 Example of one tool engagement, all force components and the torque Mz whose signal is much "cleaner" with no signal after the tool exit.

We are protecting the ten insert holder seats that are not used with smaller hard metal inserts. We can see that in some instances these protective inserts are engaging with the work piece. This will influence the wear test results if it happens too often since it reduces the amount of cutting the test insert will have to do. Fortunately, these extra tool engagements are quite rare, they occur only at the final three, deepest passes and could be due to the force measurement setup that is less stiff than the wear test setup. Also these secondary forces are small in comparison, Figure 42.

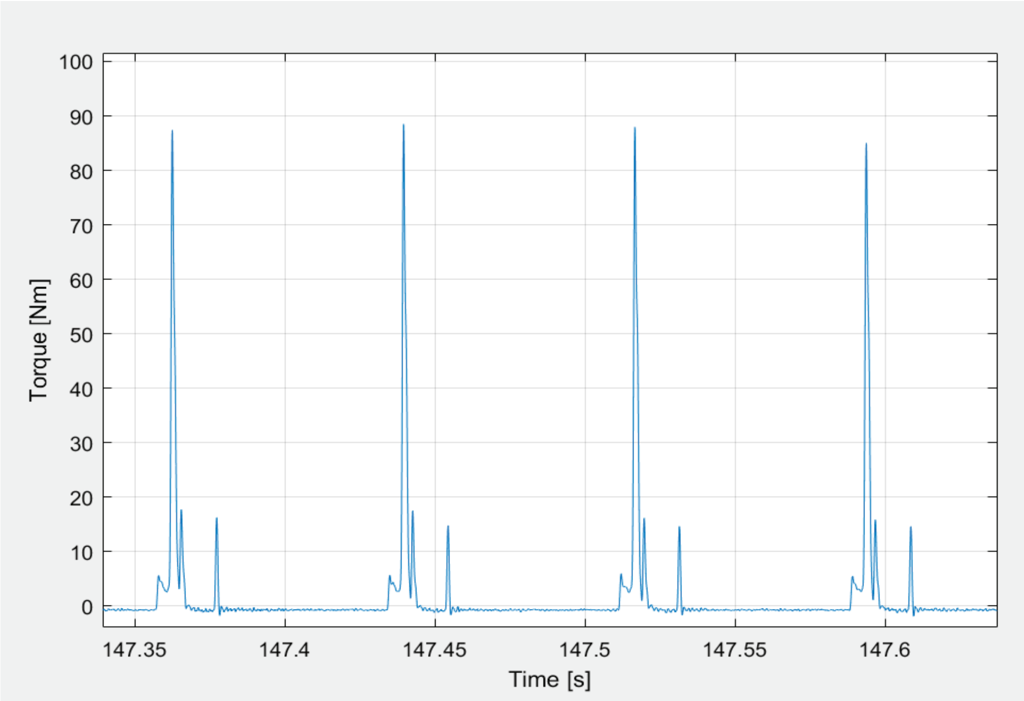


Figure 42 Torque measurement showing contact for the second protective insert

In the comparisons the maximum values of the Torque and the active force Fa have been detected for all tool engagements except 5-10 at the beginning and end of each pass as shown in Figure 43. The mean and standard deviation of the max values are calculated as well as a sum of the whole integrated signal. These values are used for comparisons.

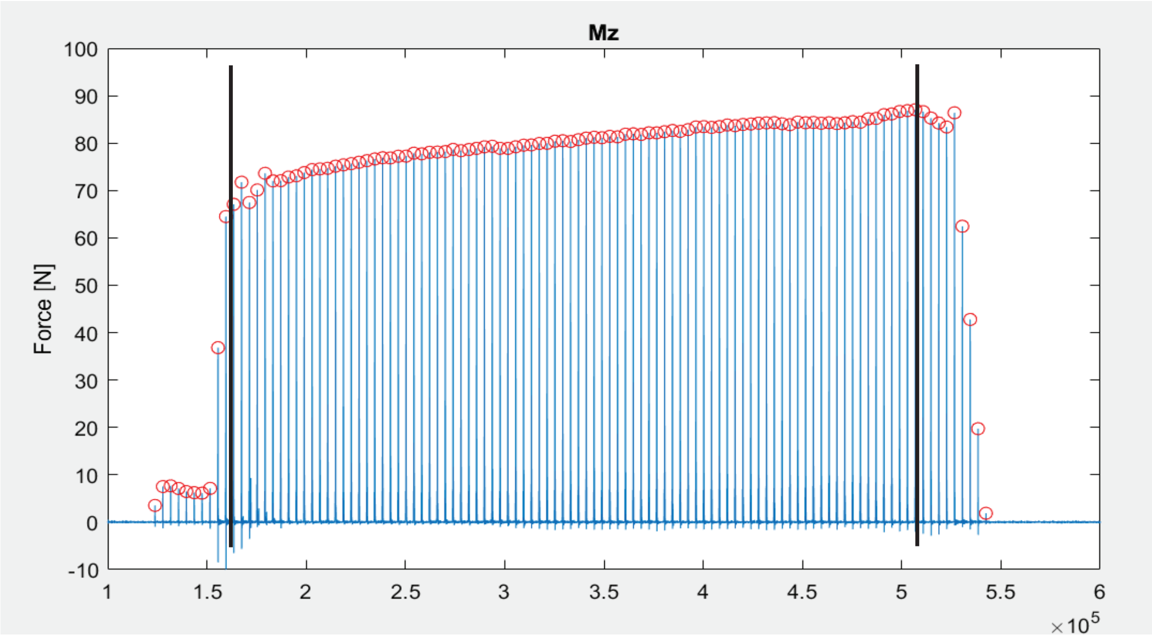


Figure 43 Maxima are detected for Mz and Fa and their mean values used for comparisons.

Some other general observations:

- The variation in the max forces are much higher at the lower feed (hex=0.08 mm/r). than at the high feed (hex=0.22mm/r) The difference between the fifth highest (1814N) and the fifth lowest force (824N) at low feed is very high.
- The forces generally increases from the start to the finish for one pass
- The variation in the max forces get bigger at the last passes, pass 10-12, especially for the low feed level.
-

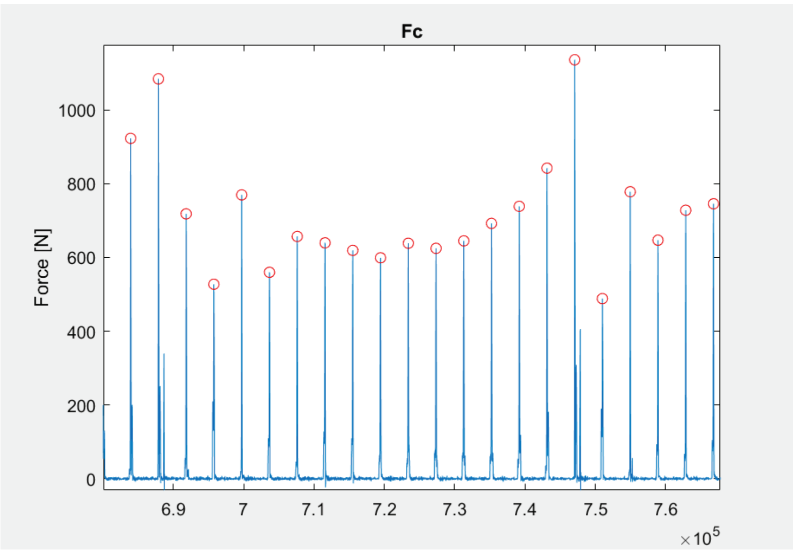


Figure 44 Variation in maximum of force component Fc during one pass.

The mean and maximum forces follows a pattern with increasing forces, up to 4 times as high at the last pass compared with the first, Figure 45. The reason for this is that the same feed is used for the whole test and more and more of the flanks are cutting as the groove is deepened and widened. In skiving one often tries to balance the feed so that the tool cuts an equal chip cross section at every pass to make the forces stay the same.

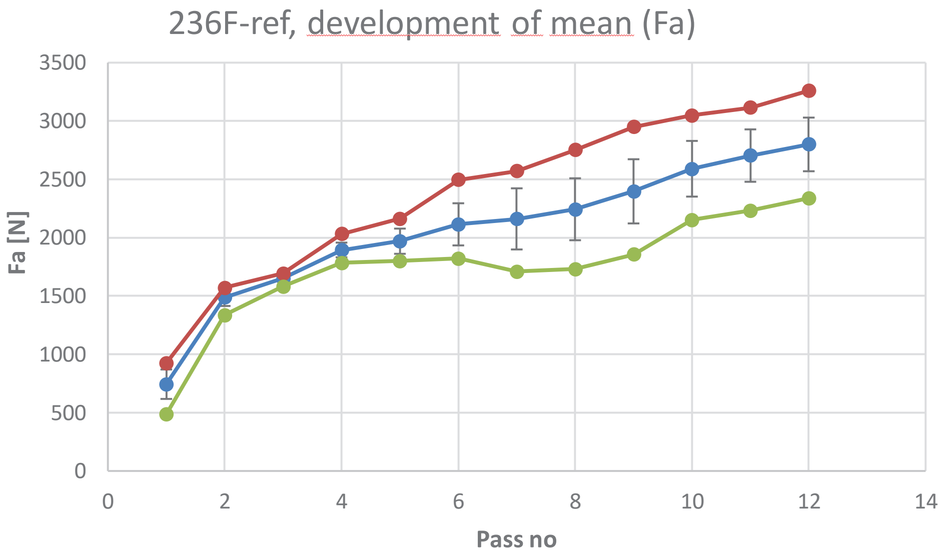


Figure 45   Development of mean, min and max force Fa at midpoint reference data

Influence on forces of different test parameters

In the following figures Fa is used for comparisons between test runs. The mean, the standard deviation and the integrated Fa signal is used. One of the test cases is used as reference to normalize the data so that the percentage difference can be plotted. 0.3 % is added so that all staples are visible. All comparisons are made for the 9th pass out of 12.

The difference between the 3 work piece materials used is shown in Figure 46. The 236F material differs from the 280 variants, showing lower mean active force Fa but a higher variation in the forces. The “dirtier” 280X shows higher integrated signal and significantly higher variation in forces compared to the clean 280T.

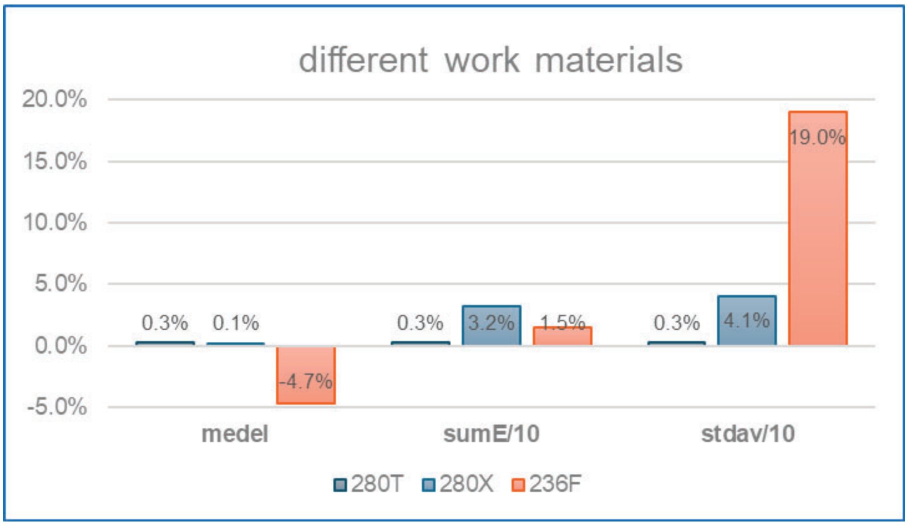


Figure 46 Comparison between the three materials used, data midpoint, 9th pass.

Forces for three infeed angles were measured. There is less variation between the mid point 20˚ and the 0˚ IFA than expected. Whereas the 30˚ IFA gives significantly lower mean values and higher Fa variations. There is no way to relate this to the wear detected. Here the Fz component could be interesting to look at.

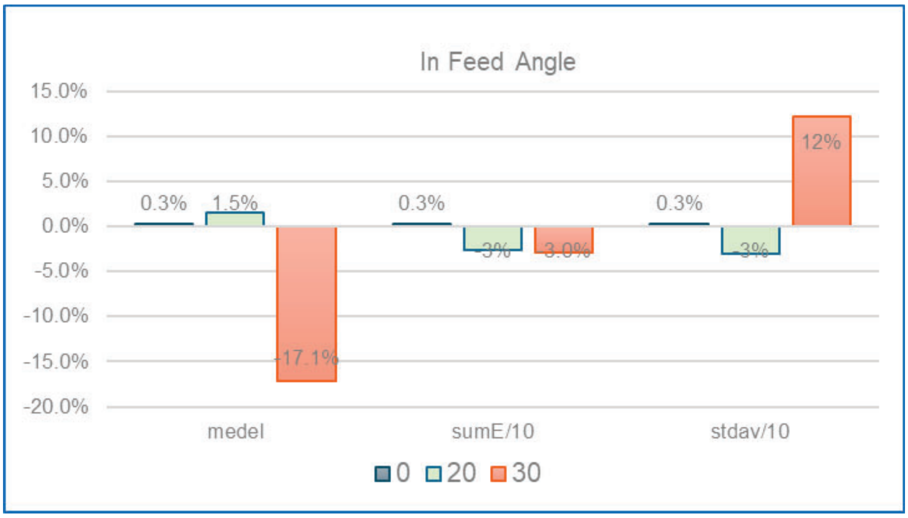


Figure 47 Three in feed angles were tested. Reference in figure: IFA=0˚

The infeed angle influences the wear level and wear pattern on the tool and which part of the tool that takes the biggest chip and the position where the wear will start. Infeed correction is also used in the skiving program for this purpose, directing the cutting to one flank.

Measurements were also made using different feeds and cutting depths. These are summarized in Figure 48.

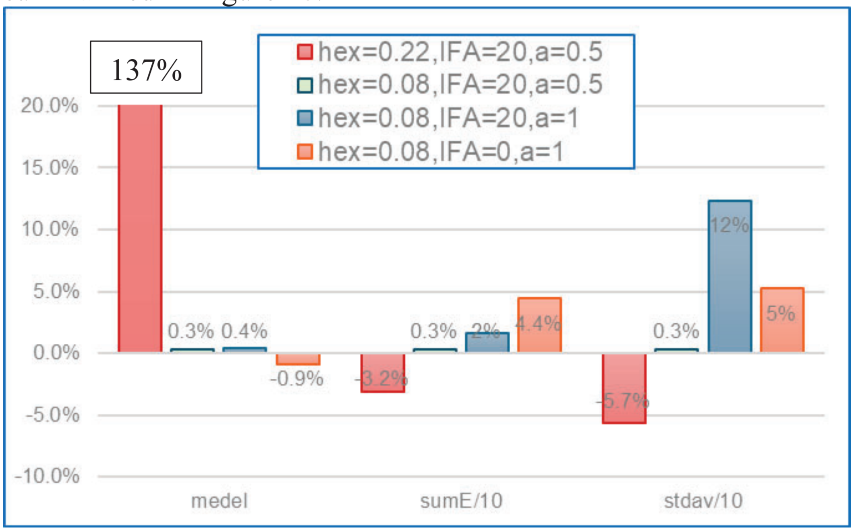


Figure 48 Forces for different feed and cutting depth combinations.
Reference is hex=0.08mm, IFA=20˚, cutting depth a=0.5 mm.

Feed from 0.22 to 0.08 mm/r lowers forces to below half but variations are relatively greater.
An *increased cutting depth from 0.5 to 1 mm* has a smaller effect on the magnitude of mean forces but make the force variations greater, potentially causing higher force peaks.
A change in IFA from 20 to 0˚ gives slightly lower mean forces but more variations.

There is no information about force directions in these measurements. Had that been the case the differing wear types and results could may have had a closer link to the forces. Relative differences in forces at different relevant cutting speeds are shown in Figure 49.

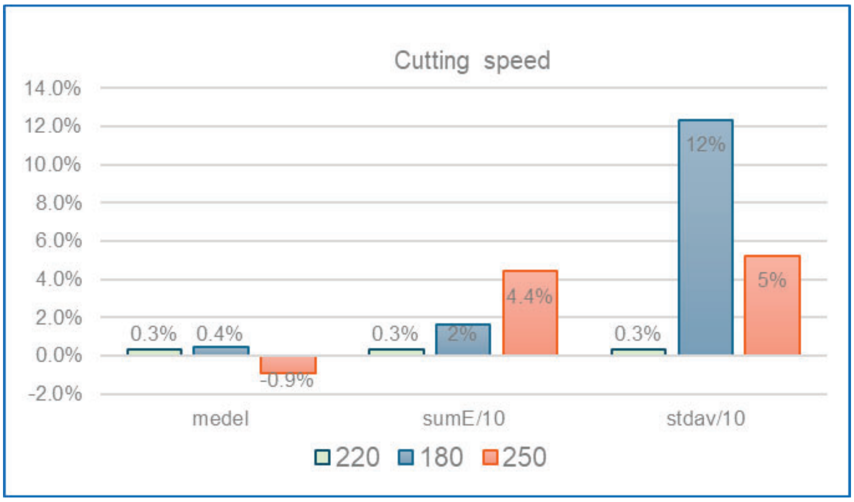


Figure 49 Force Fa at 3 cutting speeds. Reference:220m/min

The cutting speed influences mean forces very little. Increased speed lowers forces slightly. The variation in forces is highest for the lowest speed, 180m/min.

The force measurements did give some information about the cutting process but conclusions are hard to draw regarding many of the measurements. The measurement setup is new and will be refined in future projects. The direction of force components during the rotation should be possible to measure or calculate which could give valuable information of how the direction of forces are developing during each revolution.
The setup is too weak for long term wear tests so it is not a solution for any automatic failure criterion of the test method.

Vibration test results

The workpiece will be hit by the single test insert and vibrate from this during the idle part of the spindle lap. A quick attempt was made to find the natural frequency of the system in the axial direction by hitting it with a hammer. The natural frequency from this was 308 Hz so this will be a frequency that we will se in the FFT diagram. A much lower frequency is the rate of tool entries from the rpm value, 780/60=13 Hz. The setup at Erasteel had a lower natural frequency at 258 Hz.

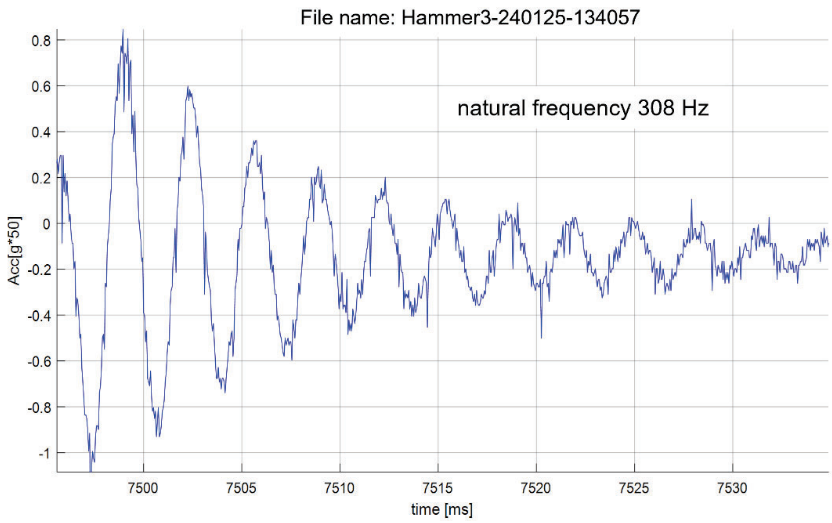


Figure 50 Natural frequency in the axial direction

A typical image of the vibrations during a pass over the length of the test piece is shown in Figure 51. We can see 109 tool engagements and the time between first and last contact is 8.4s as can be calculated. The signal in more detail reveals that the vibration event is much longer than the theoretical one, Figure 52.

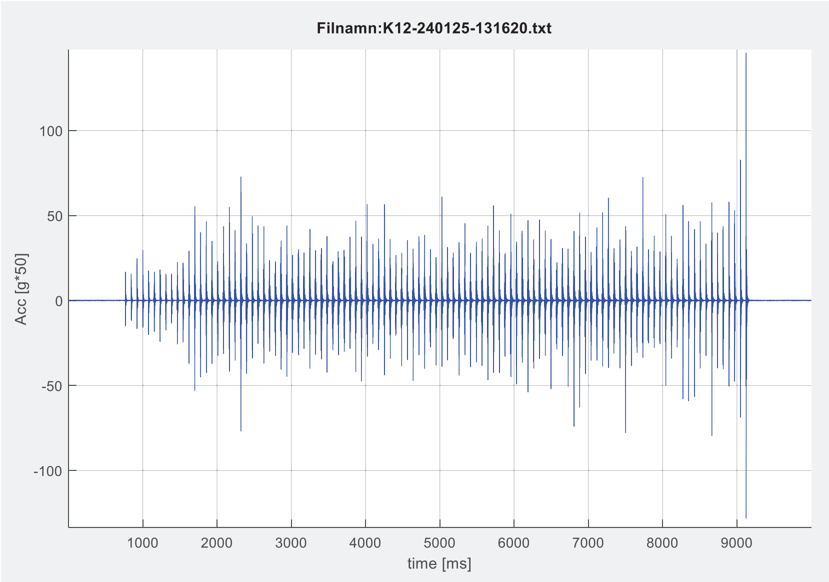


Figure 51 Axial vibrations from the 12th pass over the workpiece.

For a perfect geometry there should be no contact between any of the protective grinded down inserts and the work piece unless there is some elastic deformation that makes the groove less precise at the final pass when the forces are the highest. If that is so then it makes sense that it is the last position before the actively cutting one that come in contact.

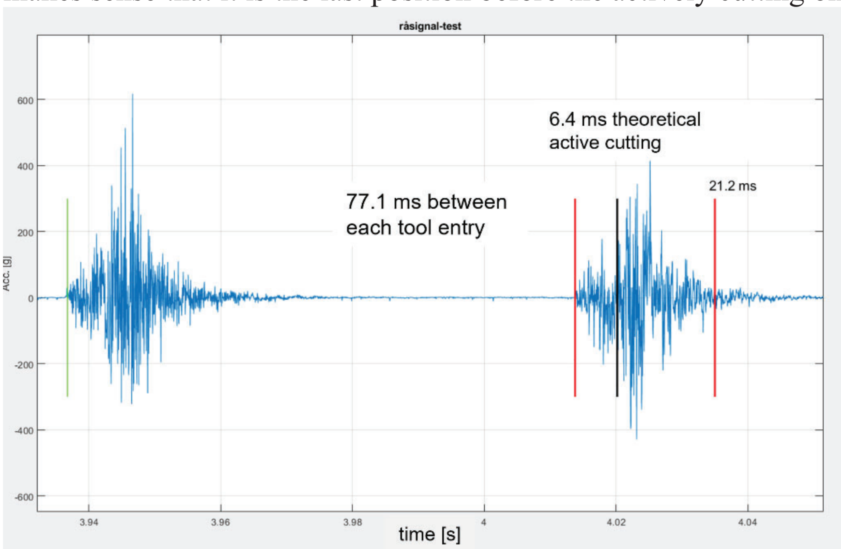


Figure 52 Detailed image of times of and between two tool engagements.

From the vibration measurements a number of parameters can be calculated and compared:

- FFT to find dominating frequencies
- RMS of the time domain signal to estimate the energy content of the vibration. The standard deviation also works.
- The power spectral density, PSD
- RMS and cumulative sum of PSD
- RMS within specific frequency bands, bins.

Power spectral densities (PSD) are used to characterize random vibration signals. A PSD is computed by multiplying each frequency bin in an FFT by its complex conjugate which results in the real only spectrum of amplitude in g^2. The key aspect of a PSD which makes it more useful than a FFT for random vibration analysis is that this amplitude value is then *normalized* to the frequency bin width to get units of g^2/Hz. By normalizing the result, the dependency on bin width is gone making it possible to compare vibration levels in signals of different lengths, getting the same amplitudes regardless of measured signal length. It also gives a sense of where in the frequency spectrum the highest energy is found. (Hanly)

Here the focus has been on comparing the vibrations between a new and a worn tool and in comparing the test setups at Swerim and Erasteel at reference cutting data, v=220 m/min, f=0.22 mm/rev IFA= 20º. The measures to be compared is the RMS value for the whole frequency band 0-10 kHz and the Cumulative PSD between 0 and 2kHz and between 0 to 10 kHz. All three vibration components VibX, VibY and VibZ has been studied.
Figure 53 shows the power spectral density in the Z direction (radially) of two vibration measurements, the first on a new tool, the second on a worn one. Clearly, there are new components occurring in the spectrum for the worn tool but it is hard to find one clear peak or band. The increase in vibration energy is across the whole frequency range. There are also new peaks occurring at very high frequencies.

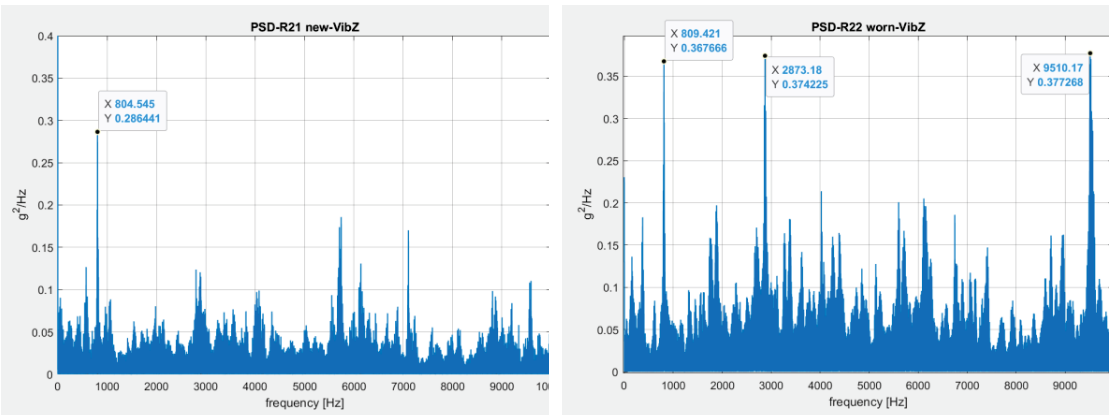


Figure 53 New and worn tool run at reference cutting data.

The Cumulative PSD for all components of the new and worn tool is shown in Figure 54. Blue lines correspond to the data in Figure 53. Several things are evident:

- The Z direction component is the biggest one, the VibX and VibY are very similar.
- The worn tool causes more vibration energy in all directions and across the spectrum.
- There are no kinks in the curves, steep parts to indicate that one particular frequency is increasing or dominating, rather the whole curve is lifted smoothly.

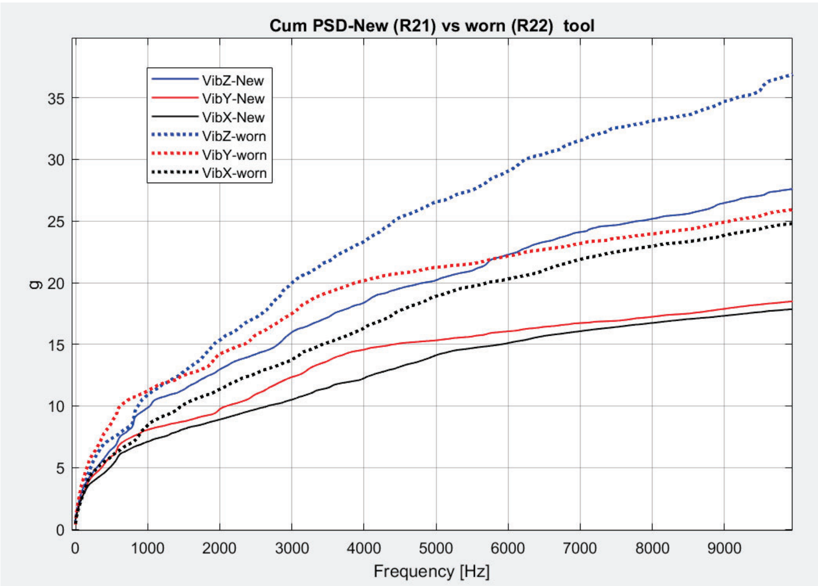


Figure 54 All three Vibration components for a new (solid lines) and a worn (dotted lines) tool.

The test was repeated one time at Swerim and one time at Erasteel with the same result, Figure 55. The vibration measurements at Erasteel showed no big differences compared to those at Swerim. The test setup has a slightly lower natural frequency but the cumulative PSDs look the same. The environment however includes some external vibrations that disturb the results. Two more machines were run in the lab at the test instance.

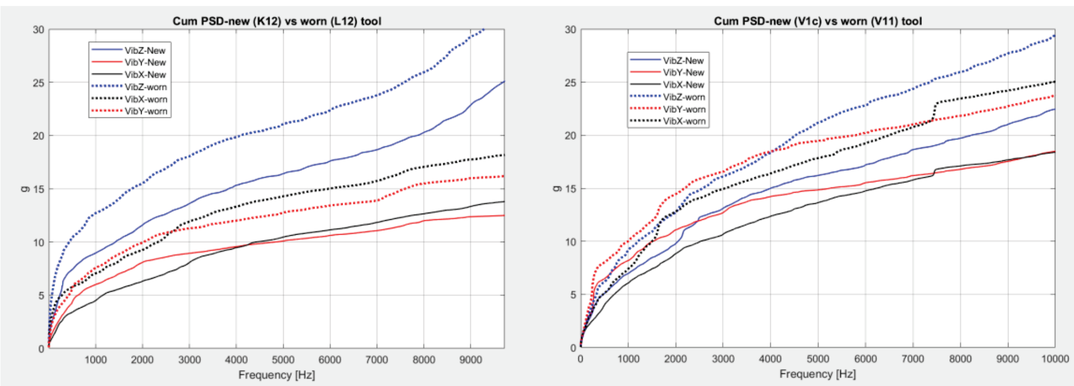


Figure 55 Repeated tests with (other) new and worn tools show the same increase in vibration energy for the worn tool. There is a peak at 7400 Hz for the Erasteel case (right)

These tests are summarized in Figure 56.

Figure 56   All measurements show more vibration energy for the worn tool.

The vibration measurements shows some promise but a lot more tests and analysis is necessary before a working diagnostic measure could be attained for use as a wear test interruption criterion.

Temperature

The temperature films are rather dark since only the chips and the inserts really get warmed up, Figure 57. The tool can barely be made out. An area of interest can be picked out and the maximum temperature in that area in each frame of the file is recorded. The shear number of measurements gives a reasonable accuracy to the comparisons.

Figure 57   Heat images from the tests showing the warm tool rake face and chips flying

The values from each frame is imported to Matlab and the maximum values are saved and used for analysis, Figure 58. The same trend as for the force and vibration measurements are seen with increasing temperatures for the latter passes. The sampling frequency (frame rate) is a lot smaller here. The 15 highest measured temperatures are picked out and compared for different cutting data. Unfortunately the temperatures here are between measuring ranges so in order not to miss the top temperatures the acquisition is set to 175 to 1000ºC.
The temperatures we see are related to the chip temperature and vary from 60 at pass 1 to 200ºC at pass 12.

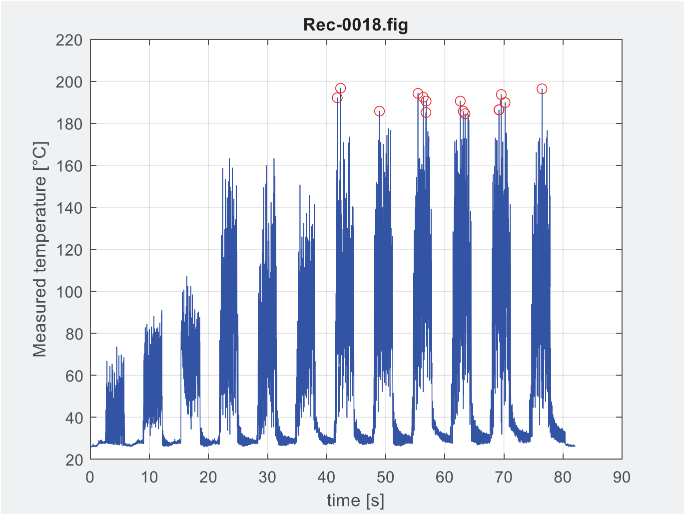


Figure 58   Temperatures from 12 passes at reference data

Some measurements are summarized in Figure 59. More measurements were made but settings were wrong for a few with the low measuring range limiting temperatures.

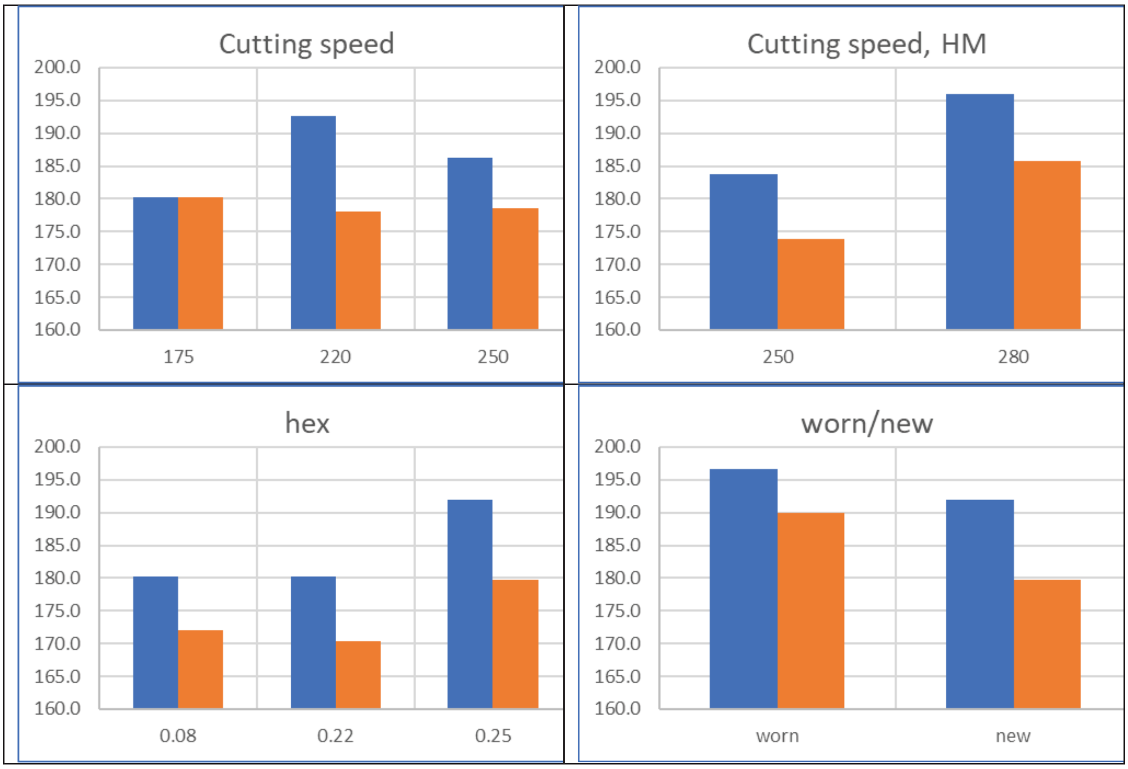


Figure 59 Blue staples – max temperature, Orange staple – mean of the 15 highest temperatures.

Temperatures are low but logical for hex and cutting speed. We see big increases for the biggest feeds and speeds. Also the worn tool generates a warmer chip.

6 Dissemination and publications

6.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Within the project group
Be passed on to other advanced technological development projects	X	For future projects
Be passed on to product development projects	X	All results are applicable and are used if deemed to give improvements in production
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

6.2 Publications

No publications are planned at this date.

7 Conclusions and future research

The test method has proven useful for ranking tool materials for the gear manufacturing processes gear hobbing and power skiving. The wear resistance of six tool materials were compared and a cobalt free variant proved to be competitive compared with the standard Co containing grades. The test method results were validated in industrial trials.

Future research may build on findings regarding the details and nature of the wear in gear manufacturing from this project to find optimal HSS material properties to handle both the crater wear associated with high temperatures and the tool's hot hardness and the fracture toughness to withstand chipping. Another way to go is to tailor the material specifically to the cutting process, skiving or hobbing which require different material property profiles. Coatings for these steels would also play a major role in handling wear resistance when the chipping wear is reduced.

The test method could play a role here in screening different variants.

8 Participating parties and contact persons

The following companies and contact persons have been part of the project steering committee and the practical execution of trials:

Oskar Johansson	Leax
Elias Hägglund	Leax
Andrés Gomero Paz	Leax
Carlo Lurisci	Star SU
Sara Saketi	Ovako
Thomas Björk	Ovako
Lars Johansson	Scania
Jörgen Hansen	Ionbond
Maran Tirou	KTH
Håkan Thoors	Swerim AB
Solmaz Sevim	Swerim AB
Jonas Jordberg	Swerim AB
Sture Sjöö	Sandvik Coromant