How the metallurgy of Ovako's M-steel makes a difference for the machining workshop

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Abstract

The current study shows how the tailored metallurgy of Ovako's M-steel is a success for the profitability of a mechanical workshop, still 40 years after its introduction.

A comparison of tool life tests was made of conventional vs M-steel including 42CrMo4 in quenched and tempered state, as well as 20NiCrMo2-2 steels in the as-rolled condition. A state-of-the-art cutting tool for medium cutting conditions of ISOP15 was used. At cutting speeds aiming at tool life of 15 minutes the tool life benefit was roughly +100% with the 42CrMo4 and roughly +65% with the 20NiCrMo22. Elemental maps recorded with energy dispersive spectroscopy (EDS) revealed patches enriched with Ca and S on the tool rake after machining with the M-steel variants. These patches are believed to chemically protect, as well as to reduce the heat transfer into the cutting tool.

An example is given of how the advantage of machining performance with M-steel can be used as means to: 1) Reduce the cycle time of the produced part, or 2) Facilitate automated, unmanned production, for the cost benefit of the machining workshop.

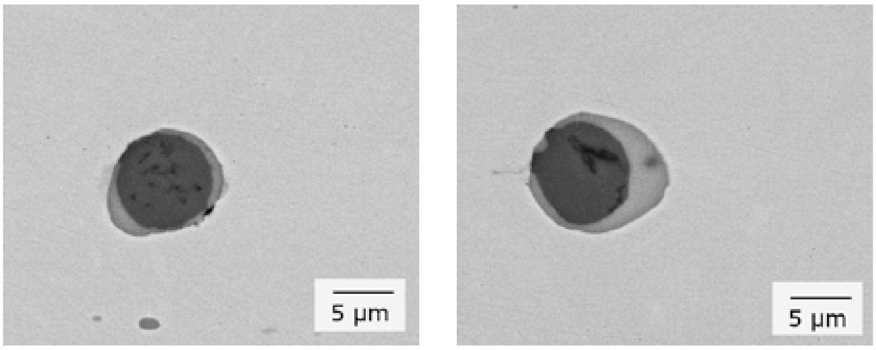


Figure 1. Representative Ca-aluminates surrounded by MnCaS shell, from Ovako M-steel. (SEM-BS)

Introduction

Ovako's M-steel family of different low alloy engineering steels with improved machinability has helped machinists to cut their component manufacturing costs during the last 40 years.

The M-steel concept is based on the modification of non-metallic inclusions to extend the service life of cutting tools. As compared to conventional Ca-treatment aimed for improved castability, the M-steel involves a significantly modified Ca-treatment. It is designed for reducing the melting temperature and increasing the ductility of the transformed Ca-aluminates. The extreme strain rates, combined with the temperature in the cutting zone, often reported to be in the range 700-1000°C, makes the Ca-aluminates to enrich and deposit on the cutting tool. The buildup of the thin non-metallic deposit protects the cutting tool in two ways: 1) It reduces the chemical dissolution of carbo-nitride constituents of a cutting tool, including ceramic coatings through CVD and PVD, as well as the cemented carbide substrate, 2) The deposit of Ca-aluminate on the cutting tool acts as thermal barrier, reducing the heat transfer from the passing chip into the rake face of the cutting tool.

For the CNC technician in the workshop, the M-steel effect is typically observed as a significantly slower progression of the tool wear, meaning that the tool life can be increased by 50-300 %, depending on the machining operation and the cutting data, as compared to conventional steel.

The metallurgical sweet spot of the desired Ca-aluminate formation basically aims at as low melting point as possible. The effective M-steel inclusion is made up of a Ca-aluminate core surrounded by a MnCaS shell, see Figure 1. The sulfide shell is equally important in its ability to distribute the load in the tool-chip contact. This is important in particular in machining operations run at smaller than optimal cutting speeds. In summary, the inclusion design of the M-steel makes a benefit in both high production rate processes, "the faster the more benefit" and at the same time, the M-steel makes a difference in unmanned production using moderate machining data.

Chip breaking is also improved, as compared to conventional steels. The somewhat higher temperature of the chips, resulting from the thermal barrier effect of the non-metallic deposit, makes the chips curl more, hence they break better than with conventional steels. However, in practice, the CNC technician probably experiences an improved chip control, foremost thanks to the longer tool life, when using M-steel.

The actual benefit in machining operation with the M-steel depends on which tool

Table 1. Elemental compositions of steels used in the study

Steel		HB	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Ca
42CrMo4	M-steel	260	0,422	0,292	0,783	0,01	0,035	0,914	0,261	0,158	0,004	0,012	0,0036
	Conventional	266	0,403	0,285	0,751	0,007	0,020	1,083	0,194	0,224	0,006	0,022	0,0004
20NiCrMo2	M-steel	188	0,22	0,244	0,853	0,017	0,029	0,469	0,426	0,16	0,004	0,018	0,0047
	Conventional	186	0,207	0,225	0,845	0,01	0,033	0,564	0,457	0,211	0,003	0,027	0,0014

geometry and tool grade is used, as well as on the cutting data. In general, a steel with improved tool wear behaviour benefits more in roughing operations. A steel with improved chip control benefits more in finishing operations.

The M-steels were introduced on the market already in 1981. They have since then been a core part of the commercial and technical success of the Ovako Imatra steel plant. Numerous customers have benefitted from improved competitiveness thanks to reduced costs of the total manufacturing process of advanced engineering parts for hydraulics, automotive, fasteners, forestry parts, among others.

The standardized machinability test of bar steel products, ISO3685, includes longitudinal passes of a bar sample using a specific tool geometry. To reveal the benefit of M-steel as experienced by a CNC technician as of today's machining methods, the current study used a state-of-the-art tool geometry of ISO-P15 type, Mitsubishi CNMG120408 MP 6115. This is also of the current generation of tool grade, meaning that the coating systems, cutting edge rounding and the cemented carbide are all designed for optimal performance with engineering steels.

The aim of this study was to display the machining performance of M-steel vs conventional steel, using a modern tool with chip breaker. This result and comparison would align very well with the experience of a CNC technician in a workshop using M-steel.

The current work includes a comparison of tool wear performance of ISO standardized steels denominated 42CrMo4 in the quenched and tempered condition and 20NiCrMo22 steel in the asrolled condition.

Experimental

The materials investigated were of type 42CrMo4 and 20NiCrMo22. Their elemental compositions are given in Table 1. The 42CrMo4 came as bars with outer diameter OD=120 mm, quenched and tempered to 260±10 HV30. The 20NiCrMo22 came as as-rolled bars of OD=115 mm and with hardness of 210±10 HV30. The hardness was recorded at mid-radius of the bar cuts used in the actual tests. The bars were cut to L=500mm for the machining tests.

The cutting tool used in the tests, Mitsubishi CNMG120408 MP 6115, is of type ISO-P15, meaning that it is of the most frequently used tool grade and type in medium and roughing turning operations of today. The tool grade is made up of the tungsten carbide substrate, CVD coated with TiCN and an outermost layer of Al_2O_3. The CVD coating technology includes textured coatings to enhance the resistance to the combined thermal and mechanical loads on the cutting tool from the chip flow. The machining tests were made up of longitudinal passes of L=450 mm with depth of cut a_p=2 mm and feed f_n=0.3 mm/rev. Dry machining was used in the tests. The work piece was clamped by a chuck spur and a tailstock. A cleansing cut of the outermost scale layer from hot rolling was done prior to the test cuts. A few cutting speeds (v_c) were tested in order to aim at a tool life of 15 minutes. Such relatively short tool life, hence short tool exchange interval, is common practice in mass production of engineering parts, based on the fact that the total manufacturing costs are primarily driven by the costs of the machinery. In comparison, the tool is a relatively minor cost. Consequently, short cycle time is aimed, often through the use of high cutting speeds.

The most relevant cutting speeds for the comparison of tool life performance of the steels used in the study were found to be 300 m/min and 450 m/min, respectively. Hence, full tool life tests were undertaken with these cutting speeds. The tool life criteria was flank wear v_b>0.3 mm in any location from the tool nose to the depth of cut position.

An in-depth analysis of tool wear mechanisms was undertaken at early stages of tool life. For this, additional pre-tool life tests were made and stopped after 8 minutes of machining. The initial tool wear was assessed with scanning electron microscopy (SEM) imaged using backscattered mode (BS), which enhances the atomic number contrast of the used cutting tool. In addition, energy dispersive spectroscopy (EDS) was used for elemental maps of the constituents of the non-metallic deposits. Note that, given the tool grade design of WC-Co + TiCN + Al_2O_3, any enrichments of these elements from the non-metallic elements of the steel could not be mapped. Hence, the mapped elements are foremost Ca and S.

Results

The two groups of steels, 42CrMo4 and 20NiCrMo2-2 resulted in different optimal cutting speeds. This is expected, given the differences in both alloy content and hardness. A few preliminary tests showed that the cutting speeds of vc=300 m/min and vc=450 m/min, were most relevant for the 42CrMo4 and the 20NiCrMo22 steels, respectively.

The tool life of the 42CrMo4 steels was 10 min and 21 min, respectively, whereas the tool life of 20NiCrMo22 was 17 min and 28 min, respectively, see Figure 2. Hence, the tool life could be increased by roughly +100 % and +65 %, respectively, with the M-steels vs the conventional steels.

The used cutting edges display both crater wear and plastic deformation of the flank faces, see Figure 3. The flank wear was, per definition of the tool life criteria of v_b>0.3 mm, relatively equal of the four tested cutting tools. However, the imaged tools had been running with the different test times of Figure 2. At the respective stage of test time, the crater wear of the cutting edges ran with

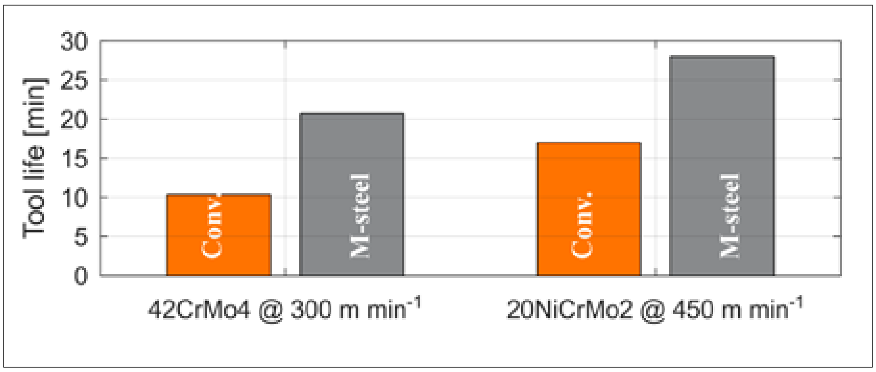


Figure 2.Tool life vs cutting speed using Taylor regression of the 42CrMo4 (left) and 20NiCrMo22 (right) steels. Conventional (orange) and Msteel (grey).

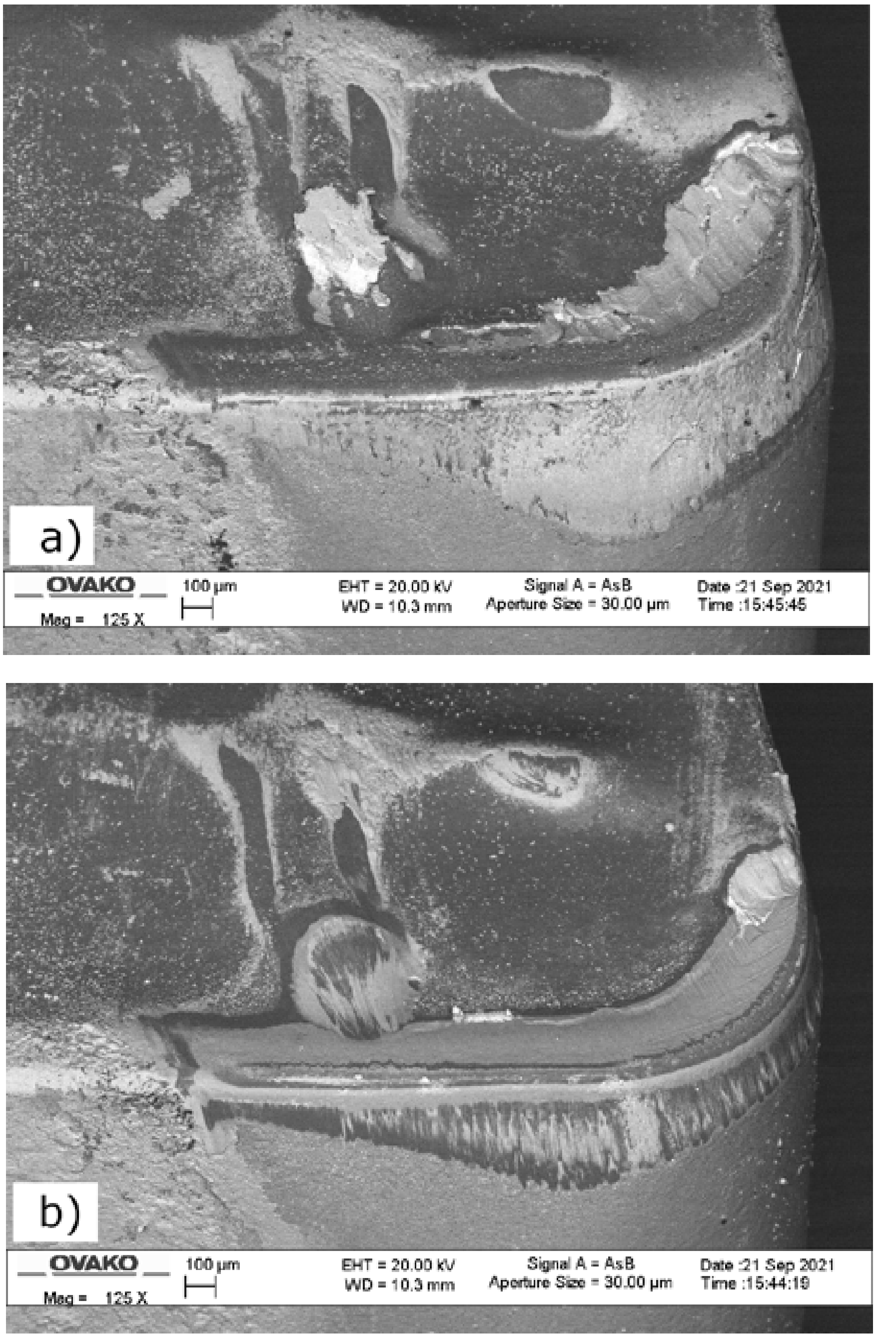


Figure 3. Cutting edge after completed tool life after machining test at 300 m/min with 42CrMo4 Q+T. a). Conventional steel after 10 min test time and b). M-steel after 21 min test time. (SEM-BS)

the conventional steels are more advanced than those with the M-steels.

The elemental mapping of tool rakes using SEMEDS revealed that the tool tested with 42CrMo4 conventional steel displayed almost no deposits from the non-metallic constituents of the steel, see Figure 4. On the other hand, the tool tested with 42CrMo4 M-steel displayed local patches of foremost enriched Ca and S, see Figure 5. The same difference of no detection of non-metallic deposits was found with the conventional steel, as compared to local patches of Ca and S with the M-steel of type 20NiCrMo22.

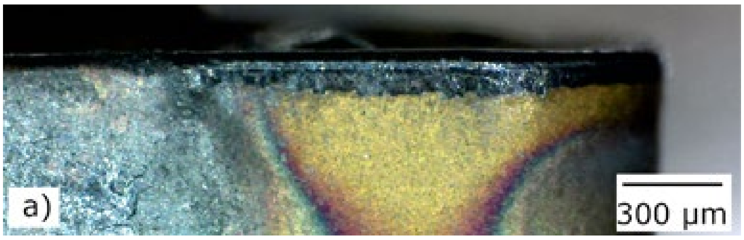
Discussion

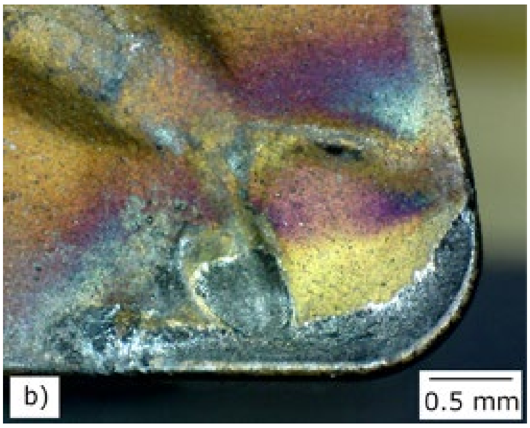
There has been a tremendous development in cutting tool and machine technology during the last four decades. Keeping that in mind, the most important finding of this study is that still, for 40 years after its introduction, the metallurgical Ca-treatment to manufacture the M-steel is still decisively beneficial for the machining performance of the engineering product. Thereby the workshop that uses M-steel will benefit from lower total costs to manufacture advanced components. This has been shown in the case of both as-rolled 20NiCrMo22 steel and 42CrMo4 steel quenched and tempered. Of course, these steels are used for different applications and segments. However, they have in common the relatively advanced machining operations made on bars and forgings of these steels to reach the final product geometry and tolerances.

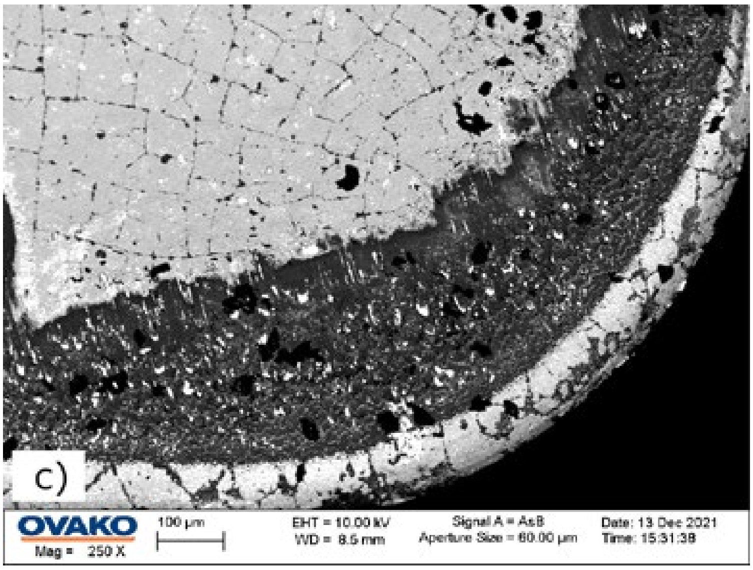
The manufacturing cost advantage of using M-steel

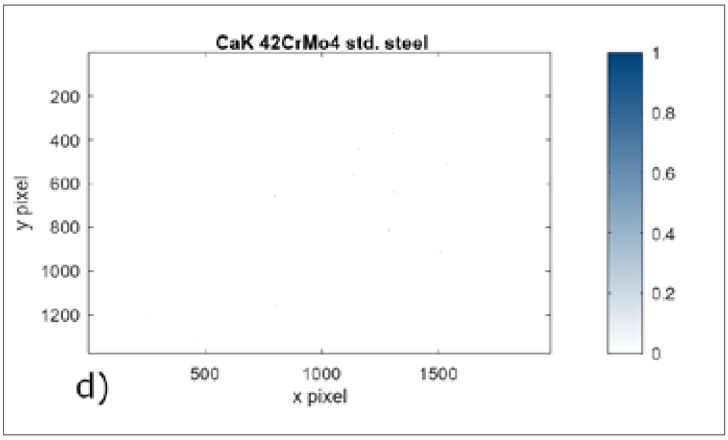
The increased tool life in machining with M-steel can be used in two different ways in a workshop.

1) Increased cutting speed. The tool life in minutes of cutting engagement or in number of parts produced is then maintained, as compared to the conventional steel. Yet,









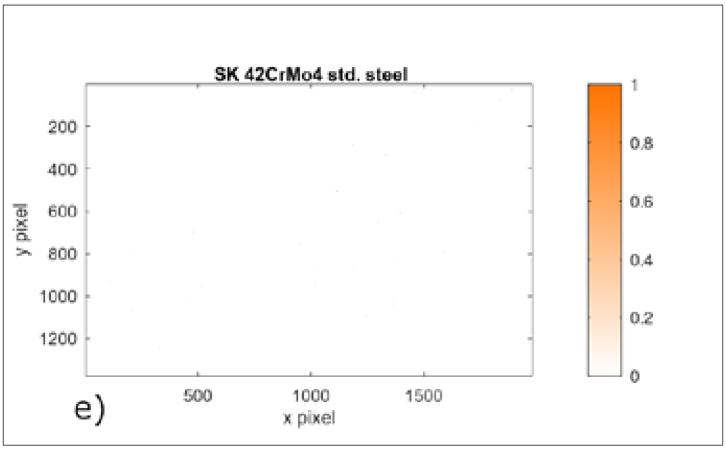


Figure 4. Cutting edge after machining for 8 min with the 42CrMo4 conventional steel. Overviews of the a) flank face and b) the rake face (LOM). c) detail of the rake face (SEM-BS), and elemental maps of d) Ca and e) S.

the cycle time is reduced with the M-steel. This enables a higher production rate in the workshop, which is most often the key factor to a financial benefit.

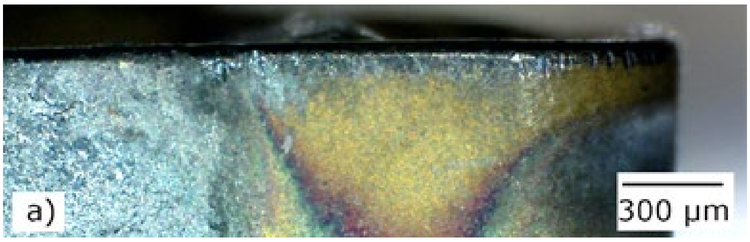
2). Extended interval of tool exchange. This can be used, of course, to minimize the tool costs. However, the prospect of automated and unmanned production is often far more profitable. Longer tool life gives more freedom to tune the tool exchange with other production stops, e.g. change of shift staff.

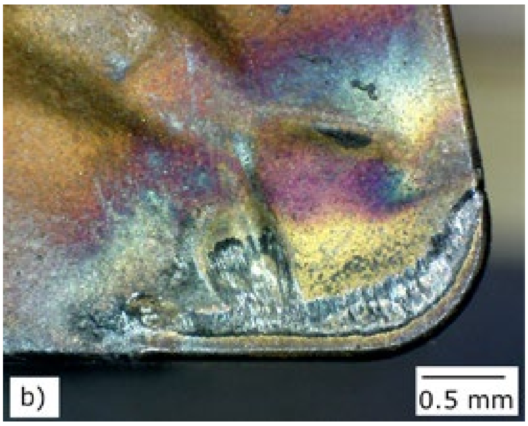
As an example of the production cost advantage with M-steel, the tool life tests displayed as tested time, compare Figure 2, can equally be transferred to the removed volume of steel, or the number of parts produced. The machining of a fictive component requires 1000 m of removed chips to reach the final part geometry. The tool life in minutes × cutting speed gives the chip cut length (CCL), see Figure 6.

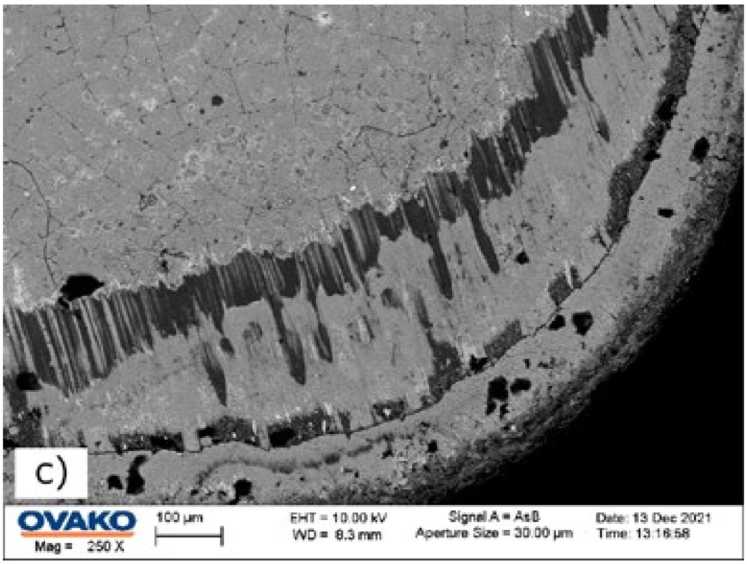
Conclusions

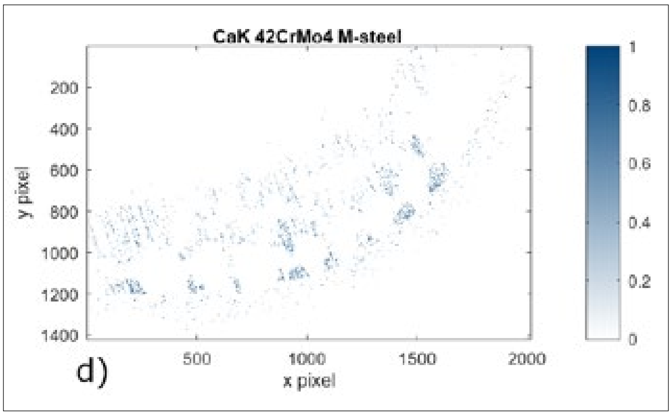
The following conclusions can be drawn from this work:

- Still 40 years after the launch of M-steel, the machining performance advantage is significant. In this study the tool life









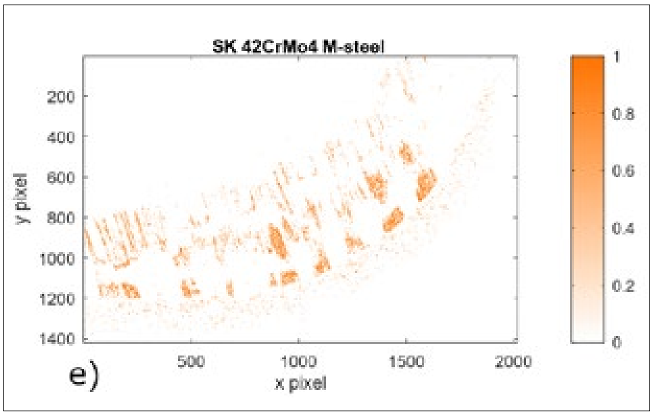


Figure 5. Cutting edge after machining for 8 min with the 42CrMo4 M-steel. Overviews of the a) flank face and b) the rake face (LOM). c) detail of the rake face (SEM-BS), and elemental maps of d) Ca and e) S.

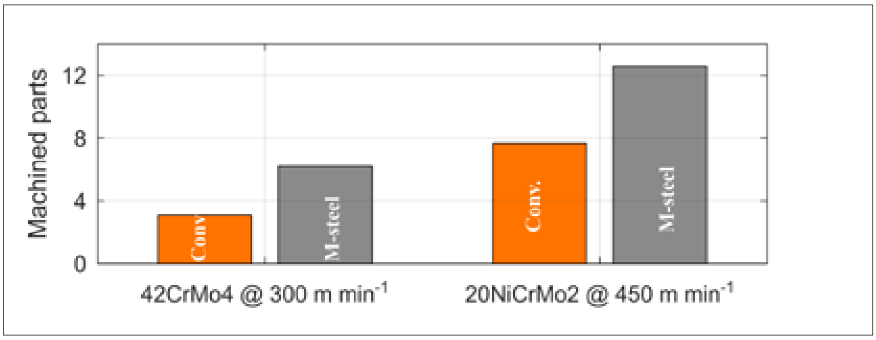


Figure 6. Schematic of parts produced with the two steels and conventional vs. M-steel.

could be increased by 60-100 % with the M-steel, as compared to the corresponding conventional steels.

- Deposits, foremost of Ca and S, were found on the tool rake after machining tests with the M-steels. This is most likely very important for the improved tool performance with M-steel.
- Two ways to obtain the machining cost advantage are shown. Either the increased cutting speed can be used to reduce the manufacturing cycle time or the extended interval of tool exchange can enable more automated and unmanned production. ▲