# Machinability improved M-Steel®
# – for reduced tool wear and increased productivity in hard part turning

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# EXECUTIVE OVERVIEW

Hard part turning is often the critical last machining operation in the production of steel transmission components. It removes the final layers of the metal from the work-piece to produce the desired surface finish and geometry. The process is a cost-effective alternative to grinding. However, it is particularly demanding on the super hard PCBN cutting tools developed to machine hardened steel. This has prompted research into methods of reducing tool wear and hence increasing productivity and lowering manufacturing costs.

One approach is to use machinability improved M-Steel. This white paper focuses on a recent research program carried out by Scania's transmission machining unit to explore the advantages of M-Steel supplied by Ovako for the high volume production of gearbox cones.

Machining tests were carried out to evaluate the life of PCBN tools as defined by the level of surface roughness achieved during actual production. The tests resulted in three main conclusions:

- The use of M-Steel resulted in a doubling of the tool life when compared with a standard steel grade
- This improved machinability corresponds to a 50% reduction in tooling costs for the industrial production of transmission components at the Scania site
- Implementing M-Steel on a wider range of components could result in a significant reduction in the manufacturing cost for each component.

# 1 – INTRODUCTION

The production of gearbox components, such as synchromesh rings, shafts, crown wheels and pinions requires a variety of manufacturing processes. Typically, the process flows are divided into soft machining, heat treatment and hard machining. Examples of machining processes are turning, hobmilling and drilling. Other common machining operations are de-burring, grinding and honing. A major challenge in the machining of transmission components is how to achieve the optimum combination of high production efficiency, high quality finished parts, low tooling costs and a robust and reliable production operation. Therefore, both the cutting tools and the workpiece materials must be carefully adapted to the machining process and the specification of the finished part.

Hard part turning is often the critical last machining process. Defined generally as the turning of steel with a hardness greater than 45 HRC the process aims  to remove the final layers of the metal from the workpiece in order to produce the required surface finish and geometry. The most frequent alternative to hard part turning is grinding, which is both costly and reduces operating production efficiency.

Cutting tools made of polycrystalline cubic boron nitride (PCBN) were developed some decades ago to machine hardened steel. PCBN is a super hard material which provides extreme strength even at high temperatures. The precise performance of a PCBN cutting tool in a specific machining process is determined by the CBN composition, the CBN grain size, and the tool edge preparation. Typically, the wear mechanisms of PCBN cutting tools are of an abrasive, adhesive, chemical or a diffusive nature. Frequently reported wear patterns are flank and crater wear, micro chipping, edge fracture and nose wear.

Carburising steels are widely used in the production of automotive components because of their excellent resistance to fatigue and their ability to carry high loads. They are produced by a thermochemical process that causes carbon to diffuse into the surface of a low carbon steels. This increases the carbon content at the surface to a level sufficient to enable it to respond to heat treatment and produce a hard, wear-resistant layer. Carburised steel components have a typical surface hardness of 60±2 HRC, which levels out at around 53 HRC within a depth of 1 mm.

There is a significant risk of inclusion induced fatigue in gearbox components at elevated stress values. Therefore, the use of a clean steel, in which the size and distribution of inclusions is closely controlled, is critical in ensuring the optimum fatigue performance.

That is why Scania classifies the carburising steel grades used for its gearboxes and diesel engines into three levels, A, B and C, based on their cleanliness level (see Table 1). Level A refers to high-performance steels while Level B refers to a default level. Steel grades of Level C are rarely used and are only selected if there is a low risk of an inclusion induced fatigue. Additional requirements may be specified to ensure the quality of a steel grade. These could include, for example, vacuum degassing, electromagnetic stirring, casting method, reduction ratio, austenitising temperature, hardenability, microstructure and delivery condition.

| Cleanliness level | Intended for | Sulfur content ppm | Oxygen content ppm |
|---|---|---|---|
| Level A | Components with high risk of inclusion induced fatigue | 150–250 | ≤ 15 |
| Level B | Most components, default level | 200–400 | ≤ 50 |
| Level C | Components with low risk of inclusion induced fatigue | 200–400 | ≤ 80 |

*Table 1. Classification of carburising steel grade that are used in automotive production*

Although high-cleanliness steels have excellent mechanical strength, the advantage comes at the expense of a reduced tool life and more difficult chip breakage. For the majority of applications a high production rate is the key objective. Therefore, many steel manufacturers have developed steels with improved machinability. Ovako's own machinability steels carry the M-Steel® brand. The common methods of achieving the improvement in machinability are through a high sulfur (S) content as well as treatment with calcium (Ca). Adding calcium during the deoxidation of liquid steel transforms hard aluminium oxide (Al2O3) inclusions into Ca-aluminates which are softer and less likely to cause cutting tool wear.

A successful Ca-treatment leading to a Ca-content of about 40 ppm (parts per million) requires a certain level of sulfur, typically around 300 ppm. Such machinability improved, Ca-treated steel grades fit into Level B of the steel qualities shown in Table 1. Therefore, they can be used to increase the production rate.

This latest test program builds on a previous study in which the influence of inclusion composition was linked to the tool wear during the hard part turning of carburised steel using a PCBN cutting tool. It was found that Ca-treated steel showed a superior machinability in comparison to standard and clean steel. In addition, the machinability improving effect of the Ca-treated steel was linked to the protective slag deposits of (Mn, Ca) S and (Ca, Al) (O, S) that form on the cutting tool rake face.

The aim of the program was to clarify the link between the characteristics of the carburising steels and their influence on the wear mechanisms and cutting tool life in the hard part turning of actual gearbox synchromesh rings.

In addition, the tool wear morphologies at different cutting speeds and frequencies of interruption were investigated. For these tests, a Ca-treated, machinability improved (M-Steel) grade was compared to a standard steel.

## 2 – EXPERIMENTAL PROGRAM

### 2.1. Work materials and cutting tools

For the tests, middle cones for a synchromesh gearbox were manufactured from two grades of carburising steel. A standard carburising grade of type EN 19MnVS6 was used as reference (R), see Table 2. The machinability improved M-Steel was also of the type EN 19MnVS6. In addition to a relatively high sulfur content the M-Steel was Ca-treated to reach a 53 ppm calcium content. The two grades fit into the same classification with respect to Scania's steel cleanliness standard.

| Des | C | Si | Mn | Cr | Ni | Mo |
|---|---|---|---|---|---|---|
| R | 0.23 | 0.33 | 1.56 | 0.18 | 0.13 | 0.06 |
| M | 0.18 | 0.32 | 1.44 | 0.38 | 0.13 | 0.03 |

| Des | Cu | Al | V | N | S | O | Ca |
|---|---|---|---|---|---|---|---|
| R | 0.14 | 0.028 | 0.09 | 110 | 260 | 11 | 11 |
| M | 0.22 | 0.020 | 0.09 | 110 | 280 | 16 | 53 |

*Table 2. Chemical composition of carburising steel used for machining tests, in wt-%*.*
** Contents of N, S, O and Ca are given in ppm.*

Middle cones (see fig. 1) of 170 mm in diameter were heat treated as follow:
(I) Carburising at 930 °C for 3.4 h.
(II) Quenching in oil.
(III) Tempering at 195 °C for 32h.

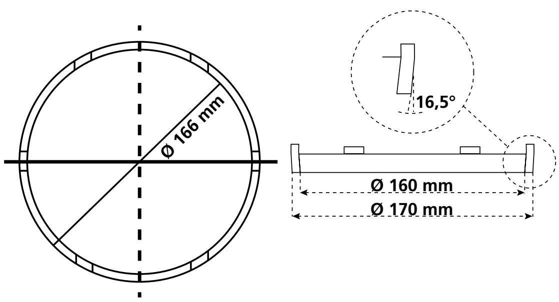


*Fig. 1. A schematic of the workpiece.*

Hardness profiles including surface hardness and case hardening depth were measured using the Vickers hardness method (HV1).

A SECO PCBN cutting tool was used, see Fig. 2. It comprised a 0.45 volume fraction of CBN mixed with a ceramic binder composed of TiCN and Al2O3 and having an average grain size below 1 µm. At the current production cutting speed of 166 m/min, the hard part machining engagement of each middle cone was about 11 s, which corresponds to a chip cut length (CCL) of 30 m.

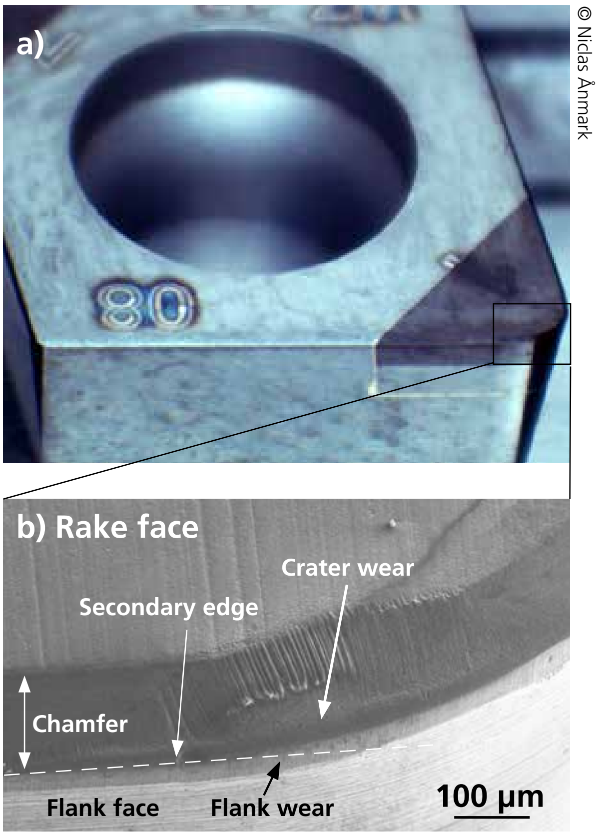


*Fig. 2. Overview of (a) a PCBN edge and (b) a tool wear together with the corresponding key terms. (LOM, SEM-SE).*
*Note:*
*LOM = Light optimal microscope*
*SEM = Scanning electron microscope*

## 2.2. Machining tests and tool wear monitoring

The machining tests were performed in an EMAG turning lathe under dry conditions. Tool life tests were performed by using a feed rate fn = 0.24 mm/rev, a radial depth of cut of ap = 0.15 mm, and cutting speeds of vc = 166–300 m/min. Most attention was paid to the tests at 166 m/min, which is the current production cutting speed.

Three consecutive machining tests were included, which used both R and M-Steel grades. The additional machining tests were stopped prior to the end of tool life aimed at studying the initial wear mechanisms, as seen in Table 3. The test duration corresponded to about 1/12 of the respective tool life. The test times were 7.5 and 16 minutes for the R and M-Steels and the corresponding chip cut lengths (CCL) were 1230 m and 2590 m.

The tool life criterion was defined as the surface roughness Ra ≥ 0.7 µm of the machined component or at a cutting edge failure. The surface roughness of the middle cone was recorded after completion of each machined component using a Mahr Perthometer S2.

| Steel | $V_c$ (m/min) | t (min) | CCL (m) |
|---|---|---|---|
| R | 166 | 7.5 | 1230 |
| M | 166 | 16 | 2590 |

*Table 3. Test matrix for interrupted cutting tests.*

# 3. RESULTS

## 3.1. Hardness profiles

The surface hardness of steel R and M-Steel was 700 ± 5HV (60 ± 0.2HRC) and the carburising depth was 0.66 mm, see Fig. 3.

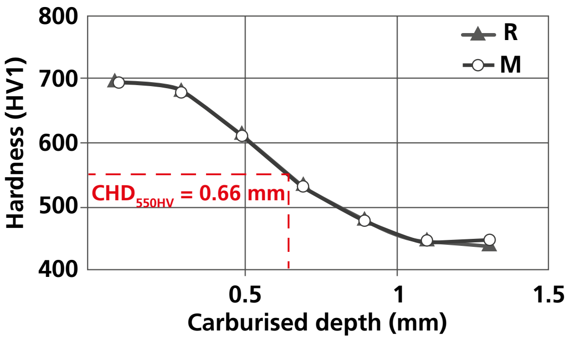


*Figure 3. Hardness profiles of the tested steels as a function of the carburised depth.*

## 3.2. Inclusion characteristics of the evaluated steels

The reference steel grade R is characterised by manganese sulfide (MnS) inclusions, which elongate during rolling to lengths greater than 100 µm. It also contains less elongated (Mn, Ca) S-Al2O3 oxy-sulfides with a plate-like shape with a typical diameter of 10 µm. In a similar way to the R-steel, the Ca-treated modified M-Steel grade contains elongated MnS inclusions with lengths of up to 100 µm. In addition, the M-Steel contains many fine and globular (Mn, Ca)S-(Al, Mg) O oxy-sulfides with a typical equivalent circular diameter smaller than 10 µm.

## 3.3. PCBN cutting tool life and tool wear

The M-Steel showed a superior machinability compared to the R-steel. The corresponding tool life was 38 minutes (CCL=6300 m) and that of R-steel was 18 minutes (CCL=3000 m), see Fig. 4a, for a cutting speed of 166 m/min. The surface roughness (Ra) measurements indicate a smaller scatter when machining the R-steel than the M-Steel, Fig. 4b. Furthermore, the distinct difference between the two steel grades is that the generated surface roughness of the M-Steel levelled out at about 0.5 µm, while the R-steel displayed a progressive growth. The chip formation of both steel grades was acceptable. The chips were short and had an arc-like shape.

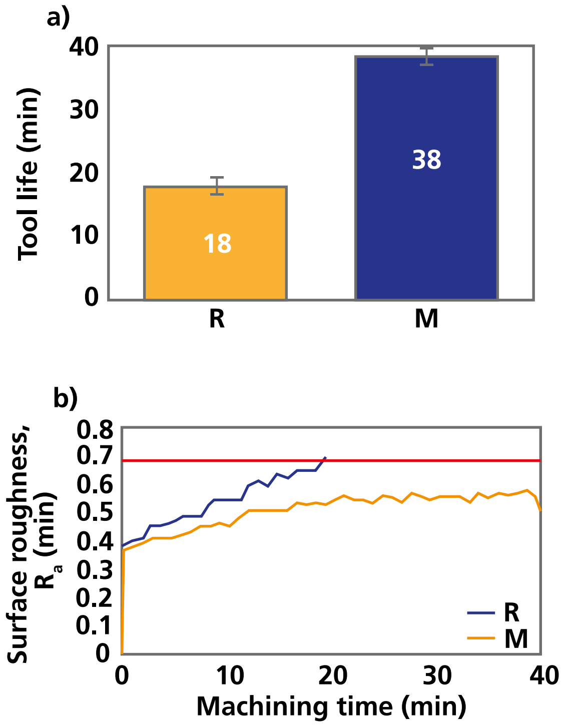


*Figure 4. Tool life of the tested steels (a) and the generated surface roughness (b) at $f_n$ = 0.24 mm/rev, $a_p$ = 0.15 mm and $V_c$ = 166 m/min.*

Typically, the R-steel generated chipping tool wear at an earlier stage, yet with significant scatter, as well as larger chippings, as compared to M-Steel, see Figs 5 and 6. In addition, a ridge formation was observed on the upper side of the rake face crater on completion of the hard part turning operation.
This ridge formation was more pronounced after machining an R-steel than an M-Steel, see Fig 5.



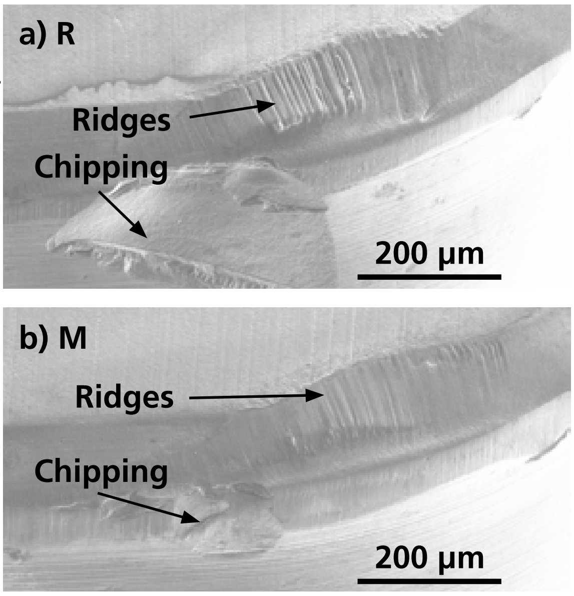


*Figure 5. The PCBN edges imaged by SEM after having reached their tool life. (a) R (t=18 min), (b) M (t=38 min). The edges were etched prior to imaging.*

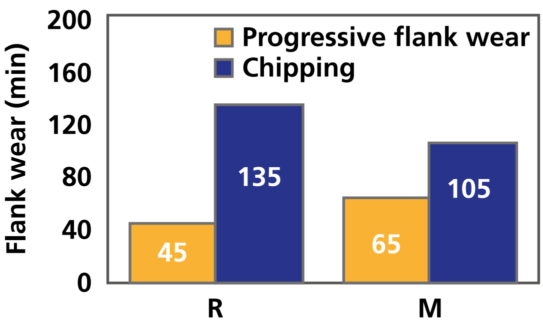


*Figure 6. Progressive and chipping flank wear of tool life tested cutting edges at $V_c$=166 m/min, $f_n$=0.24 mm/rev, and $a_p$=0.15 mm.*

An investigation of increased cutting speeds showed that 200, 250 and 300 m/min could be used with the M-Steel with surface roughness below the Ra ≥ 0.7 µm criterion for 31, 11 and 6 minutes, respectively. The corresponding chip cut lengths were 6200, 2750 and 1800 m.

In contrast, it was only possible to machine the reference steel grade R at no more than 200 m/min rate, which resulted in a tool life of about 8 minutes, see Fig 7. The cutting speeds of 250 and 300 m/min resulted in an instant edge fracture when machining the R-steels.

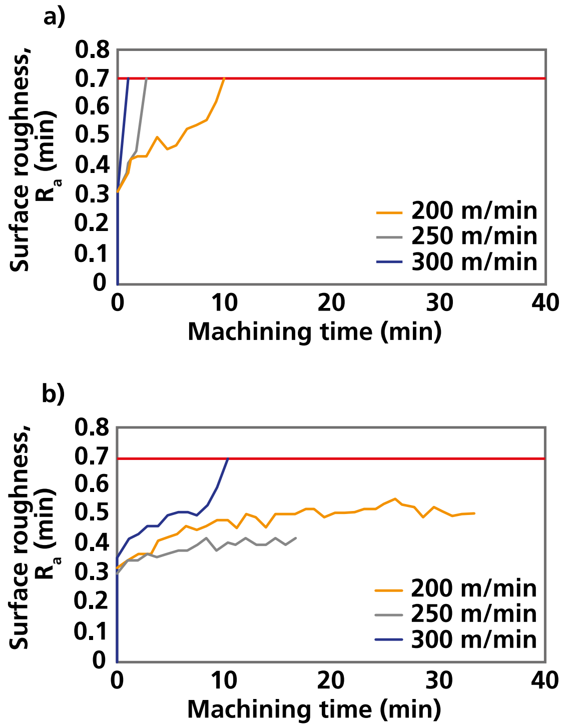


*Figure 7. Procession of the generated surface roughness of steel (a) R and (b) M recorded at the tool life tests with higher cutting speeds ($f_n$=0.1 mm/rev, $a_p$=0.1 mm and $V_c$=200–300 m/min).*

## 3.4. Adhesion of workpiece material to the cutting edge

The transfer of workpiece material was observed in the chip exit part of the rake face, after machining the R-steels. In contrast, machining M-Steel with a PCBN edge resulted in minimal material transfer to the rake face. Only small remnants of workpiece burr was found on the cutting edges, this was determined by the Fe signals of the EDS (Energy-dispersive x-ray) analysis after machining both the R and the M-Steels, see Fig 8 .



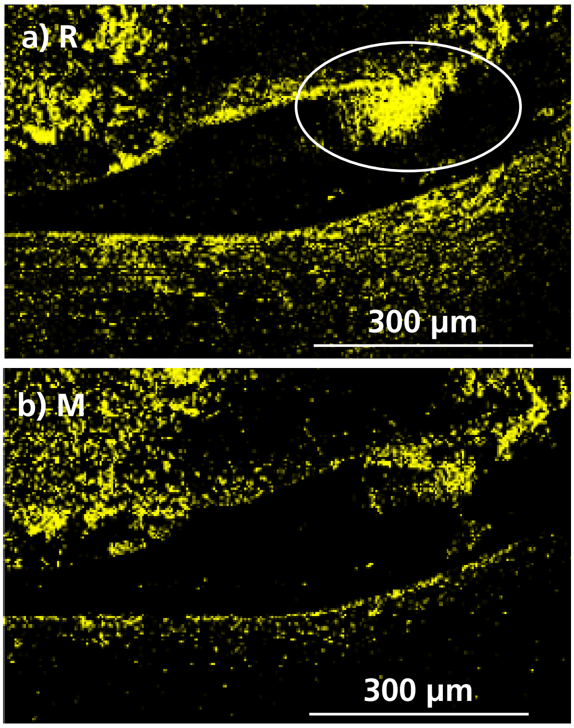


*Figure 8. EDS-map of Fe in the crater and edge region after turning tests which were interrupted after machining of 41 parts (7.5 min) and 86 parts (16 min) respectively.*

*Note: EDS = Energy-dispersive x-ray spectroscopy.*

*EDS of the M-Steel crater indicated the presence of the slag elements Mn, S, Ca, Al and O, see Fig.9. The segment rich in Mn and S has an elongated shape, parallel to the edge line. Al and O were enriched in the ridges of the rake face crater and had a less elongated shape. Also, a low and even concentration of Ca is revealed in the crater (Fig. 9c). Except for Al and O, much lower slag deposits were found in the rake face crater for the R-steel compared to the M-Steel, see Fig. 10.*



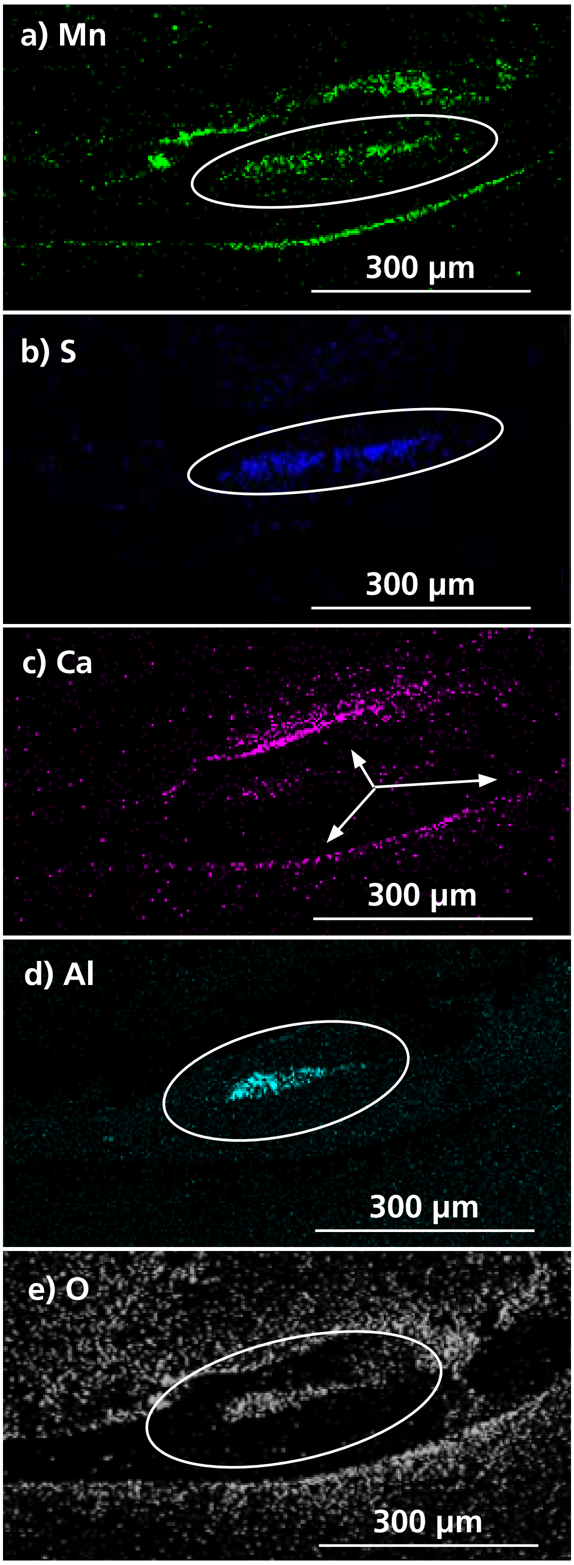


*Figure 9. EDS-map of Mn, S, Ca, Al and O, respectively in the crater and edge region of the M-steel after the cutting tests which were interrupted at 86 parts (16 min).*

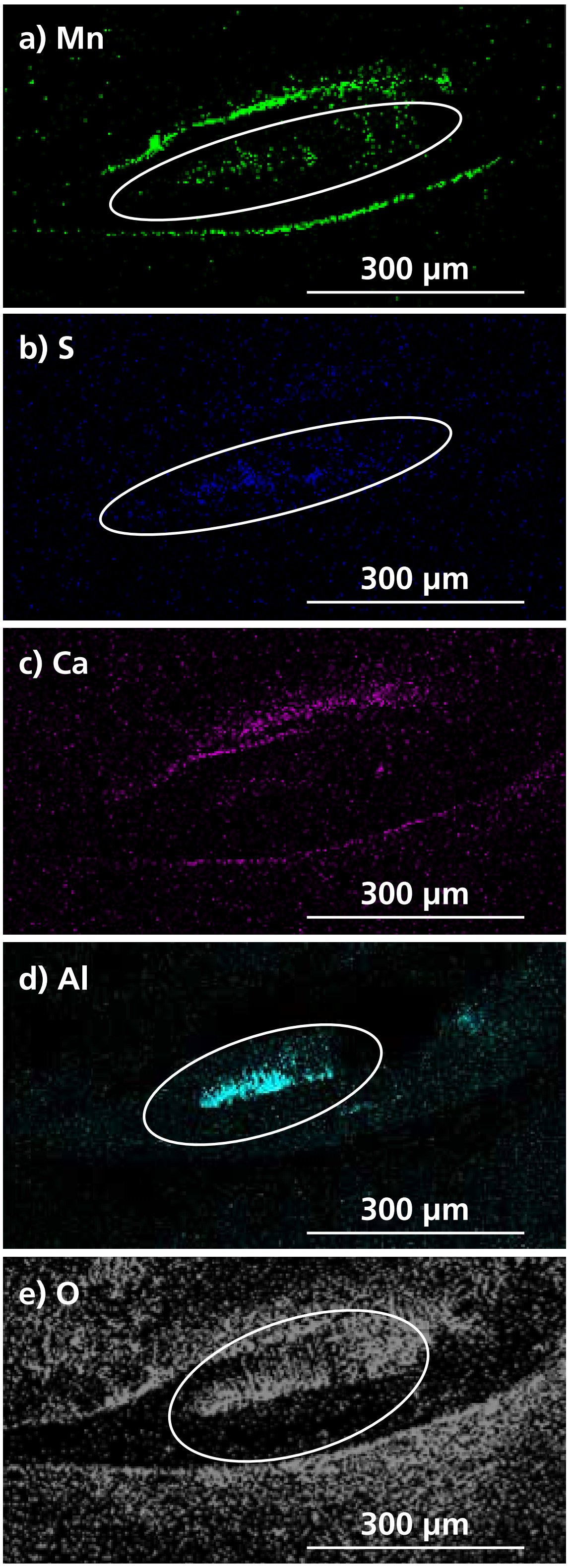


*Figure 10. EDS-map of Mn, S, Ca, Al and O, respectively in the crater and edge region of the R-steel after the cutting tests which were interrupted at 41 parts (7.5 min).*

### 3.5. The economic impact of using M-Steel

The manufacturing site produces around 200,000 middle cones a year. The SECO cutting tools tested have a list price of about €42 each. Using M-Steel increased the cutting tool life of the PCBN edges by about 110% at a cutting speed of 166 m/min and a feed rate of 0.24 mm/rev. In total, this has resulted in a reduced annual tooling cost saving of 50%, from €40,000 to €20,000, see Fig. 11.

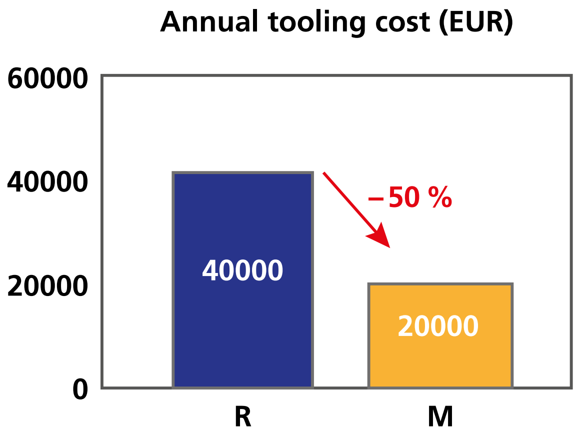


*Figure 11. A cost-save calculation based on the prolonged services life time of the M-steel.*

# 4. DISCUSSION

## 4.1. The cost benefit of improving PCBN cutting tool life

Using M-treated, machinability improved steel has more than doubled the service life of the PCBN cutting tool in hard part turning of middle cones for gearboxes. This offers an attractive annual tooling cost-saving of about 50%, as compared to the R-steel, see Figs. 4 and 11.

Even with the cutting speed increased from 166 to 200 m/min, the PCBN tool life with the M-Steel was 31 minutes, as compared to 18 minutes for the R-steel at 166 m/min, see Figs. 6 and 7. This corresponds to an increased service life of about 70% with the M-Steel in terms of machining time, and about double in terms of chip cut length. Consequently, the M-Steel allows a significantly increased production rate.

The machinability improved steel M-Steel corresponds to a Level B type of steel with respect to the cleanliness indicated in Table 1. Level B class is by far the most widespread cleanliness category used in transmission parts at Scania. Therefore, introducing the M-Steel on a wider range of components could lead to a significantly reduced manufacturing cost per produced component. In addition, the implementation of M-Steels also has the potential to markedly increase both production efficiency and capacity.

## 4.2. The wear modes that limit tool life

A surface roughness above the threshold value of Ra ≥ 0.7 µm was used as the tool life criterion for this test program. In the reference turning operation of an R-steel at 166 m/min, the progressive flank wear expanded to 45 ± 10 µm, based on the three cutting edges analysed. However, the flank wear given by the maximum extension of the edge chipping was 135 ± 50 µm. Studies of the secondary edge showed that the chipping was located near the surface generating point on the secondary cutting edge, typically 150–200 µm from the nose. Therefore, the pronounced tool chipping tendency with the R-steel is believed to have a significant influence on the workpiece surface and consequently the tool life.

The progressive flank face wear rate with the M-Steel was lower than that of the R-steel, which indicates that it is a more easily machinable steel grade. The most valuable benefit offered by the M-Steel in this case is the reduced expansion of the chipping on the flank face of the secondary cutting edge. The significantly reduced chipping wear resulted in the Ra-value leveling out at 0.5 µm with the M-Steel, see Fig. 4b, i.e. below the tool life criterion. Consequently, the use of M-Steels enables a significantly more robust machining process in terms of performance, quality and variability.

### 4.3. The general effect of non-metallic inclusions

During gearbox production the low-PCBN cutting tool (45 vol% CBN) fails primarily due to edge chipping and crater wear during hard part turning of middle cones. This program has shown that the life of the PCBN cutting tool life during hard part turning depends on the formation and stability of the lubricating slag layers that act as a barrier between the tool edge and the workpiece. It is relatively well established in soft turning that Ca is enriched on the tool rake face and thereby reduces the tool wear progression. Other test programs suggest an analogous effect of the reduced wear on the rake face is also obtained during hard part turning.

This test program has confirmed the strong positive effect of the Ca-based slag deposits formed on the tool edge and how they reduce the chemical degradation of the tool rake face. Moreover, chipping wear can be significantly reduced by using a Ca-treated steel. It is proposed that the slag deposits detected on the rake face exist also on the edge line. However, the EDS analysis is limited to a layer thickness of about 0.5 µm so it cannot examine this possibility. It is also proposed that slag deposits form on the tool edge line and that they reduce adhesion and burr formation that may be the origin of the premature chipping behaviour of the tests with the R-steel. This is vital for the tool life since it is defined by the surface roughness of the component. As chipping wear is characterised by discrete and stochastic events the reduction in chipping is extremely important to achieve a robust and repeatable production process.

### 4.4. The potential for the industrial use of M-Steels

This program has indicated that the use of a Ca-treated steel enables new possibilities for the optimisation of process productivity and robustness. M-Steel has resulted in significantly reduced chipping wear on the tool flank face and minimal crater wear on the rake face showing that it is suitable for use with PCBN tools with a higher CBN content. These tools are often considered tougher, yet more susceptible to wear by chemical dissolution than that of the tool grade used in this study. An option with the M-Steel is therefore not to increase the tool life but to further reduce the risk of chippings and edge fractures. These phenomena are stochastic in nature and therefore undesirable when aiming for a robust production process.

# 5. SUMMARY

This research program investigated the role of non-metallic inclusions on tool wear and PCBN cutting tool life during the fine machining of carburising steel grades. A Ca-treated carburising steel grade (M-Steel) was compared with a standard steel grade. Tool life tests were conducted to study the active degradation mechanisms at the end of the tool life. Additional machining tests were also carried out with an interruption prior to the end of tool life to study the initial wear mechanisms. The following conclusions have resulted:

1. The hard part machinability of a standard carburising steel (reference R) was improved by 110% with the Ca-treatment (modified M-Steel). This improved machinability corresponds to a reduced tooling cost of 50% in the production of middle cone gearbox components at Scania. Therefore, implementing M-Steel on a wider range of components would lead to a significant reduction in the unit cost of each component produced.

2. The most valuable benefit of the M-Steel is the reduced expansion of the chipping on the flank face of the secondary cutting edge and the more controlled progressive flank wear. Consequently, using M-Steel enables a more robust machining process than the R-steel.

3. The beneficial tool wear characteristics of a Ca-treated steel can be combined with a PCBN tool with a higher CBN content to further minimise the risk of stochastic chippings and edge fractures. This will facilitate an even more robust production process.

4. The improved machinability of the M-Steel is linked to the formation of protective non-metallic inclusions that help reduce the degradation of the PCBN cutting tool.

# 7 – FURTHER READING

Steel characteristics and their link to tool wear in hard part turning of transmission components (PhD thesis) – Niclas Ånmark and Thomas Björk

## 8 – ABOUT THE AUTHORS

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