

Performance and Machining of Advanced Engineering Steels in Power Transmission Applications — Continued Developments

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It is becoming increasingly apparent that material properties can and will play a greater role than before in addressing the challenges most transmission manufacturers are facing today. Making use of materials' intrinsic fatigue properties provides a new design tool to support the market changes taking place, where current and future designs will require cleaner steels that can perform at higher load levels. This paper discusses the potential gain for the transmissions industry by making use of material properties to support more demanding applications. It describes advanced engineering steels and how they can benefit the industry, through discussing material cleanliness versus performance of gear materials, standardized fatigue testing such as contact and bending fatigue, as well as the machining of clean steel.

(The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.)

Introduction

Clean steel in transmission applications. The transmissions industry is under ever-growing pressure to meet the increasing demands of handling higher loads on current and future system generations. In the strive to increase overall fuel efficiency and reach the more and more stringent emissions regulations in the transportation industry, being able to increase power density plays a major role. However, the need to increase power density is spread throughout the transmissions industry and is not only limited to the automotive or heavy duty commercial vehicles.

For a long time, upgrading the potential in the system by changing to cleaner steel has been a well-kept secret, which very few stakeholders have made use of. Seeing how the advanced engineering steels of today can offer huge improvements even without having to make major design changes, making use of cleaner steel can open up many possibilities. Large safety factors, single- and double-shot peening, and superfinishing are being implemented more and more frequently in trying to find ways of enhancing the fatigue strength of the components. Although many are costly, these methods are widely accepted. Switching to a higher quality material has, so far, not really been explored fully.

A higher cleanliness material can offer improvements for both bending and contact fatigue by reducing the probability of finding large, detrimental defects that will act as crack initiators in the loaded volume. So, steel quality does, in fact, have a huge impact on the fatigue life of a component and is the one main parameter that will give the largest gain in fatigue life. This is especially relevant when using high-hardness steels such as carburized grades used for gears and shafts in transmission applications.

Machining. Traditionally, steels with high sulphur content

have been preferred for machinability reasons. However, there exists today an urgent need for steels with improved fatigue properties; but a part of producing a steel with improved fatigue properties is also restricting the sulphur content (S-content) in order to reduce manganese-sulphide (MnS) inclusions that can have a negative effect on the fatigue strength of a component.

For machining today — with modern machines, tools, and inserts — there are no indications of a reduced S-content having a negative effect on machining operations such as soft turning, gear cutting, or hard machining. For slower operations such as broaching, series production so far has not shown any difficulties, but may require more examination before giving more general advice. Minimizing the number of unplanned stops, on the other hand, might be improved due to a consistent quality of a material with a higher capability through reduced scatter and the risk of running into large, hard oxides that might cause inserts to fail.

Current manufacturing processes normally need only minor adjustments when making the change to clean steel. An added advantage is that clean steel may also reduce the need for further processing such as shot peening. It is worth noting that for conventional steel, a sulphur content of 200–500 ppm (parts-per-million) is quite common. For clean steel such as bearing-quality steel, the sulphur content will typically be below 100 ppm. To achieve the desired properties of an ultra-clean steel such as isotropic-quality steel, the sulphur level is further reduced and is typically around 10 ppm. While this might require a slightly different approach to machining, the closely controlled properties of the steel — together with advances in tool and insert technology — have made it possible to create very efficient, cost-effective processing solutions for clean steel.

Background (Development of Clean Steels and What They Are)

Development. In order to produce clean steels suitable for today's challenges, steel producers have had to find ways of trying to understand the true inclusion population of the materials. Given that a steel with the right mechanical properties can be developed, fatigue failure is most likely to be initiated by non-metallic inclusions in the steel. In theory, "cleaner" steel with fewer inclusions should have higher fatigue strength. Therefore, it has been important to establish the relationship between steel hardness, inclusion size, and stress limit. While it is well-established that the intrinsic fatigue limit of a steel increases with its strength or hardness by a factor of approximately 1.6 (Fig. 1), it is also true that as the strength of the steel increases, the obtained fatigue limit is increasingly lower than the intrinsic limit (Ref. 1).

This is caused by defects such as inclusions acting as stress raisers and promoting fatigue crack initiation. The reason defect size is of such importance in gear materials is because the steel is used in a hardened state. Through rotating bending fatigue (RBF) testing, it has been established that high-strength steels are more affected by inclusions, and by reducing the size of the main inclusion population dramatically, high-strength steels have the potential to achieve a fatigue limit very close to the intrinsic fatigue limit.

Through a combination of different quantification techniques—light optical microscopy (LOM), scanning electron microscopy (SEM), RBF and immersed ultrasonic testing (UT-testing)—it has been possible to test for inclusions from 2 μm upward in size, and has enabled obtaining a reasonable picture of the inclusion population. Figure 2 shows how the combination of methods can cover a larger inclusion size range and the probability of being able to find a certain size range of inclusions by a certain method. This has enabled the refining of production processes for producing new, cleaner steels and isotropic-quality steels. It should be noted that in this range of isotropic, clean steels the remaining inclusions are not removed, but instead moved to a finer distribution.

Historically, inclusions below 500 μm have been classed as micro inclusions, while everything larger has been classed as macro inclusions. However, modern clean steels have very few large inclusions, and the sizes of the assessed area in standard tests using optical methods are too small to provide any statistical confidence. The result is that any clean steel producer invariably generates only zero ratings. For micro inclusions, the methods generally used today—such as those found in ASTM E45 or DIN 50602—also provide only a very vague picture of the steel cleanliness, due to the small investigated area.

Producing clean steel. Improvement in

fatigue strength is the result of a carefully controlled steel-making process. The probability of finding detrimental defects in the loaded volume needs to be minimized for materials to perform well in high-cycle fatigue applications.

As an example—for clean, scrap-based air-melted steels, the steel making can be divided into four main production stages that affect steel cleanliness. By controlling the steel making throughout the process, improvements in fatigue properties can be achieved—improvements that can and will make a big dif-

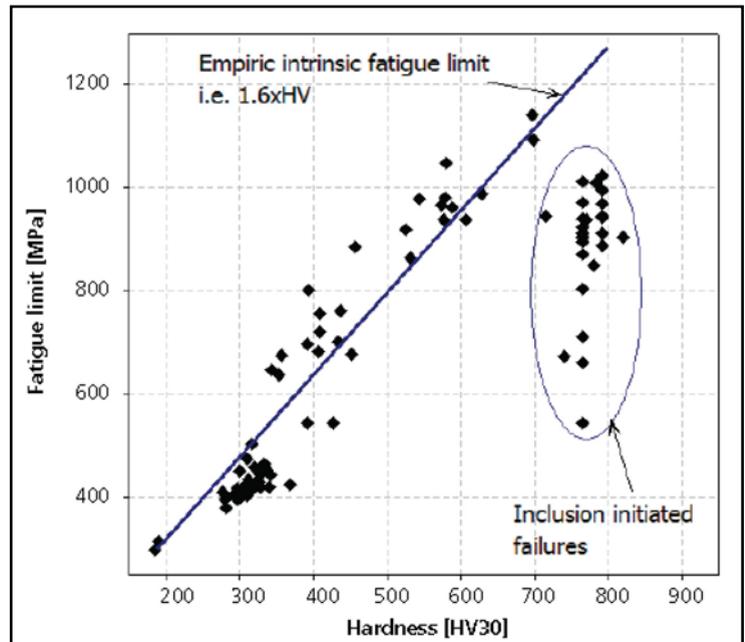


Figure 1 Fatigue limit defined as 107 cycles on rotating bending fatigue samples vs. hardness.

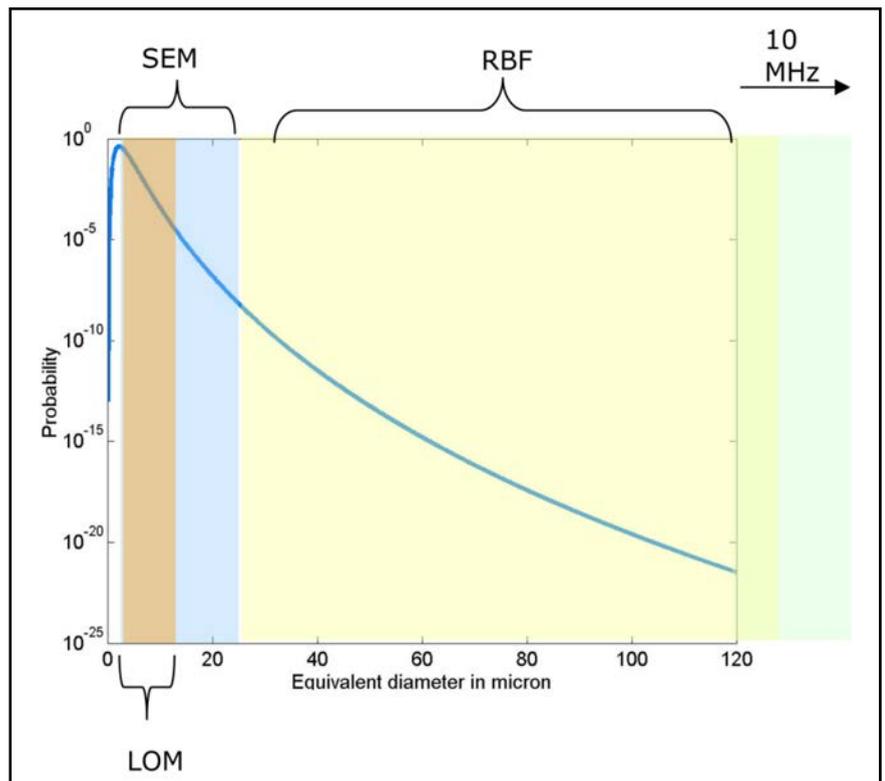


Figure 2 By combining several methods, a reasonable picture of the total inclusion content can be obtained.

ference in gear applications. The production can be divided into the following four main stages:

1. Primary metallurgy
2. Secondary metallurgy
3. Casting
4. Rolling

At each stage there are a number of different parameters of importance. In the primary metallurgy stage, for example, scrap mix needs to be controlled in order to avoid a larger quantity than necessary of certain elements that are prone to forming harmful inclusions and that will be difficult to remove later on. In the secondary metallurgy stage, it is the composition of the top slag along with alloying and degassing that can be fine-tuned to produce different steel qualities. The casting process can vary widely, and to produce clean steel a large casting format, such as ingot casting, is generally used. Some advantages of ingot casting are that it is flexible, gives a good starting format, and because the solidification process is inward and upward, inclusions are generally pushed toward the top. The top is then cut off and scrapped and the amount that is cropped can also be adjusted, depending on grade and quality produced. The final main production stage is rolling, including the homogenization and hot-working of the material into smaller formats.

Starting from a large format such as ingots results in higher area reduction (or reduction ratio) that also has a huge impact on material quality—especially affecting macro inclusions. As an example, an ingot size of approximately 500*500 mm will have a reduction ratio of 65:1 for a 70 mm bar. Actual clean steel production processes may vary depending on the route, quality, and grade, but to achieve the full potential of this type of material, all stages are equally important.

Conventional steels—where continuous casting in small formats is common—are produced in a highly cost-efficient process. It is dependent on being able to cast several heats of the same grade in a row, in order to sustain productivity. It is also often cast in a small format, generally around 240*240 mm, which gives very little area reduction down to commonly used bar sizes—approximately 15:1 for a 70 mm bar. Since hot working and area reduction are needed for eliminating porosity and reducing inclusion sizes, material from small, continuous cast routes tends to have a larger inclusion population and thus a different level of material cleanliness and performance. These types of steels are widely used in the automotive industry and are suitable in applications where loads are low on gears and systems.

Clean steels will generally have oxygen content below 8

ppm and a sulphur content below 100 ppm. Ultraclean steels tend to have even lower oxygen content and an S-content below 20 ppm, thus minimizing the presence of sulphide and oxide inclusions.

Depending on the requirements of the application and what needs to be achieved for current or future generations, there are different levels of cleanliness that will offer different potential. Figure 3 illustrates schematically how defect size affects fatigue strength and what performance can generally be expected from different types of material cleanliness. This can then be translated into a useful tool; for example, for designers looking to increase torque through the system. For many manufacturers the step from conventional steel to a clean steel, such as that of bearing quality, will be a large step, and the one that enables system functionality without major changes in system design.

An important aspect of clean steel and steels produced to suit customer requirements is the potential to reduce scatter in material behavior and properties. That means that the material for that application will behave much more consistently—not only in component life, but also through the manufacturing processes; for example, in heat treatment and machining, which in itself can have a positive effect on total cost, apart from facilitating material processing.

Discussion

Relevance for the industry. As a designer, it can be beneficial to have a certain level of knowledge of how steel cleanliness affects fatigue performance of materials used, thus providing a greater flexibility at the design stage. Through constantly increasing demands, it is likely that many other enhancement processes, such as shot peening or different finishing methods, are already in use.

So far, there are a number of clear cases showing the poten-

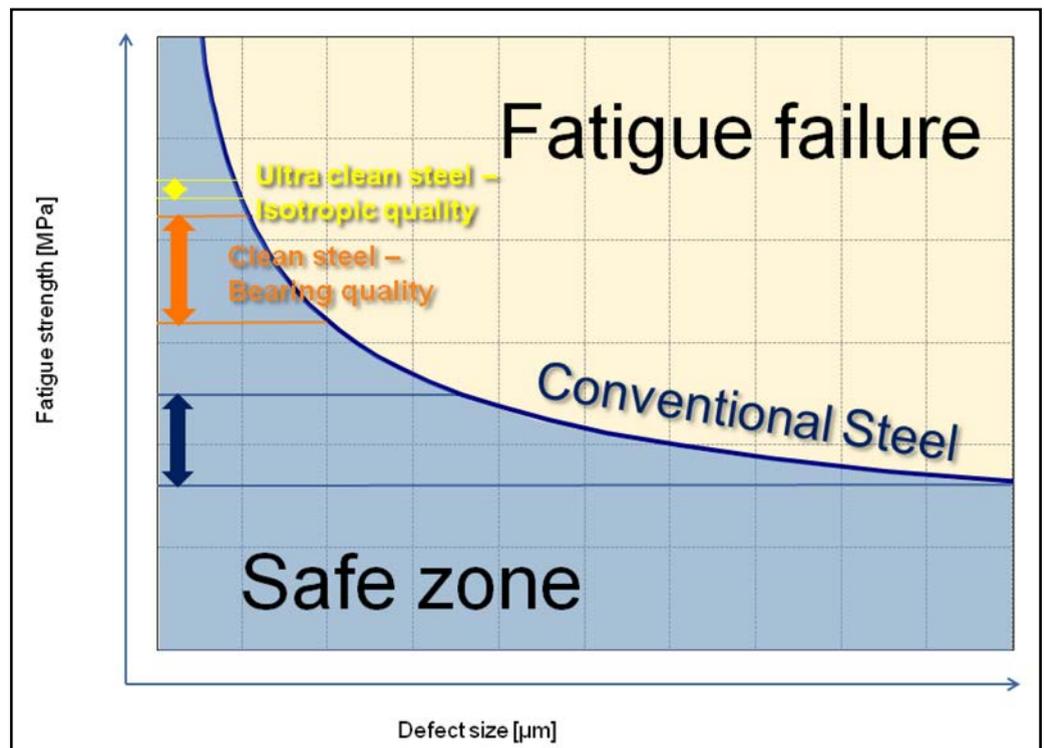


Figure 3 Fatigue strength vs. defect size—schematic illustration.

tial of clean steel. As an example, cylindrical gears handling higher loads through minor changes in the micro geometry, while making use of material properties, have shown impressive results. Through a careful consideration of how these two parameters interact, a premium brand automobile manufacturer has been able to attain the improvements needed for the system requirements in their seven-step, dual-clutch transmission (Ref. 2). By taking a step in the direction of clean steel, the demand for increased system torque could be met.

For some types of bevel gear applications there have also been some real enhancements through making use of clean steel. A well-known driveline producer needed to examine the influence of internal defects on fatigue life, due to inconsistent and inadequate material behavior. Where conventional steels could no longer handle the pressure, clean steels proved able to support the required loads in these systems (Ref. 3). Smaller defect sizes have been the determining factor for, in this particular case, bending fatigue.

The ability to take material cleanliness—defect size and distribution in the loaded volume—into account when designing gears and systems is not straightforward, but there are models that are looking at including that parameter as well. Advanced calculation methods for load carrying capacity enable designing from actual material capabilities in high-performance lightweight powertrain components where high ratios and low transmission weight are real requirements. The enhanced weakest link model (Ref. 4) is based on a deeper understanding of material mechanisms and analyses parameters such as defect size and quantity together with, among others, surface hardness, case hardening depths, and residual stresses.

How clean steel can support current and future challenges.

The question is how designers can make the best use of clean steel to solve their own power density challenge. A simplified way of looking at the challenge is to divide it into three levels of effort (Ref. 5), ranging from material substitution to total redesign:

1. The first level can be considered as a way of increasing power density through upgrading the material while maintaining an existing design or making some minor design changes. Such changes could be a change of gear tooth micro geometry, for example, to fully utilize the enhanced bending fatigue strength of the new material at the tooth root, as mentioned above, while reducing contact pressure on the gear flank. It opens up for further extending life of an existing design while delivering enhanced performance.
2. In the second level, the combination of clean steel with some significant internal design changes provides the potential for increased power density. Improved fatigue properties can enable some components to be downsized, freeing up room for the incorporation of additional components. The outcome is that a new generation of powertrain systems with enhanced performance can be dropped into the same footprint as the previous generation. The internal design receives a makeover while the external design remains the same.
3. The third level represents the ultimate use of clean steel to achieve a major increase in power density, with its enhanced fatigue properties providing designers with an important new tool as they create new powertrain concepts. A typical automotive application might be to help meet emissions legislation by introducing different degrees of hybridization and electrification into the powertrain, especially when there is a need to

create space for other surrounding systems.

Methods for Verifying Steel Cleanliness/Material Properties

It is vital to quantify steel cleanliness in order to verify that the required fatigue performance can be achieved in the final component. To be able to verify that the steel performs as desired, a combination of methods seems to be the most relevant way in trying to predict how the material will perform. And to be able to implement into material specifications, an understanding of current level of material is necessary.

Implementing a combination of requirements, such as chemical composition, micro and macro inclusions, reduction ratio, and also approved suppliers, has so far proved supportive of ensuring material quality that will live up to customers' actual demands. With the changes being driven mainly by environmental issues in the automotive industry, increasing the system demands and, for example, quality issues in the wind power industry, it is getting increasingly interesting for stakeholders to be more specific in their material requirements. Once hardenability demands are met through alloying strategy, the main factor determining how the steel will perform is cleanliness. That gain in performance cannot solely be replaced by moving to a higher-alloyed steel.

Chemical composition. Increased requirements on chemical composition, including oxygen and sulphur content, will have a positive effect on the material performance and therefore the system performance. Introducing a more stringent chemical composition will result in more consistent material quality and also have a positive impact on the production of the components, making both heat treatment and machining behavior easier to predict.

Macro inclusions. For macroscopic inclusions, relatively crude methods have been used to try to define the acceptable number of rarely occurring large-sized inclusions. These include: step-down tests, in which bars are fine-turned in distinct steps and defects greater than 0.5 mm are recorded; blue fracture tests also record defects larger than 0.5 mm on a bar cross-section that has been hardened, fractured and then tempered blue to increase the visibility of defects. However, these methods do not provide the information needed to define the performance of clean steels, since the probability of finding anything in the inspected area is too low.

10 MHz immersed UT-testing has proven to be a more useful method for inspecting commonly used steels in the gear industry today. This method has the advantage of being able to inspect a fairly large volume in a short period of time. Steel producers generally use this type of inspection as a way of ensuring process quality, but the method can easily be implemented in a customer specification to give an indication of material cleanliness. There are standards in place for this type of inspection, such as (Ref. 6), although it is not uncommon for producers of clean steel to have made improvements for their own testing routines in order to ensure that the method provides as much information as possible regarding expected performance. The result of the testing can be presented as the number of defects larger than the calibration-sized flat bottom hole (FBH) per dm^3 and limits can be set in the material specifications—0.2 mm FBH/ dm^3 , for example.

Figure 4 shows examples of ultrasonic testing on bars with a diameter of 65 mm of carburizing steels used for gears in the transmissions industry today. There is a visible difference between commonly used conventional steels (top) and clean steels (bottom), which is the result of the steel-making process as described earlier. In the conventional steel reflections of defects show up in varying color, which changes depending on the intensity of the reflected sound. White areas show 100% reflection, thus indicating large material defects.

For critical components and applications, 100% in-line UT-testing can also be implemented; this testing is generally performed on the finished bar size. For best use of this method—for example, through phased array ultra-sound—a peeled surface is generally required since it makes it possible to look for smaller defect sizes, and calibration to a 0.7 mm FBH is not uncommon.

Micro inclusions. Even though micro inclusion rating in itself will not be enough to determine the material quality and cleanliness, in combination with other methods it can still be a relevant method. Standard methods such as ASTM E45 and DIN 50602 can be improved by, for example, making sure the sampling is increased so that a larger number of samples are inspected by microscope.

To summarize: in order to ensure consistent behavior from the steel, and ultimately the system, combining a number of relevant methods of determining micro and macro cleanliness that will give a good picture of the material and thinking through requirements for reduction ratio, are a good place to start. Also, taking care in specifying chemical composition, including oxygen and sulphur content, and consequently reducing the scatter of material behavior in production as well as performance, will help in determining what to expect from the material.

Fatigue testing. Basic material data is obtained by perform-

ing RBF testing on test specimens, providing data for high-cycle fatigue, relevant for these types of applications. Testing is normally performed in the longitudinal direction of the bar since this a common loading mode for some applications and it can also be difficult to prepare test specimens for transverse testing due to bar diameters. Testing in the transverse direction is not as well documented, but for ultra-clean steels with isotropic properties, this type of testing is, of course, common practice. However, since stresses in all directions also need to be considered for gear applications, due to loading mode and material flow in the components, transverse properties are actually likely to give more relevant information about fatigue life than longitudinal testing.

To get a better understanding of the transverse fatigue strength of conventional gear materials as well as clean steels, a method of producing test specimens from a smaller bar size has been developed for a larger test program. The test program should give a clearer picture of how immersion UT-testing and RBF testing in combination can give a better indication of how the material will perform in the application.

Initial testing of the carburizing grade 20MnCr5 with transverse sampling from an rd65 mm bar validates the test method (Ref. 7). Even though the tested volume is small for this type of testing, it will still give a good understanding of how different materials behave when loaded in the transverse direction.

Contact fatigue testing. As a second part of contact fatigue testing of an ultra-clean modified 20NiMo9-7F (158Q), FZG back-to-back pitting testing was performed at WZL in Aachen. The aim was to be able to compare this type of ultra-clean steel to the ISO 6336-5 standard for materials (Ref. 8).

Set-up and method. The gears used for the FZG back-to-back rig testing are of C-Pt-type with a linear tip relief and from the same production lot as for the previous testing done at the

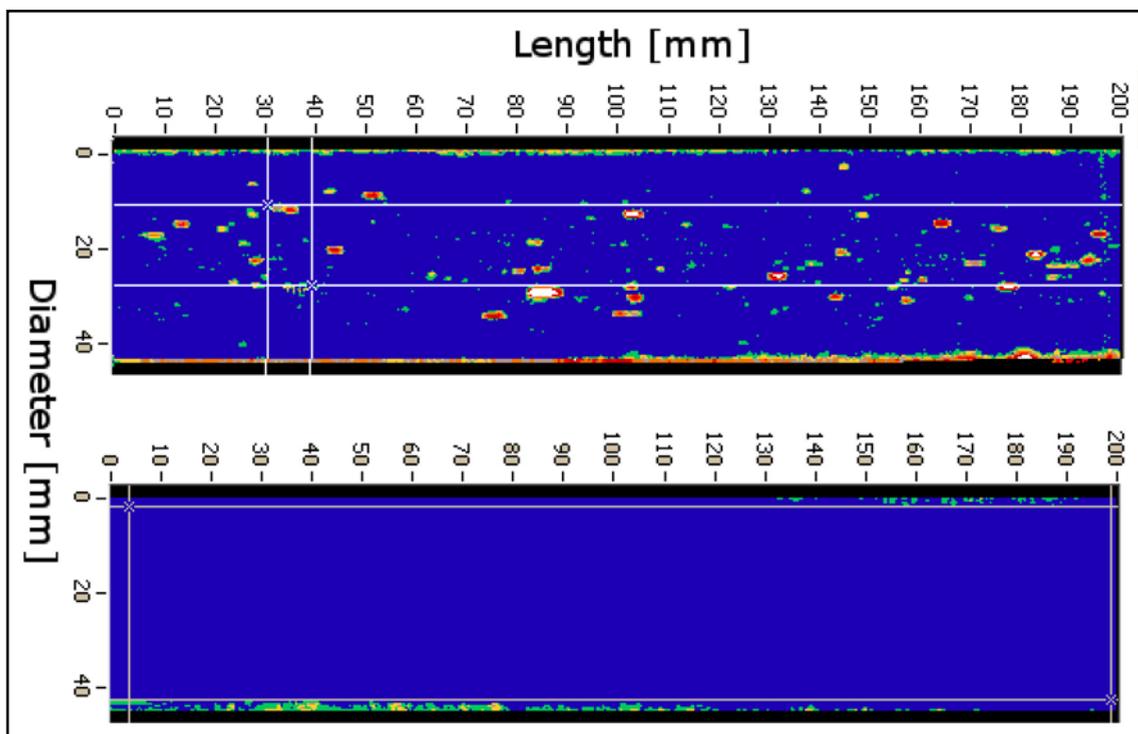


Figure 4 10MHz immersed ultrasonic testing of rd 65 mm bars, carburizing steels of different cleanliness.

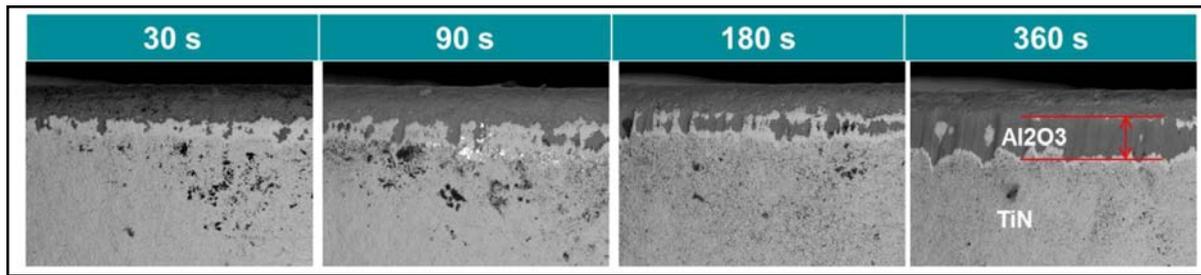


Figure 5 Micrographs of the flank face of cutting tool recorded after 30s, 60s, 180s and 360s, starting with a new cutting edge in each test (SEM).

Royal Institute of Technology (Ref. 9). After run-in for 1 h at 135 Nm with a starting temperature of 60° C of the oil, the testing was started at an oil temperature of 90° C and a variable applied torque. Failure criteria was set to pitting area of one tooth > 4% and pitting area of all teeth > 2%. The limiting number of load cycles was 50*106. The staircase method with evaluation according to IABG/Hück was applied, starting at a load torque of 300 Nm and with a step size of 50 Nm (Ref. 10).

Results and discussion. Even though the standardized C-Pt-type does not seem to be an appropriate gear geometry for testing these types of materials, the endurance strength parameter of flank stress σ_{Hlim} shows a more than 30% higher result compared to ISO 6336-5 quality class MQ (state of the art in ISO 6336-5). The evaluation was not entirely uncomplicated, since premature tooth meshing caused different types of damages on the gears. By using a different tooth geometry that minimizes premature tooth meshing, an even higher σ_{Hlim} is expected to be reached. It is also apparent that material, manufacturing and design go hand in hand. The material can never perform better than the design or manufacturing parameters, such as surface roughness, for example. This is now being discussed with WZL, together with end users in the automotive industry, in order to identify more relevant ways of testing surface fatigue of clean steels, resulting in useful data, for manufacturers of passenger car gear boxes, among others.

Machining

Machinability of clean steel. Several projects and investigations are ongoing in the field of component machining processes of clean steels. Furthermore, a screening scheme aiming at relevant and repeatable differentiation of the machinability of gear steels is in joint development with a Swedish research institute. The method enables quantified numbers of the steel's machinability displayed in bar charts. The method currently comprises abrasiveness from hard particle constituents of the steel, thermo-mechanical wear of the tool CVD coating, and numbers of chip breakability. The machinability screening method enables

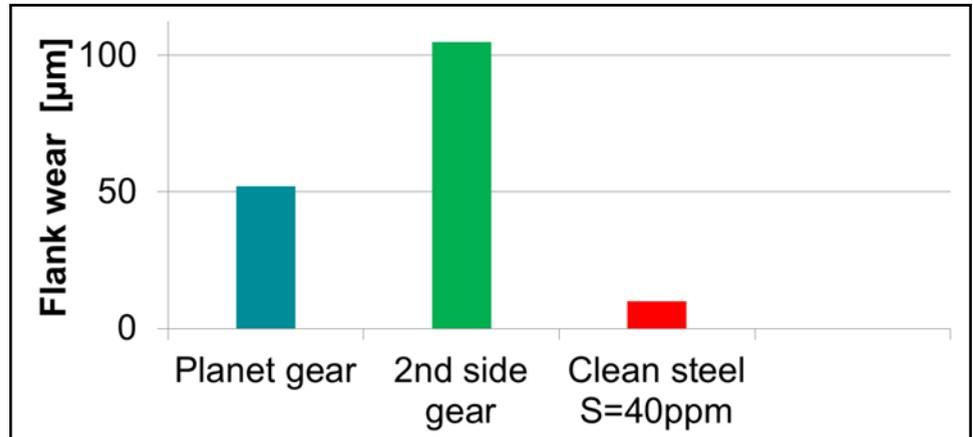


Figure 6 Flank wear progression on the flank face of the cutting tool at test time of 6 min.

industrially relevant and repeatable screening for a high degree of differentiation of steels in mass production of steel components.

In a project with Swedish industry and academia, the introduction of clean steel was considered for a secondary side gear and a planet gear. Insufficient fatigue strength of these two gears limited the possible output torque of the gear boxes, using today's conventional steels, hence the reason for the project. Consequently, increased fatigue strength of these gears would directly benefit the performance of the gearboxes.

Two conventional carburizing steels with an S-content of 200–400 ppm were compared with a clean steel with S=40 ppm; all three with very similar alloying content. Machining tests were undertaken using gear blanks of the reference steels and bars of the clean steel. The steels were compared with respect to tool life in rough turning; a dedicated machining test of the steel's abrasiveness in turning; and experimentally simulated gear cutting using circular face milling with PVD-coated HSS milling inserts.

The results show that the tool life of the clean steel is on the same level as the reference steels. The dedicated machining test for steel abrasiveness evaluation actually showed that the clean steel generates extremely little abrasive wear on the cutting tool coatings (Figs. 5–6). This is probably due to the low content of hard oxide inclusions of this steel. In addition, the large reduction ratio of the ingot casting process for the clean steel improves the microstructural homogeneity, as well as reducing the number of large oxides, adding to the minimized abrasive wear of the cutting tools of these tests.

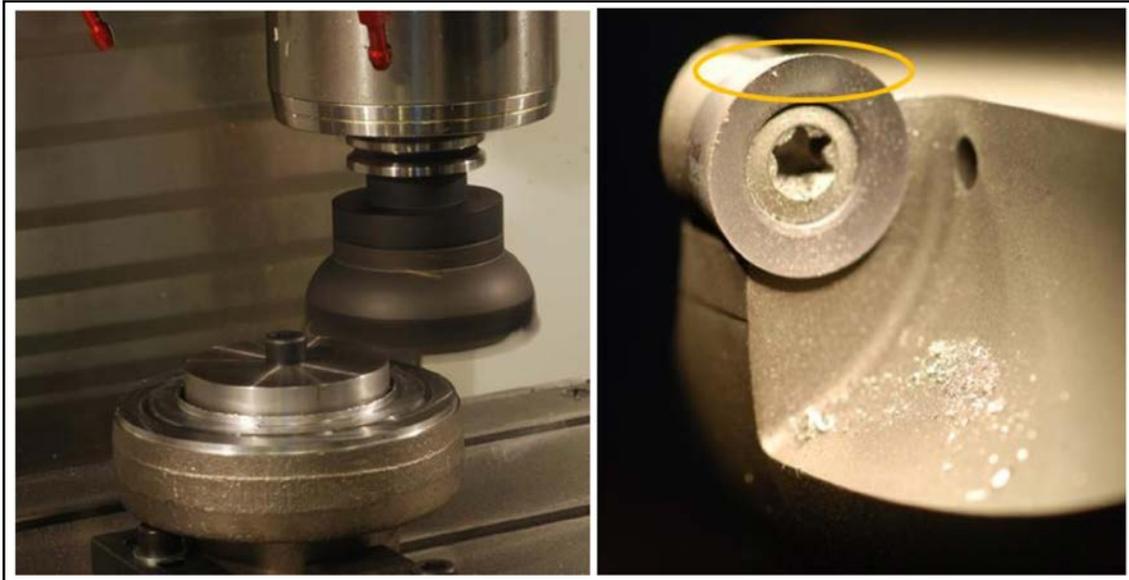


Figure 7 Setup of machining test experimentally simulating the tool wear conditions in gear hobbing.

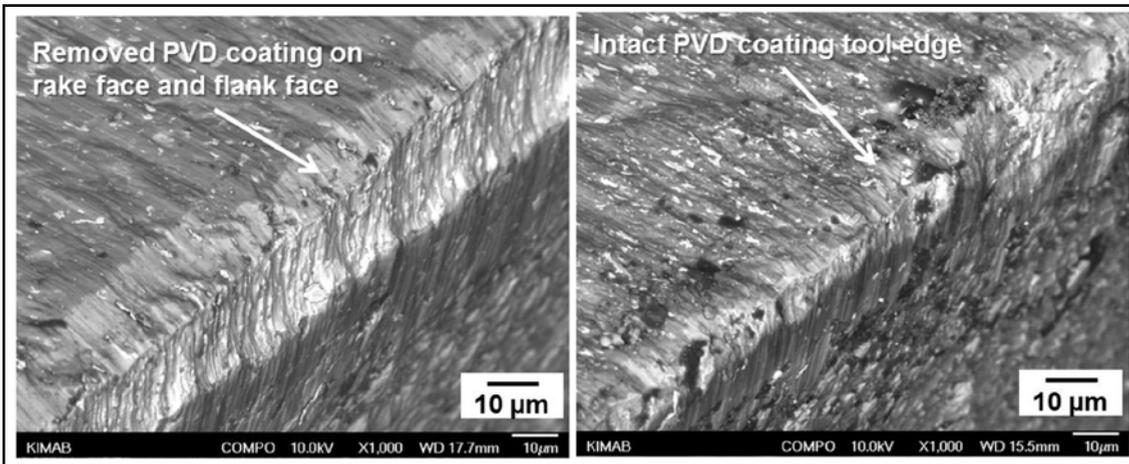


Figure 8 Representative micrographs of the PVD HSS cutting edges subjected to circular face milling at about one-half of tool life at cutting speed $v_c = 250$ m/min; (a) The reference steels of $S = 0.04$ wt% and (b) the clean steel of $S = 0.004$ wt% (SEM).

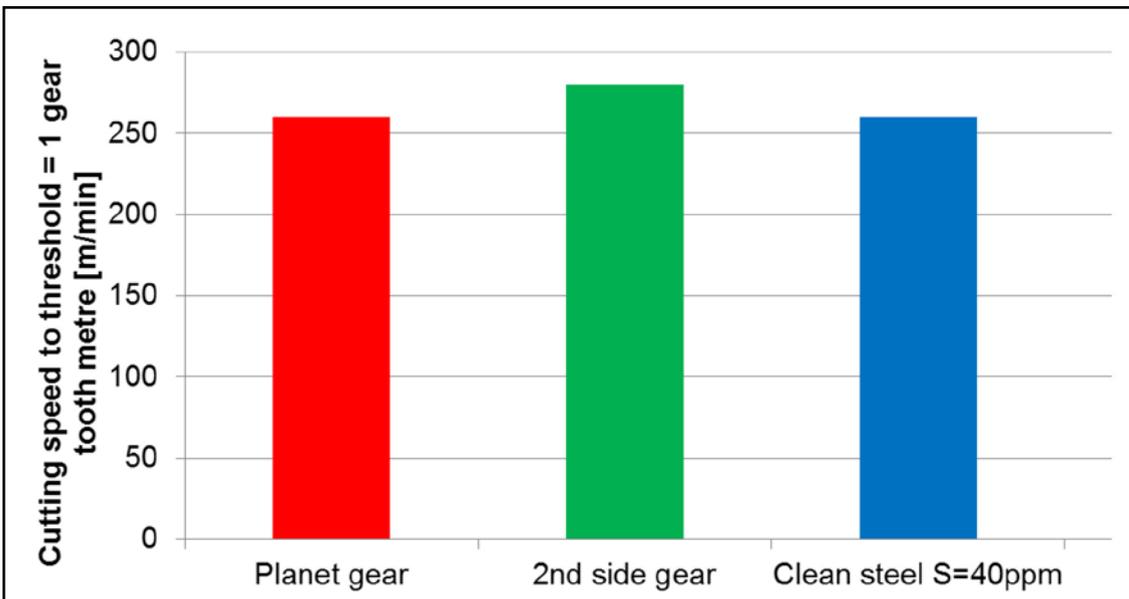


Figure 9 Experimental simulation of the tool conditions in gear hobbing, threshold cutting speed that enables tool life of ONE gear tooth meter in hobbing.

The experimental gear hobbing test (Figs. 7–9) showed that the same service interval of PVD-coated HSS hobs is expected with clean steels as with conventional steels. The cutting tool edge line remains intact longer with the clean steel with respect to abrasive wear of the PVD coating. However, more thermal softening of the HSS substrate was observed with the clean steel.

Based on the studies mentioned, as well as field tests in component machining of clean steels, the following guidelines to machining of clean steels can be derived:

- The same tooling and machine solutions as used in today's production can be used for clean steels as well.
- A rule of thumb in turning is to increase the feed by 15% and to reduce the cutting speed by 15%.
- A rule of thumb in gear cutting is to increase the tooth feed with 20% and to reduce the cutting speed with 20%.
- In hard part turning using PCBN cutting tools, select a PCBN grade with higher toughness than the one currently used. In addition, reduce the cutting speed by 10%.

Experiences from machining field tests of clean steels.

To gain enhanced knowledge of machining of ultra-clean steels, more machining trials have been and are being performed. These trials include a larger quantitative study of turning and hobbing, as a continuation on previous trials (Ref. 11), as well as gear and spline cutting with gear milling tools.

The continued quantitative study for turning and hobbing, based on more than 1,000 forged gear blanks of ultra-clean 20NiMo9-7F (158Q), will be concluded later during 2016. The reference is conventional steel in a grade similar to AISI 8620 used in series production for the same planetary gear. Both steels are forged to the same planetary gear ring geometry at the same sub-contractor. The AISI 8620 was isothermally annealed according to the specification, whereas the clean 20NiMo9-7F was subjected to a sub-critical annealing.

Another pre-study uses indexable disc cutters in a profile milling configuration. The work eventually aims at introduction of power skiving using indexable carbide tools as an option to gear hobbing. The study compares the reference AISI 8620 with the ultraclean 20NiMo9-7F.

A 15-tooth pinion of module size 4.233 (DP 6) was profiled using disc cutters (Fig. 10). Both solid HSS cutters and indexable carbide concepts were tested. A DMG Mori, NT4250 DCG, multi-task, 5-axis milling/turning center was used.

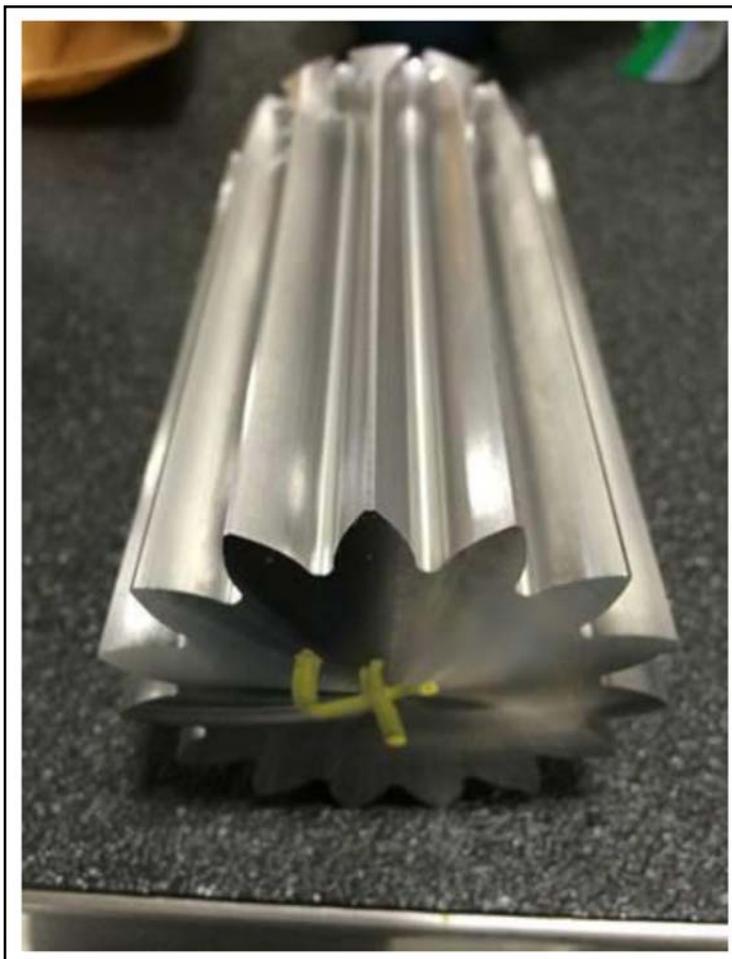


Figure 10 Pinion with 15 teeth produced in profile milling machining tests.

The indexable carbide inserts (ICI) disc cutter was a full profile disc cutter with only one insert, in order to achieve expedient test results. Inserts were Sandvik Coromant Grade GC1030, equivalent to ISO P30 carbide inserts with a PVD TiCN, TiAlN, and TiN multi-layer coating approximately 6 microns in thickness.

Cutting data was chosen according to modern gear industry tooling norms as follows:

- Cutting speed $v_c = 280$ m/min
- Feed rate $F = 191$ mm/min average
- Resulting chip thickness was 0.1 mm Hex. All cutting was dry.

Conventional (up-milling) was done according to setup requirements. Results of testing proved a tool life of 40 min-

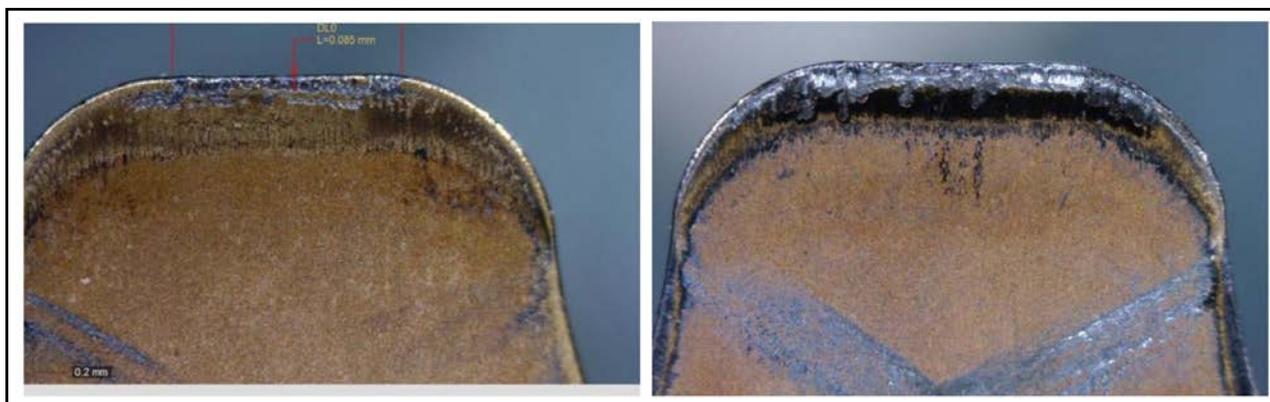


Figure 11 Rake face of carbide milling inserts after machining tests of AISI8620 (left) and ultra clean 20NiMo9-7F steel (right) (LOM).

utes per cutting tooth. The tool life corresponds to a volume of removed chips of 1.5 gear tooth meter for both steels. Both steels generate micro chipping wear on the rake face of the cutting tools (Fig. 11). However, the tool wear had progressed more with the 20NiMo9-7F steel. The micro chipping probably resulted from high thermal and mechanical loads on the rake face of the cutting tools. A weak substrate makes the wear resistant, yet brittle PVD coating, come off in patches 5–30 µm in size, as observed.

Conclusive remark and outlook. Clean steels can be machined using existing machines and existing tooling. Abrasive wear is minimized thanks to the absence of hard inclusions, primarily oxides; 20–50 µm often present in conventional steels produced by continuous casting. However, clean steels generate more thermal load on the cutting tools. The solution in both rough turning and in gear cutting is to increase the feed by about 20% from the numbers used in today's machining. With a thicker chip, more heat is removed with the chip. In fact, the machinability profile of clean steels may be used to bypass the productivity of conventional steels.

Conclusion

In advanced designs for high-power density applications, conventional steels and clean steels offer completely different possibilities. By making use of clean steel properties, there are ways of making huge improvements in, for example, gearboxes, AWDs, and final drives for both current and future generations. The difference is because of the way conventional steels have been produced, with high S-contents and a higher probability of running into harmful defects, such as macro inclusions, in combination with a relatively low reduction ratio of dimensions from cast to finished product. The results are poor fatigue performance, which for many components is the deciding factor for design. And the performance is at its worst in the transverse loading direction. Clean steels that focus on reducing the probability of finding detrimental inclusions in the loaded volume, through controlling the steel making including sulphur and oxygen content, together with a higher reduction ratio on the other hand, can contribute to impressive improvements. And to make the most of the material, it needs to be part of the design process from the first step through a more holistic approach to powertrain design. ⚙️

References

1. Ölund, P. "Developing a Lighter, Stronger and Cleaner Air-Melt Steel for Critical Applications," 2014, Ovako, Hofors. Dr. Fronius, K. et al. "The AMG Speedshift DCT from the Mercedes-Benz 7G-DCT Family," "16th International VDI Congress Drivetrains for Vehicles," 2016, VDI, Friedrichshafen.
2. Wallin, K. "Internal Defects in Case Hardened Gears and its Influence on Fatigue Life," *5th Bodycote/AGA Heat Treatment Seminar*, 2014, Sweden.
3. Pollaschek, J. "Sensitivity Analysis of Tooth Root Bending Strength Calculation According to the Enhanced Weakest Link Model," *57th WZL Conference on Gear and Transmission Research*, of WZL on May 11/12, 2016, Aachen.
4. Claesson, E., L. Kamjou and P. Ölund. "Clean Steel—Living up to the Power Density Challenges," 2016, Ovako, Hofors.
5. DIN, 2010. Ultrasonic Immersion Testing Method of Determining the Macroscopic Cleanliness Rate of Rolled or Forged Steel Bars, SEP 1927:2010-08.

6. Eriksson, K. "Fatigue Testing of 236F" 2016, Ovako, Hofors.
7. ISO, 2003. Calculation of Load Capacity of Spur and Helical Gears — Part 5: Strength and Quality of Materials," ISO 6336-5.
8. Bergseth, E. et al. "Investigation of Pitting Resistance in Ultra Clean IQ-Steel vs. Commonly Used Conventional Steel; 158Q vs. 16MnCr5 — Back-to-Back Pitting Tests," 2015, ISBN 978-91-7595-730-2, Royal Institute of Technology, Stockholm.
9. Konowalczyk, P. "Pitting Report on Gear Material — Final Report," 2016, Laboratory for Machine Tools and Production Engineering, WZL of RWTH Aachen University.
10. Hansson, H. "Summary of Machinability Ovako 158Q — Joint Study," 2014, Swepart Transmission AB, Sibbhult.

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