MACHINING AND TOOLING SOLUTIONS FOR ULTRA CLEAN STEEL FOR CARBURIZING APPLICATIONS — TURNING

Thomas Björk and Åke Nilsson

Executive overview

The use of clean steel offers a significant improvement in the fatigue life of critical powertrain components. That is why a number of manufacturers utilize its capabilities to optimize the power density of powertrain designs. However, while the design world is convinced of the virtues of clean steel, production engineers still show a general reluctance to make the switch. This is based largely on the received wisdom that clean steel is 'hard to machine' and therefore represents added cost and complexity for their processes.

That wisdom does not reflect the true story. In fact, tests carried out in collaboration with manufacturers of powertrain components using current processes show the change to clean steel can be cost-neutral, or even reduce costs. Although, it is true that the machining processes do need to be optimized to handle clean steel successfully.

Ovako is carrying out an ongoing R&D program to explore the changes necessary to enable the main machining processes – turning, milling and drilling – to be adapted successfully to handling machine steel in terms of feeds, speeds and tooling. In this white paper we have focused specifically on turning operations.

It is important to note that there are three main variables relating to the condition of a steel workpiece to be turned, namely

- Cleanness (eg BQ-Steel® or IQ-Steel®)
- Alloying
- Microstructure

For the purposes of the test program reported here the variable has been alloying, in terms of the steel composition. Cleanness has been kept constant by using IQ-Steel and the two steels investigated have the same soft-annealed microstructure.

The key results

- Guidelines for how to successfully machine ultra clean steels, eg. Ovako IQ-steels in turning have been obtained.
- Ultra clean steels are most efficiently machined using methods and tooling designed for stainless steels, ISO-M. The reason is that these tools are designed for more demanding chip breaking, as well as better resistance to notch wear.
- The recommendation for microstructural characteristics for good chip control is a ferrite/pearlite dual-phase microstructure with a grain size D>15µm.
- The two ultra clean IQ-steels tested of type EN 20MnCr5 and EN 18CrNiMo7-6 can be considered very similar in terms of machining guidelines. It is important to state, however, that they need different annealing treatments to reach the same ferrite-pearlite microstructure and hardness.
- The cutting speed of tool life 20 minutes (V20) is roughly 275 m/min with IQ-steel and roughly 340 m/min with conventional steel, using adequate tooling solutions for the respective steel. Consequently, the up-time difference is roughly 40 %. This coincides with the typical increase in fatigue strength with IQ-steel, as compared to conventional steel.

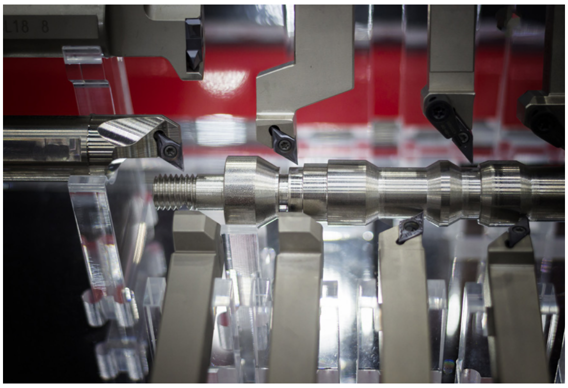


Figure 1 – A typical turning operation on a powertrain component.

1 — Why use clean steel for powertrain components?

Current efforts to minimize the environmental footprint of transportation systems requires drivetrain components to be lighter, stronger and capable of resisting ever greater and more complex loads. In a number of components, the fatigue strength of the maximum designed load is closely related to the power density, and hence the total weight.

Key factors in the component fatigue strength are, among others:

- The steel cleanness
- Heat treatment and associated residual stresses
- Stress concentrations due to:
  - The component design, eg. gear root undercut, root radii and imperfections of involute shapes of gear teeth.
  - Manufacturing defects, eg. surface topography and scratches from gear cutting and hard machining burning.
- Post-treatments, eg. shot peening, roller burnishing, polishing

Simply put, the fatigue strength is dictated by the steel hardness up to about 500 HV. Hardened steels, including case carburized steels, above that hardness become limited in their fatigue strength by their largest defects.

These can be

- Porosity and voids, in the size range 100-1000 µm
- Sulfides elongated in the rolling and forging direction of the blank. These sulfides are typically one to a few microns wide. However, they can extend up to 500-1000 µm in the rolling /forging direction, depending on the reduction from the cast format. The strong orientation of sulfides makes them on one hand relatively un-harmful in case of longitudinal loads and on the other hand they may become very harmful in case of transverse loads.
- Large oxide inclusions, often referred to as D-type inclusions, are 30-200 µm in size. D-slags are not deformed in the rolling/forging process. Therefore, their relative severity, in the same way as sulfides, increases with higher reduction from the cast.

Clean steels typically mean a low content of all kinds of inclusions. Steels for bearings are specified to be carefully controlled in oxide content, yet with some content of elongated sulfides. This steel metallurgy is called BQ-steel in Ovako's nomenclature. The roller-to-raceway contact situation in bearings means that the maximum stress is primarily in the axial direction.

A significant amount of components are loaded in the transverse or both directions of the original steel product. The actual fatigue strength is limited by the inclusion distribution in the plane in which the stress is acting. Steels with isotropic inclusion characteristics are extremely well suited for such applications.

The tooth root of a transmission gear is one such example. Parts with high internal pressure, such as fuel injectors and hydraulic parts are other applications that benefit from isotropic steel. Ovako designates these steels as IQ-steel. A comparative test using a rotating beam fatigue test configuration, including conventional steel, BQ-steel and IQ-steel, highlights both the longitudinal and the transverse fatigue strength, see Figure 2.

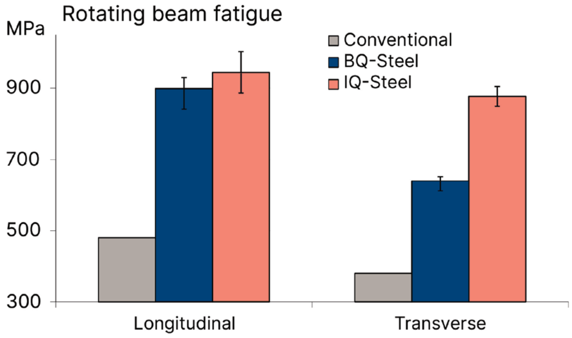


Figure 2 – Clean steel offers significant potential to improve the fatigue life of critical powertrain components.

For further information on the design benefits of clean steel please refer to this technical report: Clean Steel - living up to power density challenges

2 — Creating machining guidelines for clean engineering steels

The decision to convert from conventional steels to clean steel in a highly loaded part is not the sole responsibility of the design department of the gear or transmission producer. It is equally important to gain acceptance from the production engineering department and the CNC technicians. Production engineers can be reluctant to use a clean steel because of a general perception that they are 'hard to machine' due to prob-lems in achieving chip breakage.

The challenge is that, while inclusions are detrimental to the performance of steel components, they have a beneficial effect during machining. This is because the brittle nature of the inclusions helps to initiate chip breakage. Since clean steels eliminate these inclusions it is therefore much harder to achieve chip breakage. The result is the creation of long ribbons rather than discrete chips, sometimes even never-ending as shown in Figure 3.

Figure 3 – Long chips can tangle around the workpiece causing tool damage and health and safety issues.

The problem with long chips is that they tangle around the tool and workpiece, clogging up the machine, potentially damaging the tool and also creating issues for operator health and safety.

It is therefore of utmost importance to highlight the machining solutions available for a cost-efficient production process using clean steel. With this as a goal, Ovako has defined a 'machining cube' to obtain realistic and systematic machining guidelines in turning, drilling and gear cutting. The cube comprises three axes, cleanness, microstructure and alloy content, see Figure 4. Each of these characteristics play a vital role in determining chip breakability and tool wear in soft machining. The aim is to provide production engineers with machining guidelines for a specific set of steel alloy, cleanness and microstructure.

This work is ongoing and will, in time, generate guidelines for turning, drilling and gear cutting. For more technical details of machining process optimization, personal guidance by Ovako's experts is available on request.

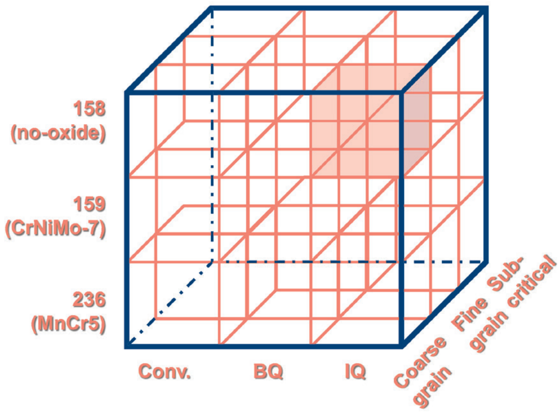


Figure 4 – The cube that defines Ovako's goal for machining guidelines.

3 — Machinability characteristics of engineering steels

In very simple terms, there are six material groups that define the design of cutting tools. They are cast iron, engineering steels, stainless steels, nickel-based alloys, aluminium alloys and hardened steels. Fine details within these groups can be found in the MC classification of Sandvik Coromant and the SMG classification of Seco Tools, among others. Engineering steels are further sub-divided as low carbon steels, micro¬alloyed steels, quench and tempering steels, bearing steels and free cutting steels.

Engineering steels, referenced by cutting tool manufacturers as ISO-P, is by far the largest group of materials machined in tons per year worldwide. To the authors' current knowledge, the metallurgical aspects, eg. cleanness, chip breakability and tool wear are not yet taken into account in existing classifications for tailored solutions in machining processes.

IQ-steels from Ovako are characterized by a sulfur content below 20 ppm. This is less than 1/20 the content of conventional engineering steels such as used in the automotive industry. At the same time, the very low sulfur content of IQ-steel is key to the transverse fatigue strength, which is unsurpassed using non-remelted steels.

However, the very low sulfur content is closely linked to the experience of difficult chip breaking in machining of IQ-steels. Ovako's current research aims to provide machining solutions that enable cost efficient and consistent production of parts made of IQ-steels.

The aim of this white paper is to provide guidelines for how to machine Ovako IQ-steels in rough, medium and fine turning operations. The guidelines include both recommendations of the microstructural characteristic that provides good chip control, as well as tooling solutions and cutting data for maximized production efficiency. This work is motivated by experiences from the field that machining solutions for conventional engineering steels using ISO P tools and methods often lead to short tool life and bad chip control. New solutions are therefore needed to offer robustness and production efficiency in manufacturing of IQ-steels.

Two types of steel frequently used in engineering components were tested, EN 20MnCr5 and EN 18CrNiMo7-6. Simply put, 18CrNiMo7-6 contains 1 wt % more Ni than EN 20MnCr5, which improves its hard-enability of the former. Ovako's ultra clean IQ-steel variants of these steels are designated 236Q and 159Q.

4 — Experimental details

4.1 Workpiece materials and microstructural characteristics
Hollow bars of Ovako 236Q (EN 20MnCr5) and Ovako 159Q (EN 18CrNiMo7-6) steels were produced by tube rolling, with the dimensions, OD=125 mm, ID=65 mm, L=200 mm.

Work pieces of the 236Q were heat treated to four microstructural conditions: (1). Normalised (N), (2). Isothermally annealed fine grain (IA-FG), (3). Subcritically annealed (SA) and (4). Isothermally annealed coarse grain (IA-CG), see Table 1.

The subsequent screening of chip control and the tool life tests were made with both EN 20MnCr5-IQ and EN 18CrNiMo7-6-IQ. Both steels were annealed to the IA-FG condition. The reason is that this ferrite-pearlite microstructure is by far the most frequently used microstructure for soft machining processes in the industry.

Heat treatment	Characteristic	Denomination
Normalized	Ferrite-pearlite	N
Isothermal annealing fine grain	Ferrite-pearlite, fine grain	IA FG
Subcritical annealing	Fine-dispersed carbides	SA
Isothermal annealing	Ferrite-pearlite, coarse grain	IA-CG

Table 1 – Microstructural conditions of EN 20MnCr5 steel included in tests of chip breakability.

4.2 Chip breakability vs microstructural characteristics of EN 20MnCr5-IQ
All machining tests were carried out using a Monforts RNC700 CNC lathe, see Figure 5 and Figure 6.

Chip breakability tests were made using the Coromant CNMG120408-PM 4325 tool, dry turning, ap=3 mm and vc=250 m/min. The feed was increased in steps, e.g. fn=0.15, 0.16, 0.18, 0.20, 0.22 mm/rev. etc. Chips were collected from each test. 25 of them were weighed individually. For easier interpretation of the results the chip length (L) was obtained by (1), where ap is depth of cut, fn is feed per revolution, ρ is density of steel, δ is the chip compression factor, set to 2 in all tests and m is the mass of each chip.

$$L=ap*fn*\delta*\rho*m \qquad (1)$$

The chip breakability was displayed as chip length vs feed, for each material tested. Good chip control was defined as a chip length below 35 mm. Unacceptable chip control and associated risk of chip jamming was defined as a chip length above 35 mm.

Figure 5 – Monforts RNC700 lathe with CNC technician.

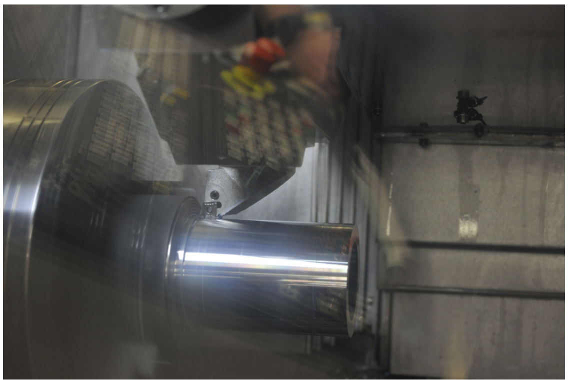


Figure 6 – Tool wear test of tube cut workpiece in progress.

4.3 Screening of tool geometries, grades and cutting data with respect to chip control.

The machining conditions were divided into rough, medium and fine turning. A large number of tool grades and chip breaker geometries was included. Different depths of cut and feeds were investigated. Chips were collected, mapped and classified into acceptable and unacceptable chip control.

4.4 Tool life tests

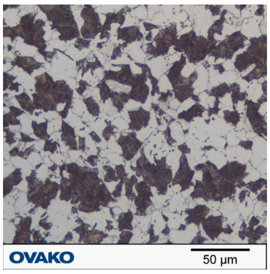
The tool geometries that enabled good chip control were tested with respect to tool life using machining data related to finishing, medium turning and roughing, respectively. Relevant depths of cut, feeds and cutting speeds were investigated for the three regimes of machining data. The work piece was longitudinally turned in passes of L=90 mm from OD=121 mm to ID=73 mm. In order to avoid chip jamming, each pass was 0.5 mm shorter than the previous one to form a staircase shaped shoulder.

The major tool wear types were flank wear, crater wear and notch wear. The tool wear was monitored and recorded throughout the machining tests by light optical microscopy (LOM). The final machining recommendations were made of the three criteria (I). Chip control, (II). Resistance to crater wear and (III). Resistance to notch wear.

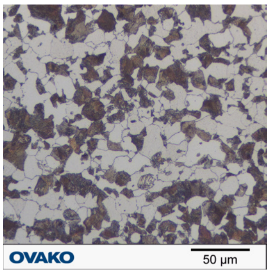
5 — Results

5.1 Workpiece materials and microstructural characteristics

The microstructural characteristics were of ferrite/pearlite type with different grain sizes, as well as the fine dispersed carbide structure of the subcritically annealed sample, see Figure 7. The grain size and ferrite/pearlite contents are given in Table 2.



(a)



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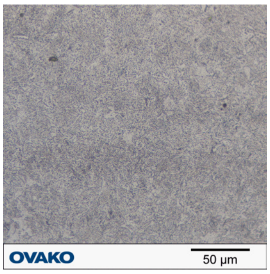

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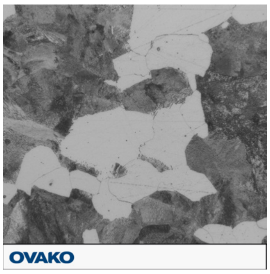

(d)

Figure 7 – Micrographs of 20MnCr5-IQ.
(a) normalized, (b) isothermally annealed,
(c) subcritically annealed and (d) isothermally annealed high temp.

	N	IA-FG	SA	IA-CG
Grain size [µm]	9±0.5	9±1	-	20±6
Micro¬-structure	Ferrite /pearlite	Ferrite /pearlite	Fine dispersed carbides	Ferrite /pearlite
Hardness [HV]	166±5	162±5	186±2	168±2

Table 2 – Characteristics of investigated microstructural variants tested.

5.2 Chip breakability vs microstructural characteristics of EN 20MnCr5-IQ

The average chip length of 25 weighed chips from each test showed that the transition from chip control to chip jamming is f_n=0.26-0.28 for N, IA FG and SA, see Figure 8. The IA CG condition, however, displayed good chip control with f_n≥0.16 mm/rev. Obviously, the scatter in chip length in each test is significant and could be included as well. However, the transition feed from good to bad chip control is distinct and consequently best shown with only the average chip length numbers.

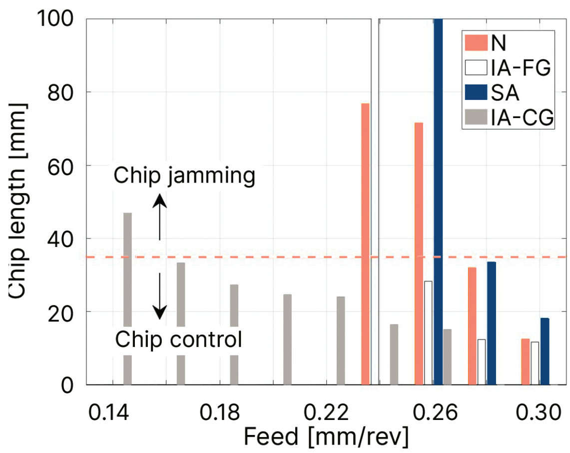

Figure 8 – Calculated chip length vs feed of (a) normalised (N), (b) isothermally annealed fine grain (IA-FG), (c) subcritically annealed (SA) and (d) isothermally annealed coarse grain (IA-CG) of 20MnCr5 IQ-steel. The threshold chip length is given by a dashed line.

5.3 Screening of tool geometries, grades and cutting data with respect to chip control
A large number of tool grades, tool geometries and machining conditions were screened with respect to chip control. A selection of the results of these tests is illustrated in Figure 9. The tests resulted in a first and second recommendation machining solutions for fine, medium and rough turning conditions, respectively.

The most important recommendation for tool selection with respect to chip control is to use grades and geometries normally used for stainless steels, often referred to as ISO M. As expected, both IQ-steels tested required more carefully selected tooling and machining solutions, as compared to a carburizing steel with S=0.03 %. However, the solutions offered by the ISO M tooling enable a high degree of production efficiency and consistency.

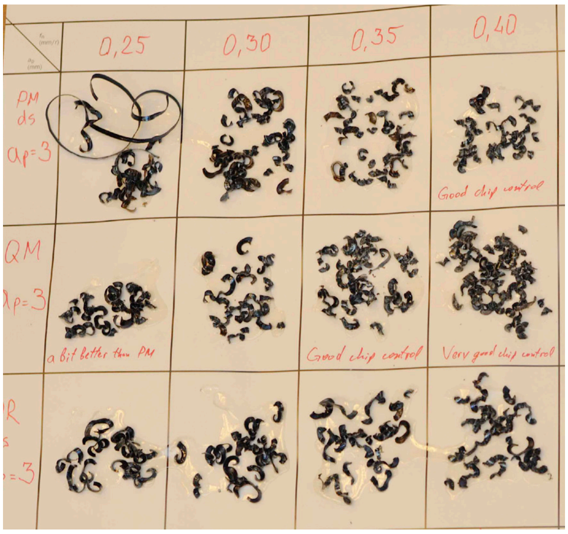

Figure 9 – Screening of chip control for various tool geometries and feeds.

5.4 Tool life tests
Turning tests were made to monitor the progression of tool wear. The test was interrupted after every two minutes of testing and the cutting edge was imaged using light optical microscopy (LOM), see Figure 3. The test was ended when any of the following criteria was reached: (1). Flank wear of vb=0.3 mm, (2). notch wear v_{notch}=0.5 mm, crater wear width k_b=0.8 mm or (4). total engagement time t=25 min.

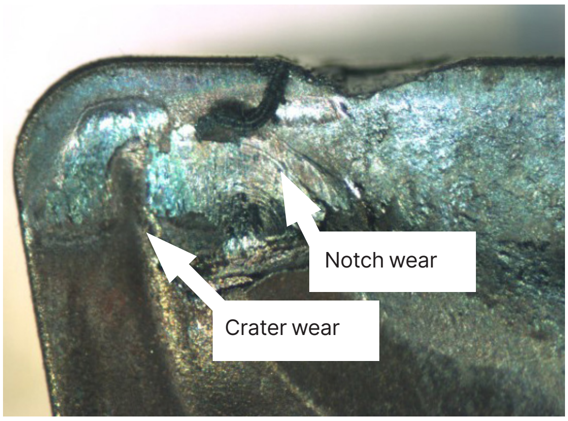

Figure 10 – Representative wear of the tool rake. (I). Crater wear and (II). notch wear are indicated.

Crater wear and notch wear were found to be the two most important life limiting tool wear types. Consequently, the progression of these two tool wear types were monitored closely. The test conditions that resulted in low progression of both notch wear and crater wear were considered for the first and second recommendation for a machining solution for fine, medium and roughing turning, respectively.

6 — Recommended machining solutions for turning of EN 20MnCr5 IQ-steel and EN 18CrNiMo7-6 IQ-steel

Machining solutions for soft turning of EN 20MnCr5 IQ-steel and EN 18CrNiMo7-6 IQ-steel were obtained. They are based on (I). Evaluation of chip control with different microstructural characteristics in soft machining, (II). Screening of chip control with available machining data, tool geometries and tool grades and (III). Tool life tests.

The most important finding of this study is that machining solutions designed for stainless steels, i.e. ISO-M tool geometries and grades are, recommended for ultra clean steels. This is explained by the fact that ISO-M tools are designed for materials with demanding chip breakability and tendency of notch wear as a life limiting type of tool wear. Ultra clean steels meet both these characteristics.

6.1 Recommendations for machining solutions in turning

Recommendations can be made for fine, medium and roughing turning, see Table 3. C-shaped tools, eg. CNMG120408, are recommended in fine and medium turning thanks to their versatility. S-shaped tools, eg. SNMG120412 are recommended in roughing turning thanks to their better distribution of heat and less tendency to notch wear, associated with the lower lead angle of this tool geometry, as compared to C-shaped tools. Recommendations for corner radii and chip breakers optimised for maximum performance for each depth of cut and feed are included.

It is important to note that this data must be considered as starting values. There are always possibilities and limitations in workpiece specifications, machine set-up, available tooling, among others, that give room for modifications and improvements in each machining cell and application.

6.2 Recommendation for microstructural characteristics and hardness

The study has also shown the significant impact of microstructure on chip breakability, cp. Figure 8. As reference, a conventional EN 20MnCr5 steel with sulfur content of S=0.03 wt % would have a transition from bad to good chip control of f_n=0.16 mm/rev. The corresponding transition of the ultra-clean steel is f_n=0.26-0.28 mm/rev. The difference is more than 0.1 mm/rev, which is clearly a challenge. Note, however, that the transition to good chip control was significantly better with the ISO-M tools that were finally recommended.

Of the four tested conditions the fine dispersed carbide structure of the sub-critically annealed condition has a transition feed of f_n=0.28 mm/rev. The corresponding feed rate for the isothermally annealed fine grain (IA-FG) is f_n=0.26 mm/rev. In addition, comparing feeds that give good chip control with both conditions the chip length of the SA condition is also generally longer than that of IA-FG. Consequently, the ferrite/pearlite microstructure is recommended over the subcritically annealed fine-dispersed carbide structure. This is important, because the former is used frequently, such as in the soft machining of gears.

The very good chip control of the IA-CG condition is very interesting. It shows the potential of using a coarse microstructure for good chip control. The reason is probably linked to a very low ductility of the IA-CG condition, which facilitates chip breakability. However, the gran size of D=25±15 µm is over the limit of acceptable grain size and there is probably a risk of brittleness of the hardened part. The solution for the too large grain size and associated brittleness of the finished part is an additional phase transformation. This can be an additional normalising before carburizing or a two-step carburizing as shown in Figure 4.

Based on the current findings a ferrite/pearlite microstructure of grain size D>15 µm is recommended. This combines on one hand relatively good chip control and on the other hand the toughness demands of the finished part are maintained.

Fine turning

Feed [mm/rev]		0,15	0,20	0,25	0,30	0,35	0,40	Cutting speed	Corner radii	Geometry & grade
Depth of cut ap [mm]	1,5		F	F	F	F	F	235-335	0,8	CNMG ISO-M15
	1	F	F	F	F	F	F	235-335	0,8	CNMG ISO-M15
	0,5	F	F	F	F			260-300	0,4	CCMT ISO-M15

Medium turning

Feed [mm/rev]		0,25	0,30	0,35	0,40	0,50	0,60	Cutting speed	Corner radii	Geometry & grade
Depth of cut ap [mm]	4		M	M	M	R	R	220-300	1,2	SNMG ISO-M15
	3	F	M	M	M	M	M	200-270	0,8	CNMG ISO-M15
	2	F	F	M	M			250-270	0,8	CNMG ISO-M15

Rough turning

Feed [mm/rev]			0,30	0,35	0,40	0,50	0,60	Cutting speed	Corner radii	Geometry & grade
Depth of cut ap [mm]	5		M	M	R	R	R	225-290	1,6	SNMG 2015
	4		M	M	R	R	R	215-300	1,2	SNMG 2015
	3		M	M	R			225-255	1,2	CNMG 2015

Table 3 – Recommended machining solutions in finishing, medium and rough turning of IQ-steel.

6.3 Difference of EN 20MnCr5-IQ vs EN 18CrNiMo7-6-IQ vs conventional steel

The same machining guidelines can be used with both EN 20MnCr5-IQ and EN 18CrNiMo7-6-IQ, if their microstructures and hardness levels are comparable. However, there is a difference in both holding temperature and holding time of the two steels to reach the same ferrite/pearlite characteristics. The holding temperature of EN 20MnCr5 is T=630°C and that of EN 18CrNiMo7-6 is T=660°C.

The difference in possible change of cycle time between a conventional steel and a ultra clean IQ-steel is obviously highly interesting. A representative comparison of cutting speeds possible in medium turning using a_p=2 mm and f_n=0.35 mm/rev shows that the difference in cutting speed for a tool life of 20 minutes (V20) is roughly 340 m/min with a conventional steel and roughly 275 m/min with the corresponding ultra clean grade, see Table 4.

The machining up-time would therefore increase by 40 % with ultra-clean steel. However, the change in actual cycle time is in fact less, since down-time is also included. The reduced cutting speed with ultra-clean steel coincides with the typical increase in fatigue strength of about 40 % with ultra-clean steel. That enables a down-sizing with no detrimental effect on performance. Hence, the total manufacturing cost could be the same with conventional and ultra-clean steel, yet with a very significant weight saving and more compact design.

EN 20MnCr5	Tool	Grade	Geometry	V20
Conven-tional	CNMG120408	4315	QM	340
IQ	CNMG120408	2015	QM	275

Table 4 – Comparison of tooling solution and cutting speed at tool life of 20 minutes between conventional and ultra-clean EN 20MnCr5.

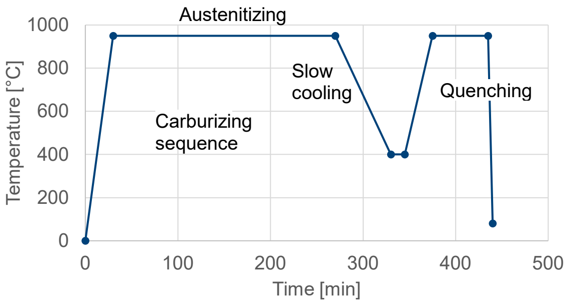

Figure 11 – Schematic two-step carburizing that enable small grained structure and thereby good toughness of the finished part.

7 — Summary & Next step

The following conclusions can be drawn from this work

- Guidelines for how to successfully machine ultra clean steels, eg. Ovako IQ-steels in turning have been obtained.
- Ultra clean steels are most efficiently machined using methods and tooling designed for stainless steels, ISO-M. The reason is that these tools are designed for more demanding chip breaking, as well as the better resistance to notch wear of ISO-M tools.
- The recommendation for microstructural characteristics for good chip control is a ferrite/pearlite dual-phase microstructure with a grain size D>15µm.
- The two ultra clean IQ-steels tested of type EN 20MnCr5 and EN 18CrNiMo7-6 can be considered very similar in terms of machining guidelines. It is important to state, however, that they need different annealing treatments to reach the same ferrite-pearlite microstructure and hardness.
- The cutting speed of tool life 20 minutes (V20) is roughly 275 m/min with IQ-steel and roughly 340 m/min with conventional steel, using adequate tooling solutions for the respective steel. Consequently, the up-time difference is roughly 40 %. This coincides with the typical increase in fatigue strength with IQ-steel, as compared to conventional steel.

7.1 Next step

Machining guidelines are also to be obtained for IQ-steels in gear cutting and in drilling. These investigations are ongoing.

8 — References / Further reading

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