OVAKO

CLEAN STEEL — LIVING UP TO POWER DENSITY CHALLENGES

Erik Claesson, Lily Kamjou and Patrik Ölund

Executive overview

Clean steel offers major possibilities for automotive designers who need to step up to the challenges that the industry is facing – the demand for increased fuel efficiency, decreased emissions and ultimately, increased power density in powertrain systems. Metal fatigue is one of the main factors in powertrain design. So a switch to clean steel can offer a very significant enhancement in fatigue performance. This can enable individual components to be downsized while maintaining equivalent performance, offering the potential for a useful extension in the application life of an existing design. While ultimately, clean steel can facilitate the creation of new space-and weight-saving designs incorporating hybridization.

In this white paper, Ovako, one of the world's leading developers and manufacturers of clean steel explain what it is, why it enhances fatigue performance and how it is applied in practical applications. The 20-50-100 concept is introduced to explain the different levels of utilisation of clean steel from simple material substitution through to total powertrain system redesign.

A switch to clean steel can be a cost-effective choice in terms of the added-value it offers. Some specific powertrain applications are already producing dramatic results.

In addition to designers, this white paper is also relevant to production engineers, automotive engineers and purchasing professionals as well as anyone with an interest in finding cost-efficient solutions to address powertrain design, performance and lifetime issues.

Overall, two key messages emerge
The best replacement for steel is in fact clean steel rather than more exotic materials Optimum performance is achieved when design engineers and metallurgical engineers work in partnership to ensure that the design utilizes the properties of clean steel.

1 — Introduction

The automotive industry is under ever growing pressure to increase fuel efficiency and reduce its carbon footprint. For example, EU legislation requires that by 2021, phased in from 2020, the fleet average to be achieved by all new cars is 95 grams of CO2 per kilometre. There are also correspondingly increased demands that are being introduced, step by step, for heavy duty and off-road vehicles all over the world.

Achieving these targets requires a step change in the industry. Clearly, enhanced materials properties will play a vital role in this step change, especially in meeting the key aims of compact size, lower weight and superior fatigue performance. However, while it is tempting to think that the answer lies in the replacement of traditional steels with new and exotic materials, this is not necessarily true. In many cases, the best replacement for steel is in fact clean steel with carefully controlled inclusion sizes and also in some cases, isotropic properties.

The graphs in Figure 1 illustrate the evolution of power density in terms of the torque available from the powertrain system.

Clean steel is already playing a major role in diesel fuel injection systems in vehicles, where it has enabled manufacturers to achieve significant reductions in fuel consumption. For example, clean steel has enabled cars to reduce fuel consumption by 1 liter/100 km.

As we examine in this white paper, clean steel can have many more applications throughout the powertrain, ranging from material substitution of individual components to facilitating a complete redesign of the entire system, for example to enable hybridization.

We look at why metal fatigue is the enemy of powertrain design, how clean steel can offer superior fatigue properties and how it can be utilised in powertrain design by introducing the '20-50-100' concept (this is described in detail in section 4).

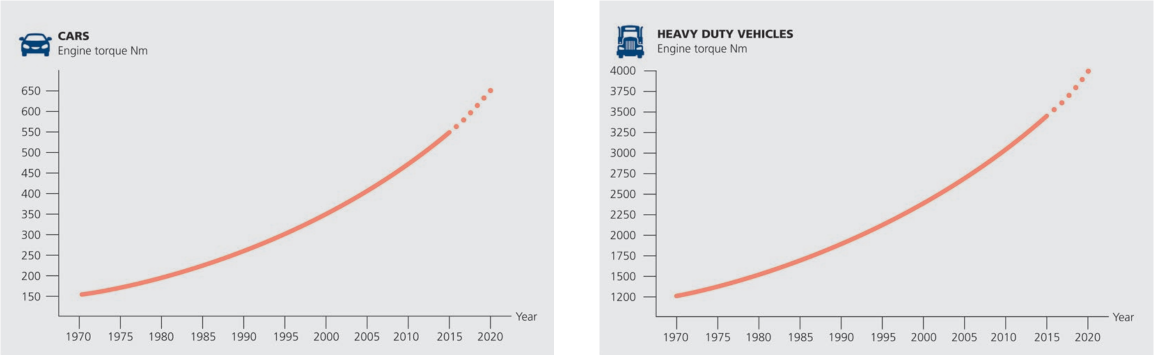

Figure 1 – the evolution of engine torque

2 — Fatigue — the material enemy of powertrain designers

Powertrain components are increasingly expected to be lighter, stronger, and capable of handling more power while subjected to ever greater and more complex loads. These factors naturally demand materials with high mechanical strength. Yet it is fatigue that accounts for the majority of all mechanical service failures. It is therefore relevant to take some time to understand fatigue and how it can be mitigated by materials selection.

2.1 What is fatigue?
Very simply, fatigue is what happens when a metal component fails when subjected to a number of repeated loadings, even when the maximum load is well below the normal load it could easily sustain on a single loading cycle. One of the 19th century pioneers in establishing the relationship between components life and cyclic loading was August Wöhler, a German railway engineer. He investigated the premature failure of axles and gave his name to one of the main forms of fatigue test – the rotating bending fatigue (RBF) or 'Wohler' test.

2.2 How is fatigue testing carried out?
To determine the fatigue performance of a material we carry out a large number of laboratory tests on test specimens. Basic material data is obtained by rotating bending fatigue (RBF) testing which provides data for high cycle fatigue. More specific gear tests, such as contact fatigue testing and tooth bending fatigue, can also be performed.

Different types of gears have different types of main failure modes. While surface fatigue may be the dominant failure mode for cylindrical gears, hypoid gears are usually more likely to suffer from bending fatigue. It is therefore vital that fatigue test data is obtained using a test regime that corresponds to the specific application.

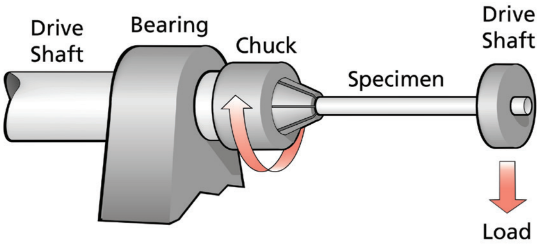

Figure 2 – showing an RBF test being carried out

In the RBF test, a known, constant bending load (stress) representing a certain percentage of the material's ultimate tensile stress (UTS) is applied to a cylindrical sample of the material. The fatigue test machine then rotates this sample at high speed, effectively subjecting it to fully reversed loading from tension to compression. The number of cycles to failure at this stress is recorded – the statistical nature of fatigue requires a number of tests to be carried out at each load. A series of tests are carried out at varying percentages of UTS. Eventually it is possible to establish a 'safe load' or 'fatigue load limit' at which the sample will survive without failure beyond a certain number of cycles (typically 3–10 million).

If the desire is to achieve 'infinite life' then the presence of inclusions that initiate failure becomes a limiting factor. Therefore, using clean steel helps to achieve a dramatic increase in the safe load to beyond the point on the Wöhler curve that represents infinite fatigue life.

3 — How can clean steel improve fatigue properties?

3.1 – The relationship between inclusions and fatigue
As a globally leading clean steel manufacturer, Ovako has built up an extensive database of fatigue data. From this experience it is clear that defects in steel such as non-metallic inclusions can initiate fatigue failures. (See figure 3 and figure 4). These inclusions, typically larger sulfides for conventional steels and smaller oxides in more clean steels, act as stress raisers – that is they can multiply the nominal load applied to the component to above the safe limit. This causes the formation of incipient cracks that propagate under stress reversals, eventually resulting in failure.

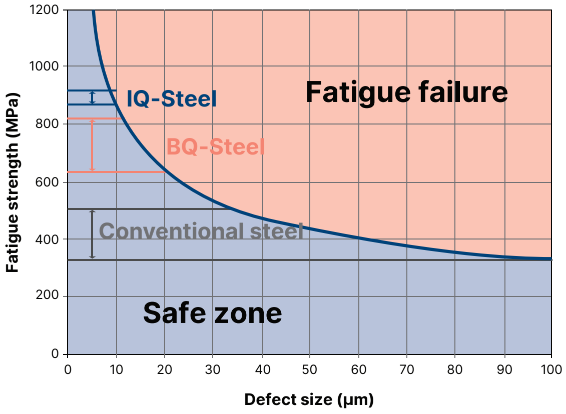

Figure 3 – relationship between defect size and fatigue strength

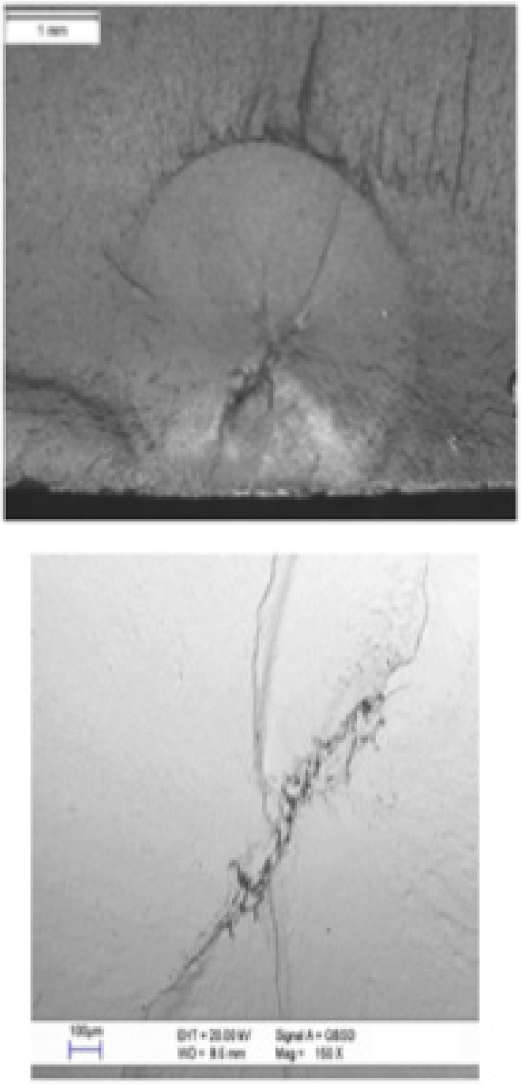

Figure 4 – photograph of an inclusion in failed gear tooth. Crack initiation has occurred at large defects and it is believed that subsequent propagation has given rise to the circular features on the fracture surface.

Steel quality has a huge impact on the fatigue life of a steel component. In particular, when using high-hardness high-strength steels, steel cleanliness is a crucial factor for fatigue performance. A clean steel that contains smaller sized defects compared with conventional steel offers a longer fatigue life. The most important difference between conventional steel and clean steel is the probability of finding detrimental defects in the area or volume of the component subjected to high load. This is because these defects can initiate fatigue failures that will result in premature failure. Essentially, using a clean steel decreases the probability of encountering these larger defects or inclusions. It is not only the nominal stress level that is of importance when comparing the performance of different steel types. For clean steel there is a much closer distribution of test results and this reduces the need to use a high safety factor to take account of the potential scatter in capabilities.

3.2 Producing clean steel

Ovako has focused on refining its production capabilities to exploit the major design opportunities offered by steel cleanliness. This is important news for designers who have in the past relied on old standards, since modern steel practices have opened up a new level of performance that makes it possible to downsize or redesign major powertrain components.

Improvements in fatigue strength have been realised by carefully controlling steel making throughout the process. And it is the combination of all the production stages which will determine the actual outcome.

Steel making can be divided into four main stages:
1) Primary metallurgy
2) Secondary metallurgy
3) Casting
4) Rolling

At each stage there are a number of different parameters that are of importance. In the primary metallurgy stage, scrap mix and melting are the main processes that need to be controlled. In the secondary metallurgy stage, it is the alloying and degassing, which 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 used. The advantage of ingot casting is that it is flexible, gives a good starting format and that because the solidification process is inwards and upwards, inclusions are generally pushed towards the top, which is then cut off and scrapped.
The final main production stage is rolling, including the homogenisation/soaking and the hot working of the material into smaller formats. Starting from a large format results in a higher area reduction/reduction ratio, which also has a huge impact on the material quality.

In summary, the actual clean steel production processes may vary depending on the quality and grade, but to achieve the full potential of this material there can be no compromise at any stage. The main objective is always to produce clean steel with an optimised balance between quality and economy.

3.3 Type of clean steel – BQ-Steel® and IQ-Steel®

Bearing Quality (BQ) – Steels are a range of high cleanliness steels with reduced defect size. The effect of reduced inclusion sizes in BQ-Steel can help improve design life and/or increase torque on existing generations of powertrain systems. Moderate design changes can also be made while securing high and consistent quality end-user products. Moving to BQ-Steel is normally the first step when upgrading from conventional steel.

IQ-Steels represent the next level as a range of isotropic, clean steels, designed to have small and isolated inclusions and with a cleanliness comparable to re-melted steels. The small and evenly sized inclusions create the isotropic properties that can withstand heavy loads in all directions. This makes IQ-Steel suitable for complex load cases, such as those in gears.

In Figure 5, results from RBF testing show how different types of steel handle cyclic loading in both the normally loaded longitudinal direction as well as the transverse direction. Depending on loading mode, both BQ-Steel and IQ-Steel offer an improvement over conventional steel.

WZL of RWTH Aachen University recently carried out some investigations in cooperation with Ovako to investigate the surface fatigue of gear material. The clear conclusion was that not only was the quality of the steel a determining factor in the endurance strength parameter, the use of Ovako material could offer a 30 percent improvement above what was considered to be the ‘state-of-the-art’ steel.

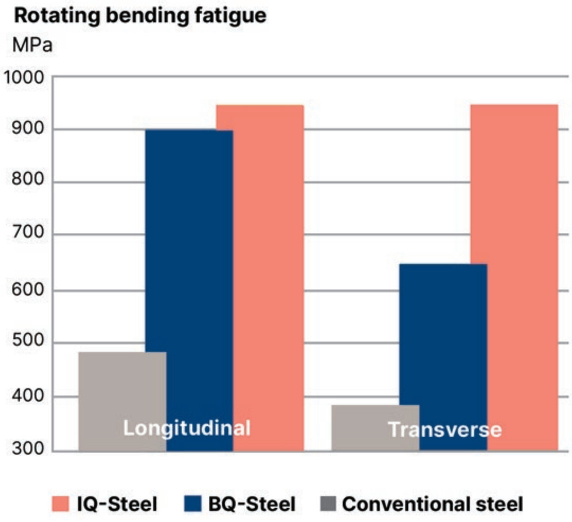

Figure 5 – Rotating bending fatigue test performance conventional steel compared with BQ-Steel and IQ-Steel in both longitudinal and transversal direction

Impressive as that 30 percent figure is, the limitations of the test regime do not portray the full picture of the potential benefits of clean steel. If the gear design was refined to give a better tooth meshing that allows for a higher load on the flank, then spectacular results could be achieved. This offers the possibility to sustain increased loading and a better balance of life across the entire transmission system including the bearings and housing.

This raises a very significant point. To get the most out of clean steel it is crucial for mechanical design engineers to work in close cooperation with metallurgical engineers. This will ensure that the design complements the advantages offered by clean steel.

3.4 – Verifying steel cleanliness

It is vital to quantify steel cleanliness in order to verify that the required fatigue performance can be achieved in the final component. For macroscopic inclusions, relatively crude methods are used to define the acceptable number of very 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.

For today's most commonly used steels in the powertrain industry, 10 MHz immersed ultrasonic testing has proved to be a relevant testing method. This method has the advantage of being able to inspect a fairly large volume in a short period of time.

Figure 6, shows examples of ultrasonic testing on bars with a diameter of around 70 mm. Here, two samples have been evaluated by 10 MHz ultrasonic testing; the sample on the top is a typical carburized steels currently used for gears in the transmissions industry today and the lower sample is typical for clean carburized steels from the Ovako ingot route.

The reason for the clearly visible difference between the different steels is how they are produced. One important factor is the reduction ratio, which is up to 10 times larger from this ingot route compared with commonly used conventional steels from continuous cast routes that have a reduction ratio in the range of 8–25. Another factor is that the Ovako steel used in this specific test has been verified to have an oxygen content below 8 ppm, while the conventional steels have an oxygen content up to 30 ppm.

Historically, inclusions below 500 µm or 0.5 mm have been classed as micro inclusions while everything larger was classed as a macro inclusion. However, modern clean steels have very few inclusions above 25 µm, and the size of the assessed area in standard ASTM and DIN tests using optical methods was too small to provide any statistical confidence. The result is that any clean steel producer invariably generated only zero ratings. For micro-inclusions, the methods in routine use today, such as those found in ASTM E45, also give only a very vague picture of the steel cleanliness, due to the small investigated area.

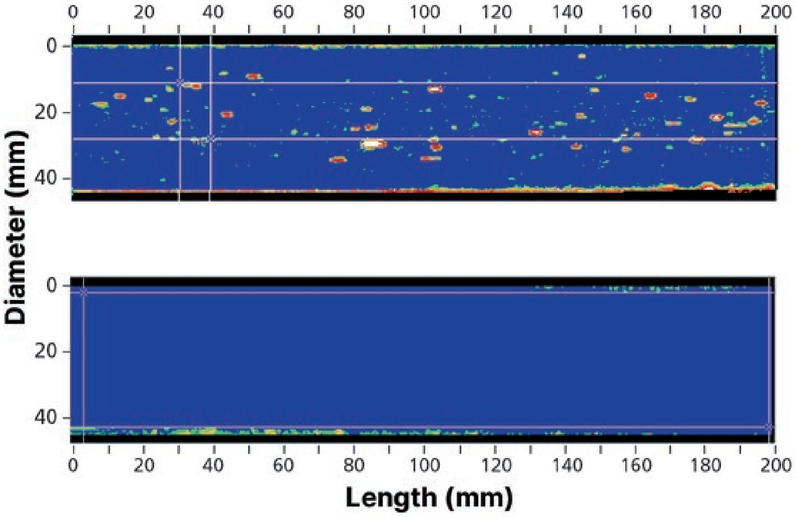

Figure 6 – 10 MHz ultrasonic scans of two different steel samples

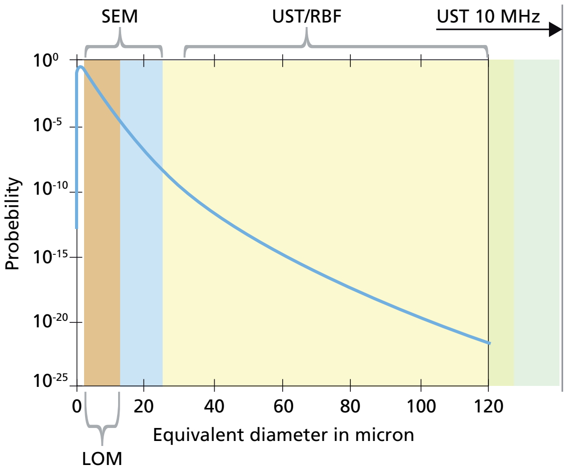

Figure 7 – summary of inclusion quantification methods

Ovako has therefore adopted a mix of three quantification techniques – optical microscopy (LOM), Scanning Electron Microscopy (SEM) and immersive ultrasonic testing – to test for inclusions from 2 μm upward in size (see Figure 7). This has helped refine production processes for new, cleaner steels such as IQ-Steel. To obtain a full picture of the relationship between inclusion population and fatigue properties RBF testing is recommended. It should be noted that in this range of isotropic clean steels the remaining inclusions are not removed.

3.5 – Clean steel – the added value solution

Clean steel is a premium starting material compared with conventional steel. However, when looking at the economics of its use it is important to take a holistic view, particularly in its capability to add value for the end user both in product performance and manufacturing processes.

Clean steels steels enable the design of components that would not be feasible using conventional steels, allowing power density increases, reductions in size and weight, and potentially decreasing the amount of steel required to manufacture the component.

Overall, it is entirely possible for the selection of clean steel to provide a cost-efficient solution that adds significant value to the powertrain.

4 — Meeting the power density challenge — Introducing the 20-50-100 concept

Switching to clean steels such as BQ-Steel and IQ-Steel have already helped a number of powertrain system manufacturers to address significant power density challenges. While saving weight is a useful benefit, it is the potential to achieve an enhanced performance for both individual components as well as the entire powertrain system that is most important. For example, it has been possible to increase loads on gearboxes as well as other systems in the powertrain. There is also the potential to increase torque and/or down size through new designs.

But how can a designer 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 3 levels of effort – based on the 20-50-100 concept – ranging from material substitution to total redesign.

20 level – is the typical target for increased power density when upgrading the material while maintaining an existing design or making some minor design changes. Such minor changes would be a change of gear tooth geometry, for example, to fully utilize the enhanced bending fatigue strength of the new material at the gear root while reducing contact pressure on the gear flank.

Full scale rig testing has proved that this is a realistic possibility when moving from conventional steel to clean steel. There can be immense value for OEMs and Tier 1 suppliers in this capability to further extend the useful life of an existing design while delivering enhanced performance.

50 level – is a typical goal for increased power density when the use of a clean steel is combined with significant internal design changes. Enhanced 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 offering superior performance can be dropped into the same footprint as the previous generation. In essence, the internal design receives a makeover while the external design remains the same.

100 level – this 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 brand new powertrain concepts.

A typical 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. Another application would be electric vehicles (EVs where clean steels could be integrated into gearboxes that have to cope with high torque.

Clean steel also offers major possibilities for engine design, especially in increasing the performance of pistons, crankshafts and camshafts etc. This is however outside the scope of this white paper.

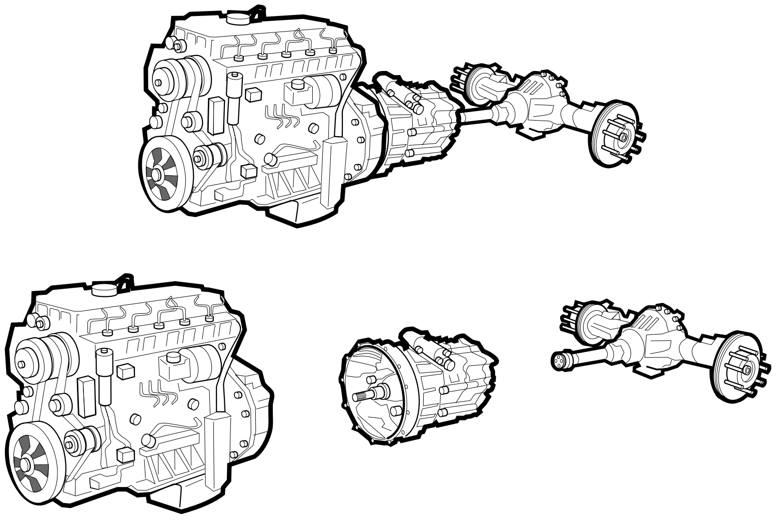

Figure 8 – potential powertrain applications for clean steel

5 — Clean steel — practical benefits

The performance advantages of clean steels have been used to great effect for many years in the manufacture of bearings and diesel injection components. Recent full scale exercises have shown that clean steel offers significant advantages for key powertrain applications such as gears for gearboxes and final drive units as well as engine applications.

5.1 – Powertrain

As the demand grows for powertrains to handle higher torque, be lighter, stronger and more compact, conventional steels are no longer suitable. The problem is that they are produced by processes where large inclusions are still present in the steel. As a result, they have poor fatigue and impact properties in both the longitudinal and transverse directions. The deterioration of performance is extra pronounced in the transverse direction, which is often not well enough tested and observed.

A particular advantage of BQ-Steel and IQ-Steel is that they offer increased performance in all directions. So for example, when designing gears, it is possible to accommodate stress levels significantly higher than what would be the accepted limit for conventional steels. Therefore, downsizing or increased loading become possible options.

Volvo Penta put the isotropic properties of IQ-Steel to use when developing its IPS marine ‘pod-drive’ system with counter-rotating forward-facing propellers. The steel has enabled the powertrain performance to be optimized. An additional very important effect was that the drag force under water for the boat could be reduced by the reduced transmission dimensions, improving overall vessel performance. A Gear Development Engineer from Volvo Penta commented:

“As a premium brand, Volvo Penta produces systems for extremely demanding marine and industrial applications. The load cases, combined with design demands, have to be optimized and always in the frontline of technology. When it comes to gear steel material, our clear view is that the cleanliness and in particular the inclusion control is crucial in determining design possibilities. The isotropic properties of IQ-Steel provide just those conditions and is thus our gear material of choice.”

5.2 – Diesel injection systems

IQ-Steel has also played a vital role in the development of the current generation of diesel injection systems. Without the capability to produce pumps for high pressure and long lifetimes, recent advances in performance and economy simply would not have been achievable.

The ever increasing demand for improved fuel efficiency continues to drive the development of new generation systems based on clean steel, as Dr Maximilian Kronberger, formerly of Bosch and now an independent consultant and researcher, says:

“A main driver in the automotive industry has been environmental legislation, which has become increasingly stringent over the past 20 years. Complying with this legislation while maintaining a positive driving experience for customers has required a considerable increase in injection pressures – by about three times. As a consequence, the stress on critical components has increased by three times. It was a particular challenge to find materials that could withstand this high level of stress. Fortunately, Ovako was able to provide a suitable steel, and since then IQ-Steel has become well established in the industry for high-pressure applications.”

5.3 – Manufacturing

Current manufacturing processes normally need only minor adjustments when making the change to clean steel. The closely controlled specification of clean steel with significantly reduced scatter in properties does in fact lend itself well to optimising machining operations. 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 sulfur content of 200–400 ppm (part per million) is quite common. For a BQ-Steel, the sulfur content will typically be around 80–100 ppm. To achieve the desired properties of ultra-clean steel such as the IQ-Steel, the sulfur level is further reduced and is typically around 10 ppm. This requires a different approach to machining, however the closely controlled properties of the material, together with advances in tool technology, have enabled very efficient, cost-effective production solutions for clean steel.

This is supported by the practical experiences of a production manager with a leading Tier 1 drivetrain component supplier who says: “High sulfur content has been highlighted as important in the past, especially for low cutting speed operations like broaching and shaving. However, my experience is that sulfur content can be reduced considerably because of the potential in new tool design/material as well as machine capability”.

The machining of clean steel will be addressed in more detail as the subject of a future white paper.

6 — Summary

Clean steel offers considerable benefits for designers who want to achieve significant improvements in powertrain power density. As a starting point, clean steel can be used as an upgrade material on existing components. In this case, enhanced fatigue performance can add considerable value by further extending the commercial life cycle of a current powertrain system design. However, the ultimate application of clean steel is to provide the basis for innovative design concepts for the total powertrain system.

Conventional steel have serious shortcomings when it comes to advanced designs for high power density in powertrain systems. This is due to the way they have been produced, with high sulfur contents and macro-inclusions, together with a relatively low reduction ratio of dimensions from cast to finished product. This results in a poor fatigue performance, which for many components is the deciding factor on what can be done with regards to design. The performance is at its worst in stress loading directions transverse to the rolling direction.

Clean steel is already delivering significant performance advantages across a range of powertrain applications and its importance can only grow as the global emphasis on energy efficiency continues to increase.

Contact fatigue testing has confirmed that clean steel can offer a 30 percent improvement in fatigue strength against conventional state-of-the-art steel. However, the limitation of these standardised tests do not reflect the full possibilities. When full-scale, real-world testing is carried out on complete powertrain systems adapted to maximise the benefits of clean steel then very significant benefits are realised – making ‘infinite life’ a realistic goal.

To get the most out of clean steel it is vital that design engineers and metallurgical engineers work in close partnership. And to fully appreciate the full added value benefits of clean steel it is important to take a holistic view that considers the performance of the components and systems together with their manufacturing processes.

There are some important machining considerations related to optimising the use of clean steels in manufacturing processes. They will be addressed in a future white paper.

7 — References / Further reading

Lily Kamjou, Patrik Ölund, Erik Claesson, Joakim Fagerlund, Garry Wicks Ovako, Mats Wennmo, Sandvik Coromant and Hans Hansson, Swepart Transmission (2015) Innovative Steel Design and Gear Machining of Advanced Engineering Steel American Gear Manufacturers Association (AGMA)
ISBN: 978-1-55589-016-2

Philip Konowalczyk M.Sc. (2016) Pitting Investigation on Gear Material WZL/Fraunhofer IPT/RWTH Aachen University

Patrik Ölund (2015) VDI presentations at International conference on gears www.vdi-gears.eu

Figure 7 – came from the article in Gear Solutions 01/2016 – Developing a lighter, stronger amd cleaner air-melt steel for critical applications
http://www.gearsolutions.com/article/detail/6629/developing-a-lighter-stronger-and-cleaner-air-melt-steel-for-critical-applications

8 — About the authors

Lily Kamjou
Lily Kamjou is a Senior Specialist in Ovako's Industry Solutions Development department. In her current role, she focuses on application development specializing in the powertrain area. Kamjou joined Ovako in 2008 and is based at the company's headquarters in Stockholm, Sweden. She has held a variety of positions in the automotive sector including working with the highly demanding market for diesel injection systems. Kamjou has a master's degree in materials engineering from the Royal Institute of Technology (KTH, Stockholm) and a bachelor's degree in social science from Stockholm University.

Erik Claesson
Erik Claesson is head of the group function Industry Solutions Development with main responsibility to increase end-user value. The scope is global and a special task force including design and manufacturing competences has been added to the steel product performance perpective. Claesson joined Ovako in 1998 and has held various management positions in manufacturing. Since 2010 he has heading group responsibilities aiming towards increased value creation. Claesson has a master's degree in materials technology and metal forming from the Royal Institute of Technology (KTH, Stockholm).

Patrik Ölund
Patrik Ölund is head of group research and development at Ovako. Educated at The Royal Institute of Technology (KTH, Stockholm, Sweden (1985-1990), he worked at the Swedish Institute for Metals Research (1990-1995) doing research relating to inclusions, fatigue and heat treatment. In 1995 he joined Ovako in the research department, which he now heads. Ölund was the winner of the Kami Prize 2013, presented to a distinguished scientist whose research has become the basis of a technical development within the Swedish steel and metal industry.

OVAKO

Disclaimer
The information in this document is for illustrative purposes only. The data and examples are only general recommendations and not a warranty or a guarantee. The suitability of a product for a specific application can be confirmed only by Ovako once given the actual conditions. The purchaser of an Ovako product has the responsibility to ascertain and control the applicability of the products before using them.

Continuous development may necessitate changes in technical data without notice. This document is only valid for Ovako material. Other material, covering the same international specifications, does not necessarily comply with the properties presented in this document.

Ovako Head Office
Box 1721
SE-111 87 Stockholm, Sweden

+46 8 622 13 00
ovako.com