OVAKO

M-STEEL® — REVIEWING THE MECHANISMS THAT IMPROVE STEEL MACHINABILITY

Thomas Björk and Johan Backman

Executive overview

For decades, Ovako's M-Steel process - in which the 'M' stands for machinability – has been helping manufacturers enhance the productivity of their machining processes. This white paper outlines the philosophy behind M-Steel, particularly that it is not a steel grade. Instead, M-Steel is a constantly evolving machinability improvement treatment that can be applied to almost any steel grade in Ovako's stock program. Essentially, the M-Steel treatment is used to modify and control the non-metallic inclusions in the steelmaking process by adding calcium before applying a number of proprietary steps.

Historically, sulfur has been added to steel to improve machinability by forming sulfides that appear as elongated inclusions. These non-metallic inclusions act as stress raisers that help break the chip into short pieces. The downside is that these sulfides can cause inferior fatigue performance.

The M-Steel process takes an alternative approach that transforms the long sulfide inclusions into spherical calcium-treated oxysulfide soft inclusions. This offers many advantages: Some customers report a 30-40% reduction in total machining costs compared with conventional steel. Others report that M-Steel enables the hard turning of case-hardened steel with cubic boron nitride (CBN) inserts at roughly double the speeds previously possible.

There is a further benefit that results from the deposition of a protective layer on the cutting tool during machining. This deposit reduces the chemical adhesive wear of the tool from the passing steel. It also acts as thermal barrier so that more heat is carried away with the chip and less heat flows into the cutting tool. Moreover, the hot chips curl more, resulting in better chip breaking.

This white paper outlines how Ovako has continued to fine-tune the M-Steel process – without affecting any of the other steel prop-erties such as hardenability, fatigue resistance or toughness. It also explains the concept of the 'sweet spot' that represents the optimal balance between cutting speed and tool wear.

The white paper concludes with a number of case studies illustrating the practical advantages of M-Steel in machining processes. It also introduces the M-Steel Calculator. This is part of a special digital platform – the Steel Navigator – developed to help customers identify the optimal steel grade for their application.

1 — Why machinability matters — and how M-Steel can make a difference

Machining operations constitute a large proportion of the total cost of finished components. It is therefore important for manufacturers to optimize their total production costs without sacrificing other properties. That makes machinability a critical aspect of metal cutting operations that require good chip control, reliable cutting action and a long and consistent tool life.

There is no absolute definition of machinability in grades or numbers. Broadly, it covers the ability of the workpiece material to be machined, the wear it creates on the cutting edge and the chip formation that can be obtained.

1.1 What is good machinability
The concept of 'good machinability' usually means undisturbed cutting action and a reasonable tool life. Most evaluations of the machinability of a certain material are made using practical tests, and the results are determined in relation to another test on another type of material under approximately the same conditions. In these tests, other factors, such as microstructure, smearing tendency, machine tool, stability, noise, tool life, etc. are taken into consideration.

There are usually three main factors that must be identified in order to determine a material's machinability:

1. Classification of the workpiece material from a metallurgical/mechanical point of view.
2. The cutting tool:
   - geometry to be used, basic tool geometry, e.g. CNMG, SNMG, etc. entrance angle, nose radius, chip breaker, among others.
   - tool material (grade) with its proper constituents, e.g. coated cemented carbide, ceramic, CBN, or PCD, as well as details of the cutting edge rounding.
3. The cutting process, foremost depth of cut (ap), feed (fn), cutting speed (vc), cutting fluid and its application, the length of each machining pass, etc.

The selections above will have the greatest influence on the machinability of the material under review. Other factors involved can include: cutting data, cutting forces, heat treatment of the material, surface skin, metallurgical inclusions, tool holding, and general machining conditions, etc.

1.2 Improving chip control
To improve chip control, sulfur is usually added to form sulfides that appear as elongated inclusions. These non-metallic inclusions act as stress raisers that help break the chip into short pieces. The downside is that these sulfides can cause inferior fatigue performance.

An alternative approach is to modify the inclusions during the steelmaking process. This process requires precise control and the addition of minor elements to the melt. During the modification process, long sulfide inclusions are transformed into spherical calcium-treated oxysulfide soft inclusions. This forms the core of Ovako's M-Steel process in which the 'M' stands for machinability.

1.3 M-Steel – a 30-year history of continued development
M-Steel treatment can be applied to any steel grade and any as-delivered condition. As a general rule of thumb: the harder the machined steel, the more benefit M-steel will offer. This means that hard quenched and tempered M-steel (300-400 HB) is very suitable to machine, as compared to standard steels.

Some customers have recorded a 30-40% reduction in total machining costs compared with conventional steel. Others report that M-Steel enables the hard turning of case-hardened steel with cubic boron nitride (CBN) inserts at roughly double the speeds previously possible. Remarkably, at higher speeds, crater wear on the tool edge is actually reduced and the life of the cutting tool is doubled or even trebled.

2 — Producing M–Steel

While M-Steel was developed several decades ago ago it has remained under constant improvement. Compared with the hard, non-metallic inclusions found in conventional steel, the M-Steel treatment offers improved machinability during production and better fatigue performance for the finished product. Where optimized fatigue performance is critical, however, a clean steel approach is required such as in BQ- and IQ-Steel grades.

During the mid-1970, tests were carried out with the aim to reduce the sulfur content of steel by the injection of calcium-silicon (CaSi) in the ladle furnace. The addition of CaSi also resulted in a significant reduction in the clogging of the tundish nozzles in the continuous casting process. This provided significant improvements in both the castability and process yield. In 1976, Raimo Karling, an application specialist at the Imatra steel works, pioneered the use of the same CaSi treatment as a method to significantly improve the machinability of steel. It was found that cemented carbide cutting tools could be used at much higher cutting speeds and their tool life was multiplied. The formation of a protective transfer layer on the cutting tool was found to be the key element of this new steel characteristic.

The M-steel effect involves the modification and control of non-metallic inclusions with calcium treatment. A key element in the production of M-Steel is how Ovako optimizes the material properties at every stage of the manufacturing process. M-Steels are based on treating non-alloyed or low-alloyed special steel. Typical examples include Ovako's 520 grade and 34CrNiMo6.

When these standard steels are 'M-treated', Ovako applies careful control to the metallurgy in everything from the raw material through to the melt, casting, hot rolling and final heat treatment. Because Ovako operates fully integrated facilities it can optimise the composition, heat treatment and more.

Over the past 30 years, Ovako has fine-tuned how it controls the non-metallic inclusions using a special calcium treatment process to achieve optimal cutting ability – without affecting any of the other steel properties such as hardenability, fatigue resistance or toughness.

On the contrary, for M-Steel we find that fatigue strength and toughness are better than conventional steels and other types of machinability improved steels, especially when we consider the transverse properties. M-Steel has spheroidal inclusions and for this reason the transverse fatigue and impact toughness properties are better than in corresponding steels with M-treatment.

3 — The M–Steel protection effect

A protective layer, originating from the calcium inclusions in M-Steel, is deposited on the cutting tool during machining (See Figure 1). This deposit reduces the chemical adhesive wear of the tool from the passing steel. It also acts as thermal barrier so that more of the heat stays in the steel, and also to a larger extent is carried away with the chip, and less heat flows into the cutting tool. This has an important effect on the life of the cutting tool or alternatively on how the productivity can be maximized. Moreover, the hot chips curl more, resulting in better chip breaking.

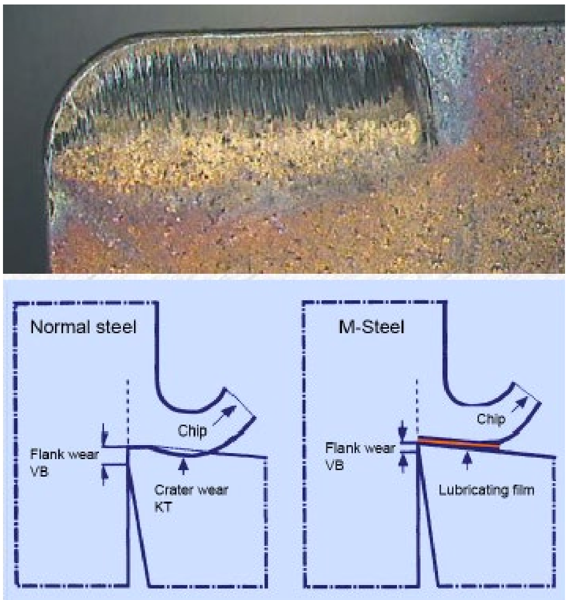

Figure 1 – M-Steel forms a protective layer on the tool edge.

Figure 2 provides a practical example of the beneficial effect of the protective layer. A test was carried out to compare the cutting behaviour of 42CrMo4 (hardness 255 HB) with an M-Steel, 42CrMo4 M (hardness 255 HB). The cutting speed (272 m/min), feed (0.4 mm/r) and depth of cut (2.5 mm) were the same for both materials, with no cutting fluid used.

The standard 42CrMo4 had a cutting time of 56 seconds. With the M-Steel the cutting time was increased to 6 minutes.

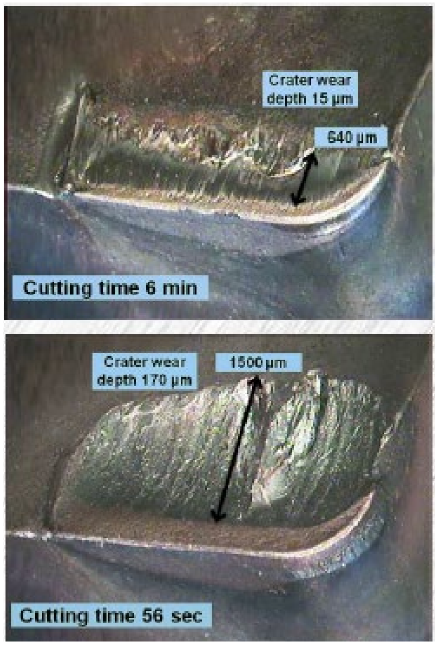

Figure 2 – With the M-Steel (top) the cutting time is increased by six times over the equivalent conventional steel (bottom).

M-Steel can also have a beneficial effect in facilitating the use of increased cutting speeds, as shown in Figure 3.

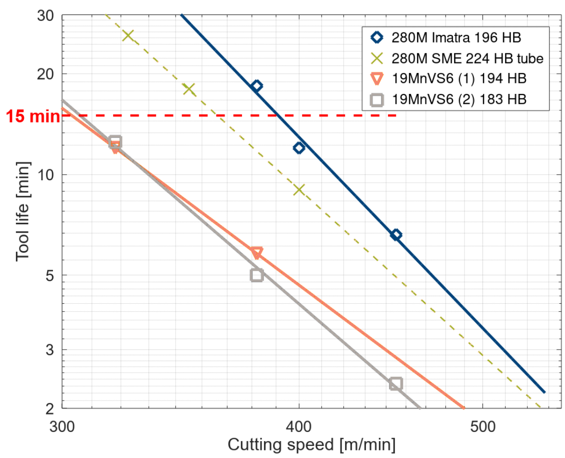

Figure 3 – Relation between cutting speed (v, m/min) and tool life (T, min), Taylor's curve.

4 — Finding the sweet spot

The 'sweet spot' in machining represents the optimal balance between cutting speed and tool wear. This depends on multiple factors such as the steel grade, tool properties, tool exchange times and the desired product surface characteristics.

An Ovako customer based in Sweden carried out a test program to investigate the sweet spot for the automated CNC machining of automotive components.

The company wanted to find the optimal machining speed to reduce its cost per component with M-Steel, compared to standard steel. In making the calculation it also factored in tool and tool exchange costs as well as cycle times. It should be noted that using M-Steel can influence machine uptime by increasing tool life, but it cannot influence the time required to change a tool, as this is the same whatever material is being machined.

Figure 4 illustrates the results. With conventional steel, the optimal speed to achieve the highest cost savings (the orange curve) is 276 meters per minute. This results in a total cost of €3 per piece.

With M-Steel, the optimal speed is increased to 359 meter per minute, and the total cost per piece is reduced to €2.4.

In other words, this particular customer is achieving a total saving of €0.6 per component by changing over to M-Steel. These cost savings start to add up significantly in series manufacturing at higher volumes.

In addition, a 30% increase in cutting speed will significantly free up capacity in installed equipment and delay the need for further investments.

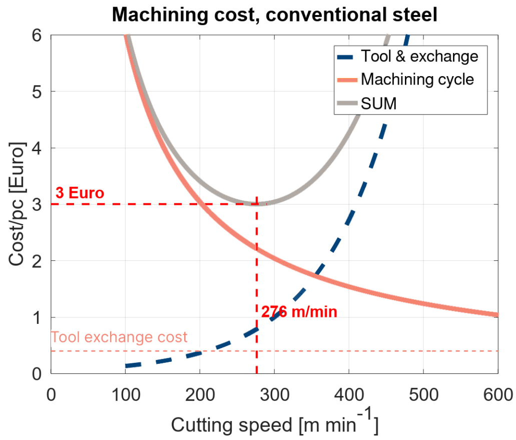

Figure 4a

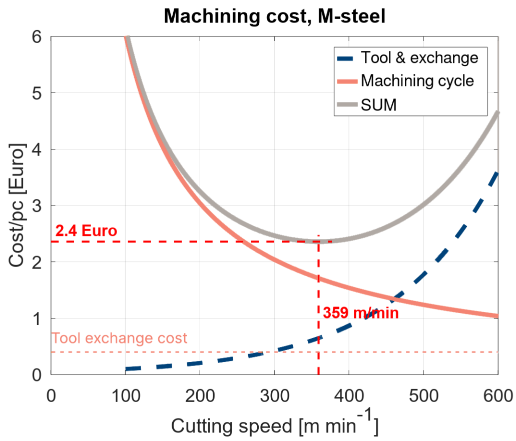

Figure 4b

Figure 4 – Finding the optimal balance between cutting speed and tool wear – comparison of conventional steel (top) and M-Steel bottom.

5 — Hard-part turning

Hard-part turning (HPT) is often the crit-ical last machining stage when producing steel transmission components. Following the development of new tool materials, such as super-hard polycrystalline cubic boron (PCBN) inserts, it is now possible to turn materials over 55 HRC in hardness at high cutting speeds.
That means for many components, HPT is now a cost-effective alternative to grinding or heat treatment. The M-Steel effect is particularly beneficial in HPT. Simply put, the more thermal and mechanical load the chip exerts on the cutting tool, the more the protective layer builds up. Thereby, less heat goes into the cutting tool and more heat goes with the chip. In addition, the deposit protects the tool from chemical wear from the passing chip. This can cause the chips to glow with heat as shown in Figure 5.

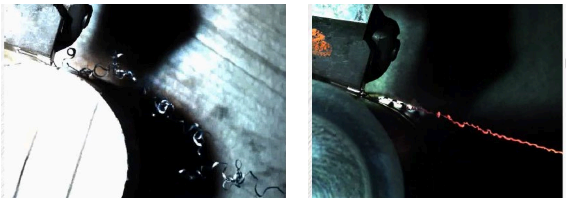

Figure 5 – Using M-Steel in hard part turning can result in chips glowing with heat as shown in the photograph on the right.

The cutting speed can be increased by 30%, leading to smoother component surfaces. At the same time, it can be possible to double the tool life. An added advantage is that using M-steel significantly reduces the micro- and macro- chipping of the sensitive PCBN cutting edges.

To verify the advantages of M-Steel, SWERIM, an independent test institute, put some carburized steels to a field test of synchro-mesh gears used in a heavy vehicle gear box. The advantage of the M-steel was found with respect to a doubled tool life, significantly less micro-chipping and macro-chipping of the PCBN tool edge, as well as the possibility to machine at up to 50% higher cutting speed with retained surface roughness and tool life, as compared to the non-M-steel.

For more detailed information on hard part turning using M-Steel please refer to this technical report:
Machinability improved M-Steel® – for reduced tool wear and increased productivity in hard part turning

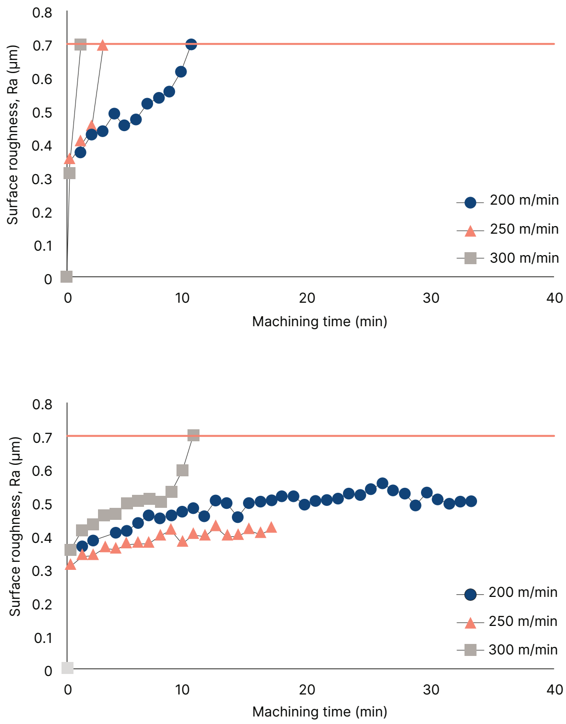

Figure 6 – Comparison test on two steels used in truck gearbox components.

6 — M–Steel improves fatigue performance at moderate stress levels

In addition to offering superior machinability, a key advantage of M-Steel over conventional steel is that it improves fatigue strength , primarily in the transverse direction, as compared to conventional steels. This is useful for manufacturers producing components that will be exposed to cyclic stresses.

The main factor that gives M-Steel its improved fatigue performance is the spheroidal inclusions, as shown in Figure 7. A conventional steel (R on Figure 7) features long and thin inclusions that act as stress raisers. That gives it satisfactory performance when loaded in the longitudinal direction (i.e. parallel to the length of the inclusions), but poor performance when loaded in the transverse direction. In contrast, M-Steel offers good fatigue strength when loaded in either the longitudinal or transverse directions, as illustrated in Figure 8.

The very close control of the size and distribution of inclusions, as shown in C and UC on Figure 7, is what gives clean Bearing steel and ultra-clean IQ-Steel their exceptional fatigue properties.

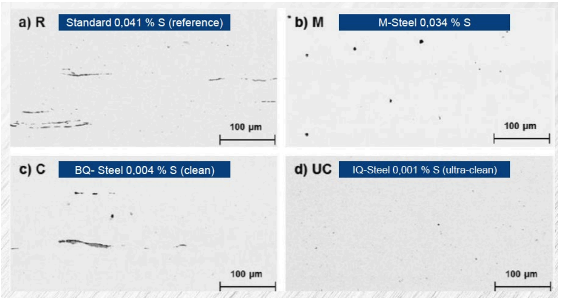

Figure 7 – The size and topology of inclusions in steel is a key factor in fatigue performance.

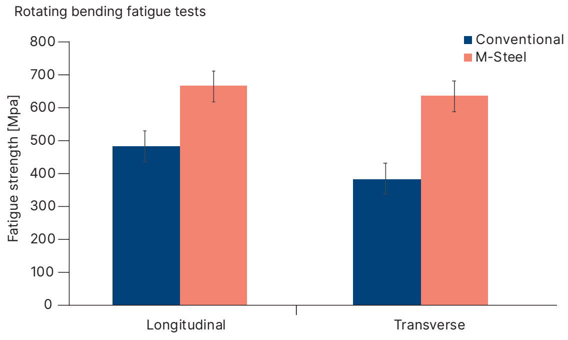

Figure 8 – Comparison of fatigue strength in the quenched and tempered condition.

M-Steel may be suitable in fatigue-critical applications for components that are exposed to moderate stress levels. It is though essential for the performance requirements to be evaluated very carefully for certain very high stress items. As shown in Figure 9, there are clear trade-offs in terms of matrix-induced or inclusion-induced fatigue failure. For example, M-Steel offers higher fatigue strength than conventional steel for components exposed to moderate to medium stress levels, but it is not at the same level as BQ-Steel® and IQ-Steel®. Using these steels will generally offer better protection against cracking or failure, particularly at higher stress levels.

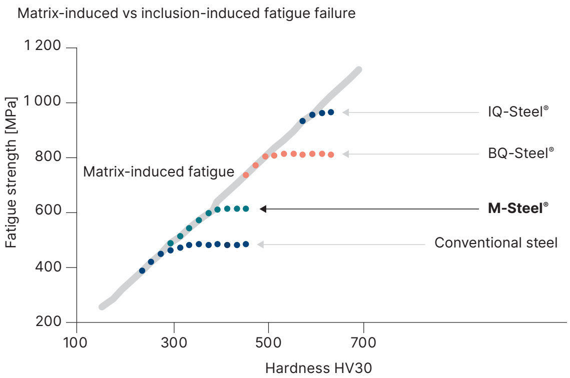

Figure 9 – Where M-Steel fits on the fatigue strength curve.

7 — Steel Navigator — a digitalshortcut to finding the right M–Steel

The Steel Navigator helps designers and engineers find exactly the right steel grade, explore material data sheets, consult heat treatment guides and use a machining calculator. It contains a number of modules, which are dedicated to different design functions.

The Material Data Sheets (MDS) module makes it possible to search Ovako's data-base of hundreds of steel grades to compare options and select the best steel for a specific application. It has been designed by Ovako experts to provide complete flexibility in the way it is searched. Users can build a candidate list of potential steel grades by searching directly for a steel according to its numbering system (WNr), standard or steel grade number. They can also enter the steel composition and specify the weldability and hardenability required.

The M-Steel Calculator was developed to get the best out of M-Steel. It helps users to choose the right cutting set-up depending on their tool and material. They can also access information on machine power, chip stream and the expected surface quality of the workpiece. The module will also calculate the difference between these parameters when using M-Steel and conventional steel. Using M-Steel it is normal to save up to 30–40 % in production costs with no impact on quality.

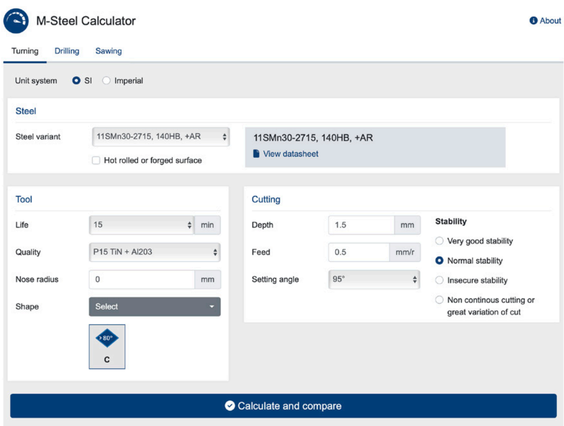

Figure 10 –The M-Steel Calculator makes it possible to calculate and compare standard steel grades against M-treated grades.

Another module is the Heat Treatment Guide, a very sophisticated tool to calculate the heat treatment response of any steel grade. Users can choose from hundreds of pre-defined grades (both Ovako grades and international standards) or define their own chemical composition. The module provides information on hardenability and tempering response, making it easy to compare how different grades respond to heat treatment.

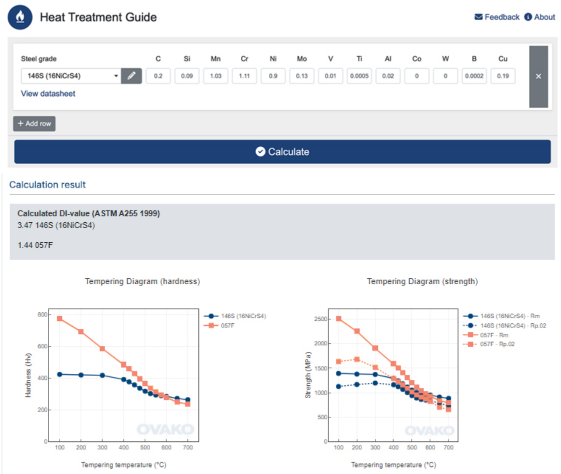

Figure 11 – Ovako Heat Treatment Guide is a tool developed to increase the understanding of how different alloying elements influence steel hardness after quenching and/or tempering.

The Piston Rod Predictor lets engineers compare the resistance of different steel grades to buckling in piston rod applications. The emphasis is on buckling because it is the key design consideration for hydraulic cylinders, especially in single-action, push-only applications.

In Steel Navigator there are features that enable access to all Ovako's Technical Reports, a steel glossary and other useful links.

8 — Case studies

These case studies provide practical examples of the benefits of using M-Steel.

8.1 Juhani Haavisto Oy – saving over 24% on every component produced
Juhani Haavisto Oy is Finnish custom engineering subcontractor that supplies parts to the Nordic pulp and paper, mining and process industries. The company is always looking for ways to streamline and modernize its highly varied production. For the shafts it was producing, it decided to establish a new manufacturing cell to optimize productivity using unmanned production.

In the past, the machining production of shafts had required three steps and was fraught with problems relating to straightness, vibration, high-carbide insert tool wear and long chips. Haavisto wanted to save money and time by combining a robot, standard CNC machine and superior material – in just one step.

A test was made using M-Steel-treated 42CrMo4 + QT Ø100 mm bar (1091 mm length) against products from three other European producers – see Figure 12. The steels were comparable in composition and mechanical properties according to EN10083-3. While the cutting speed could be increased by 20% for all steels, the M-Steel-treated bar had far fewer problems with straightness, vibration and chip performance – and tool life was extended fivefold. Of all the tested materials, only M-Steel could be considered for automated production.

Figure 13 summarizes the cost saving calculation. This indicates that with the new setup and using M-Steel, Haavisto is saving over 24% on the cost of every component produced.

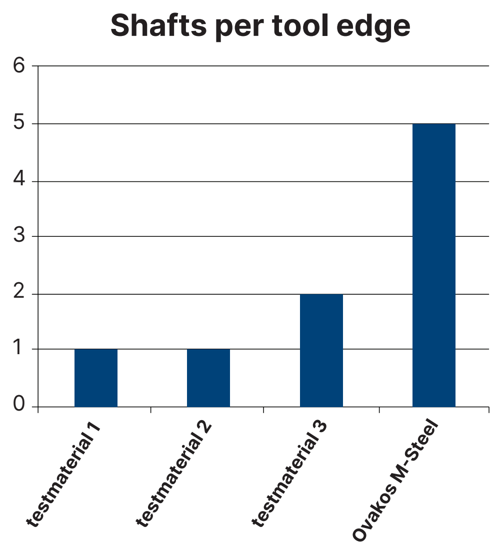

Figure 12 – Tool wear was much lower with M-steel, with up to 5 x longer tool life.

Total cost savings through automation with M-Steel (including investment for 1 robot)

Old setup	**Three steps in machining, always manned operation, ordinary steel**		
		Time	**Cost per piece**
Machine costs	€ 20/h	1.2 h	€ 24
Labor costs	€ 25/h	1.2 h	€ 30
Tools	€ 10/h	1.2 h	€ 12
Materials	€ 1/kg	68 kg	€ 68
			€ 134

New setup	**Done in one, automated operation, M-Steel**		
		Time	**Cost per piece**
Machine costs	€ 30/h	0.75 h	€ 24.50
Labor costs	€ 25/h	0.1 h	€ 2.50
Tools	€ 2/h	0.75 h	€ 150
Materials	€ 1.1/kg	68 kg	€ 74.80
			€ 101.30

Figure 13 – Cost savings calculation for Haavisto.

8.2 Hellstens Mekaniska AB – unmanned production runs smoothly throughout the night
Since the 1990s, Hellstens Mekaniska, an innovative company based in southern Sweden, had been manufacturing components like bushings (see Figure 14) using the standard steel grade S355J2. As an untreated steel, S355J2 generated a lot of large chips during machining that gummed up the CNC operations and contributed to excessive tool wear. This contributed to unplanned production stoppages and cost increases.

In 2010, the company decided to try out M-Steel and see if it would enable it to cut costs and boost productivity by adding night-time runs. The expectation was that M-Steel would be more consistent than standard steel from batch to batch, which would improve the machining process and reduce tool wear. This was confirmed by a test program.

Making the change from standard to M-Steel was easy, although Hellsten spent some hours fine-tuning the CNC machines. The results were evident almost immediately in terms of the consistency of the material and cutting characteristics that produced less wear on the tools. This has effectively eliminated any problems occurring with broken drills during an unmanned night shift.

Today, the company can produce three pallets of M-Steel bushings, each containing about 270 pieces per pallet, without a tool change. Standard steel required a change after every pallet – a third of the capacity. In total, Hellstens produces 40,000 bushings a year.

Although the price of M-Steel is a little higher than the standard S355J2 steel, the gains are obvious. Hellsten has been able to cut production time by about 20% and increase tool life from 80 pieces to 150 pieces.

Figure 14 – Hellstens produces bushings for agricultural cultivators.

8.3 Pameto – tool life doubled with M-Steel
Pameto manufactures M42 bolts with 12.9 strength. Previously, the company used 34CrNiMo6 quenched and tempered bar, 45 mm in diameter. It was not possible to achieve a significant increase in the cutting parameter due to vibrations caused by stability issues. However, tool life has been almost doubled by switching to M-Steel for this very hard material.

Figure 15 – Pameto manufactures M42 bolts in M-Steel.

8.4 PB Machine Tech – M-Steel enables problem-free automatic production

PB Machine Tech is a company based in Ireland that produces around 26,000 bushings a year for hydraulic components. Following a switch to M-Steel it has been able to reduce its total cycle time by 8% combined with better tool life both in inserts and tool holders, when compared to standard S355J2 steel.

The most important benefit of M-Steel is that it has enabled PB Machine Tech to adopt automatic production without any problems. This is because there is no poor chip breakability or sudden tool breakage. Consistency means that the same cutting data can be used from batch to batch as well as ensuring a predictable tool life. There are also no vibrations in the bar feeder.

Figure 16 – PB Tech has achieved an 8% reduction in cycle time by manufacturing bushings for hydraulic components in M-Steel.

9 — Summary

M-Steel is not a steel grade. It is a machinability improvement treatment that can be applied to almost any steel grade in Ovako's stock program. The M-Steel treatment is used to modify and control the non-metallic inclusions in the steelmaking process by adding calcium before applying several proprietary steps. M-Steel has a consistent machinability from heat to heat, meaning that machines can be run with fixed high-cutting rates and predictable tool change intervals from one production run to another. This makes them very suitable for un-manned production. M-Steel is a well-established process that has been in use for over 30 years but is continuing to evolve.

The advantages of using M-Steel include

- Reduced machining costs and faster throughput by up to 30 %
- Zero production interruptions, enabling un-manned production
- Improved machining of pre-hardened quench and tempered steel products
- Improved hard part turning (HPT) with PCBN tools
- Suitability for multi-axially fatigue loaded components, thanks to spheroidized inclusions, as compared to standard

10 — References / Further reading

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Johan Backman is working as Senior Advisor at Ovako's Imatra Steel plant, where he started in 1977 as a product development metallurgist. He was involved in the early marketing projects for M-steel starting 1981 and has been deeply involved in M-steel testing at customers in different countries throughout the years. He has also worked for Ovako's steel plant in Smedjebacken and in Ovako's sales office in Germany.

Johan has a M.Sc. degree from Helsinki Technical University in 1977 (today Aalto University)

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