HOW CLEAN IS YOUR STEEL?

— why quantification of inclusions provides confidence in a long fatigue life

Erik Claesson, Joakim Fagerlund, Lily Kamjou and Patrik Ölund

Executive overview

The use of clean steel is known to offer a dramatic improvement in the fatigue life of critical automotive powertrain components. This is due mainly to the precise engineering of the inclusions that initiate fatigue failures. Therefore, to have confidence that a clean steel will perform as expected it is vital to quantify both the size and statistical dispersion of the inclusions present.

There is however a significant challenge for the industry created by present standards that are effectively ‘obsolete’ – they rely on outdated methods of quantification that are incapable of recognizing the benefits of clean steel. The net result is that powertrain designers are unable to access the potential of these materials to optimize their components in terms of performance, size and weight.

In this white paper Ovako explains how it has addressed this quantification challenge with a new approach that combines the traditional technique of light optical microscopy (LOM) with the modern techniques of scanning electron microscopy (SEM) and immersed ultrasonics. This approach provides a comprehensive overview of the size and distribution of micro and macro inclusions.

Ovako has codified this new approach to inclusion quantification within the new standard that now enables powertrain designers make use of full benefits of clean steel.

While this white paper is aimed mainly at designers, especially those that make structural calculations, it will also be of interest to automotive engineers, purchasing professionals and anyone involved in specifying steels for demanding applications.

Four key messages emerge

- Inclusions are the main factor that limit fatigue life (assuming correct design, heat treatment and surface finish)
- Current international standards do not enable designers to benefit the full potential of clean steel
- A combination of test methods are now available to quantify inclusions in modern clean steels
- Ovako has developed its own publicly available standard that embraces these test methods so that designers can access the advantages of clean steel

1 — Introduction

The drive for higher levels of fuel efficiency requires powertrain components to be lighter, stronger and capable of resisting ever greater and more complex loads. In many cases it is fatigue strength that is the most critical factor when selecting a powertrain steel com-ponents since fatigue accounts for the majority of all mechanical service failures.

Fatigue occurs if a metal component fails when subjected to repeated loading, even at loads well below what it could easily sustain on a single loading. The 'safe load' or 'fatigue load limit' is the load at which a component will survive without failure beyond a certain number of load cycles.

Ovako has drawn on decades of industrial experience to develop a large database of fatigue data. This experience shows that the presence of unwanted particles in the steel, known as 'inclusions' represent a significant danger. This is because they act as local stress raisers that multiply the nominal load to above the component's safe fatigue limit.

Clean steels, such as Ovako's BQ and IQ-Steels, in which the size and distribution of inclusions is closely controlled can have a hugely beneficial effect in improving fatigue characteristics. The potential improvement in fatigue is illustrated by the rotating bending fatigue properties for conventional steel, BQ-Steel and IQ-Steel as shown in Figure 1.

Rotating bending

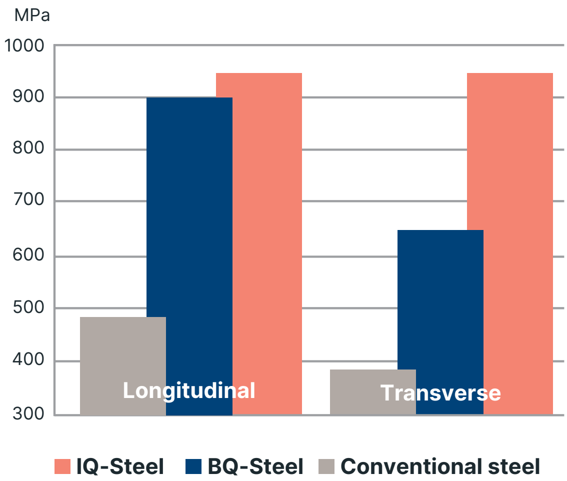


Figure 1 – Clean steel offers significant potential to improve the fatigue life of critical powertrain components.

The issue is that current international standards for steel inclusions do not reflect the recent major advances in steel quality, particularly when inclusions are small and/or widely dispersed.

It is not just a case of measuring the size of inclusions. Because large inclusions are found so rarely in clean steel it is vital to sample a sufficiently large volume of material to be confident that the tests reflect a true picture of the probability of them occurring.

It is no exaggeration to say that current steel standards are effectively obsolete in that they offer no effective guidance for designers in considering clean steels. Therefore a new approach to quantification has been developed that brings together a range of methods providing a full and statistically valid picture of the inclusion population in a steel sample.

It is particularly in the use of 10 MHz immersed ultrasonics that Ovako has made advances in limiting the defects that have the most influence on the final performance of the finished component. This is also a method that can be readily adopted by most steel producers. SEM of large areas is a technique that will take more time to become established as a standard cross-industry procedure. However, SEM is currently used as part of Ovako's in-house process and product development procedures.

The effective quantification of steel inclusions now provides the basis for a new standard for clean steels. While it is primarily intended for use with Ovako's own products it is freely available for public use.

Key points

- Clean steels in which the size and distribution of inclusions is closely controlled can offer the possibility to improve component fatigue life by up to 50% (see figure 2)
- Current steel standards are effectively obsolete as they do not offer guidance in selecting clean steels
- Ovako has published a new standard based on the effective quantification of steel inclusions

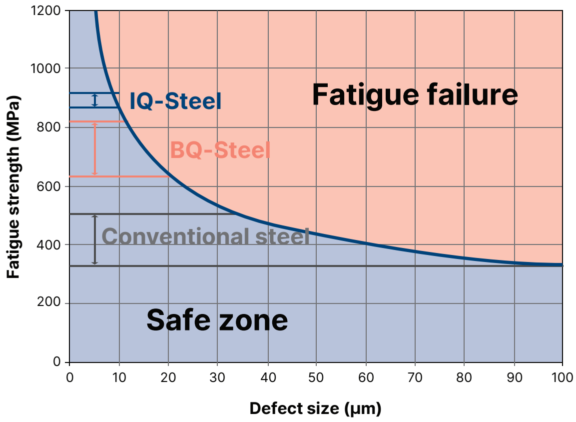
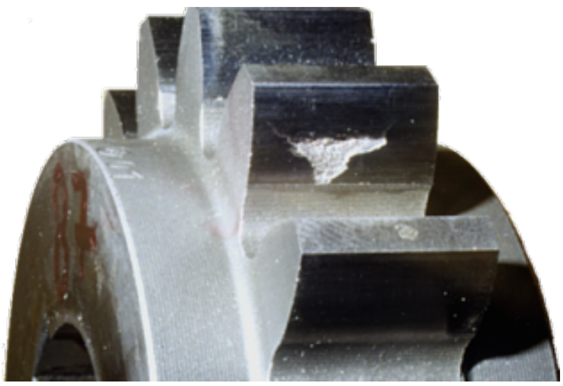
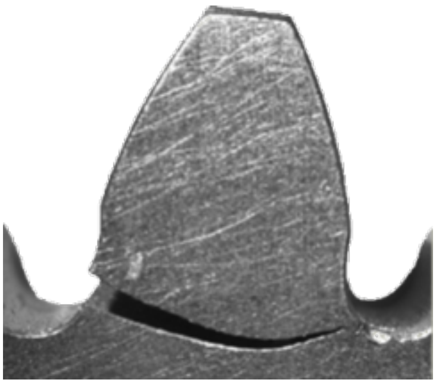


Figure 2 – the fatigue strength of steel transmission components is related directly to the defect size.





Fatigue failure is a major challenge for gear design – photos with thanks to the Institute of Machine Elements Gear Research Centre (FZG), Technical University of Munich, from an original article in Gear Technology magazine.

2 — Where do inclusions come from?

It is useful to understand how steel inclusions are formed and how they are categorized. There are two main types – endogenous and exogenous:

- Endogenous 'micro' inclusions are formed by the physical-chemical effects that occur during the melting and solidification process. They can be formed from the oxygen and sulphur remaining after the deoxidation and desulphurization process or through reoxidation, see figure 3a and 3b.

- Exogenous 'macro' inclusions result from parts of the slag, refractories, teeming powder, or sand from a casting mould, see figure 3c.

ISO 4967, ASTM E45 and DIN 50602 are the current standards that apply when assessing micro inclusions. 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 is too small to provide any statistical confidence.

Blue fracture is currently used to assess macro inclusions. But invariably, using this method a clean steel producer will generate only zero ratings for macro inclusions.

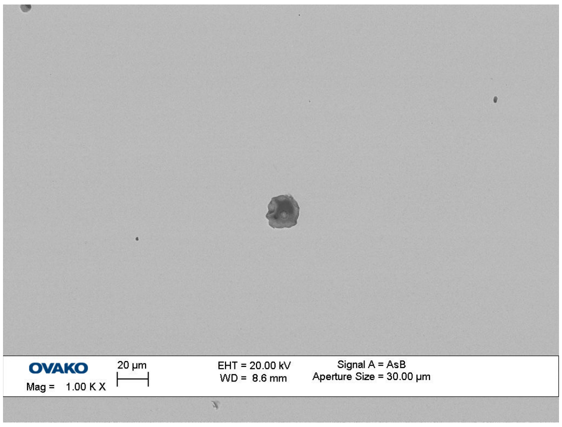


Figure 3a – type D micro inclusion

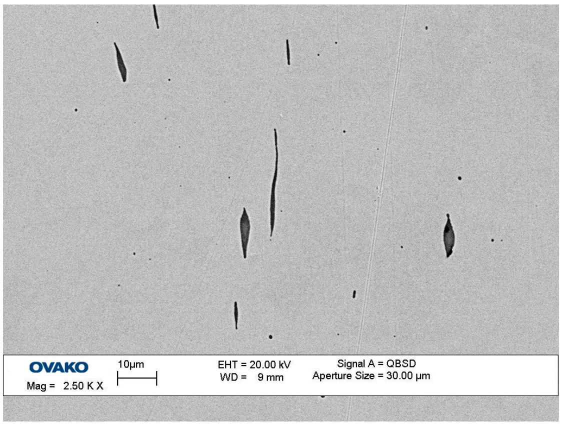


Figure 3b – type A MnS (Manganese Sulphide) micro inclusions

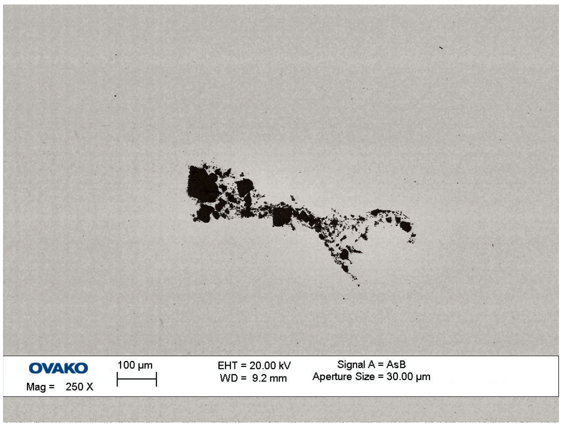


Figure 3c – Macro inclusions

3 — Inclusion quantification methods

Ovako has focused on reviewing and developing methods to create an approach that can accurately reflect a realistic inclusion content in clean steel. This is vital for both improving steel quality and also in predicting how a component will perform.

3.1 Light Optical Microscopy (LOM)
Light Optical Microscopy is the traditional technique. It is covered by standards such as ISO-4967, ASTM A295/E45 and DIN 50602. The results are evaluated using charts such as the JK reference scale.

This technique is only suitable for qualifying inclusions between 2 μm and 15 μm and is limited to very small sample sizes – typically the evaluated area is 1200 mm^2. LOM does not provide any data on the chemical composition of inclusions and is therefore not a suitable tool for process development. Figure 4 illustrates that the small sample size is a specific issue with LOM.

3.2 Blue fracture testing
Blue fracture testing is an historically well-established technique used to reveal macro inclusions larger than 0.5 mm. It is performed on a bar cross-section area that has been hardened, fractured and then tempered blue to increase the visibility of defects.

This technique is used by Ovako only due to customer demand. It is of little relevance in clean steel though, as it is over 30 years since an inclusion has been found using this method.

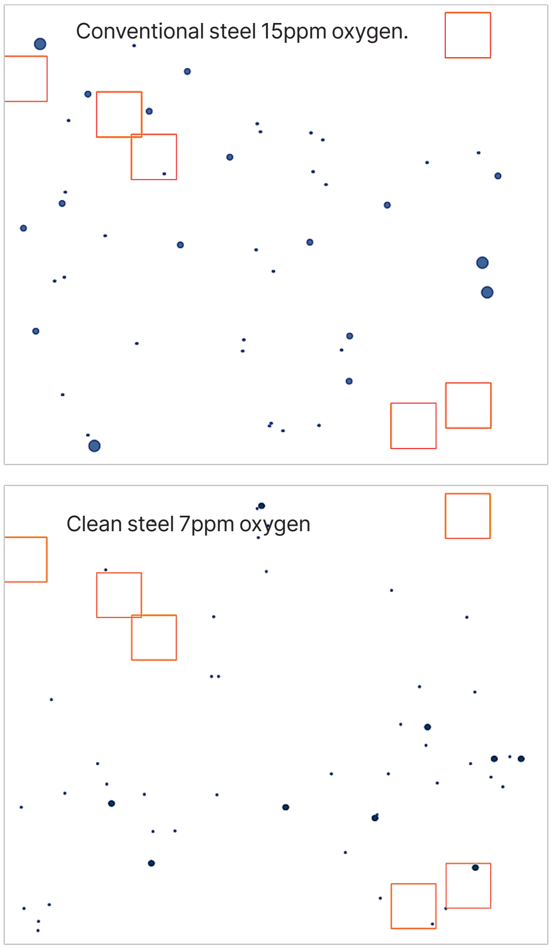


Figure 4 – A specific issue with LOM is the small sample size as shown in this schematic illustration (not to scale). Normal procedure is to examine 6 samples. But their small size does not represent the true size and distribution of inclusions. In this particular case it is even possible to obtain the false impression that standard steel (4a) has fewer and smaller inclusions than a clean steel (4b).

3.3 Scanning Electron Microscopy (SEM)

In contrast to LOM, scanning electron microscopy, see figure 7, is capable of assessing large areas – typically 5,000 mm^2 and provides rich data on inclusion chemistry, morphology and size. The chemistry of inclusions is vital for process development, while morphology and size is vital for product development. This quantification method is used for inclusions between 2 μm and 25 μm.

3.4 Immersed ultrasonic testing

Fully automated ultrasound testing methods used by Ovako to test for larger inclusions have produced impressive results, see figure 5.

To test for inclusions above 120 μm, a single sample of 500,000 mm^3 steel, milled plane parallel, and immersed in a water tank is scanned with a 10 MHz probe, see Fig 6. This is the equivalent of 16,000 blue fracture tests. This test does not produce information about the chemical composition of the inclusions, but it is an important tool for process development.

To test for smaller inclusions, it is possible to increase the ultrasonic probe frequency to 15, 25, 50 or even 80 MHz. However, as the frequency and resolution is increased the size of the sampled volume will decrease.

3.5 A combination of techniques creates the full picture

Three techniques – LOM, SEM and ultrasonics – are combined to obtain a complete overview of the total inclusion content that feeds directly into the refinement of our production processes for new, cleaner steels, see Figure 7.

It should be noted that to obtain a full picture of the relationship between inclusion population and fatigue properties Ovako recommend that rotating bending fatigue testing (RBF) should be carried out on appropriate samples.

Figure 5 – SEM equipment at Ovako.

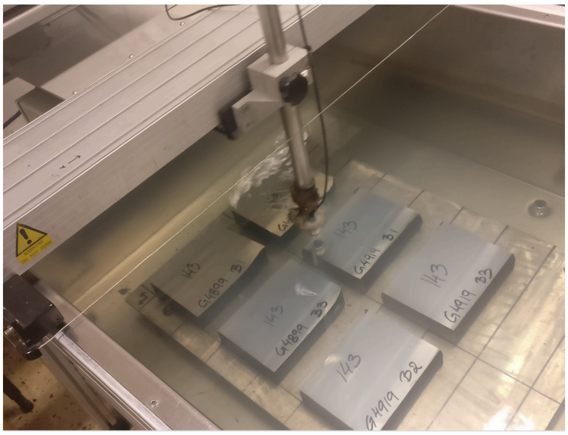


Figure 6 – immersed ultrasonic testing at Ovako

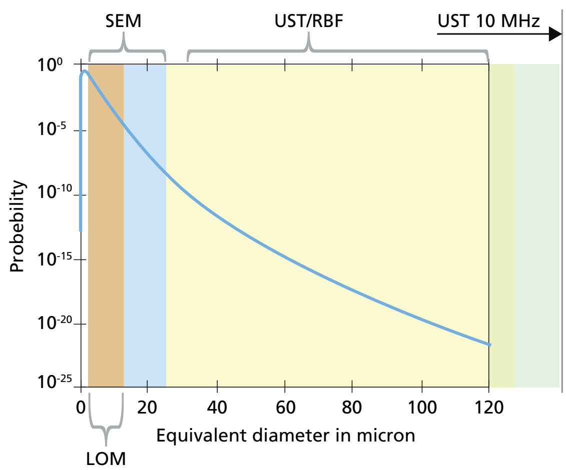


Figure 7 – summary of inclusion quantification methods.

4 — Closing the standards gap

Reliable quantification of inclusions has made it possible to develop a new generation of clean steels. However, current design standards do not take into consideration the benefits of these materials in terms of fatigue properties. It is therefore difficult for powertrain designers to select clean steel.

The result of this effective gap between the available standards and the capabilities of clean steels is that significant opportunities are being missed to optimize components in terms of their performance, size and weight.

Customers sometimes request the blue fracture testing procedure described in ISO 3763. In Ovako's experience, 10 MHz immersion ultrasonic testing is a much more powerful method of generating information regarding macro inclusions. This has resulted in the development of an in-house ultrasonic testing procedure that Ovako offer to replace blue fracture testing.

Ovako ultrasonic standard
The Ovako internal test procedure involves the testing of steel billets. Through experience, Ovako has concluded that the 'worst part', of the ingot is at the very bottom. Therefore, sampling is made on material originating from this area.

A central part of the billet is prepared by milling. The samples are scanned in an immersion ultrasonic tank with a focused 10 MHz transducer. The equipment is calibrated with known defects and calibrated so that the smallest feature that will be detected is as a defect corresponding to a 0.12 mm FBH (flat-bottom-hole).

The minimum detected feature size and tested mass (or volume) are important testing parameters. Immersion ultrasonic testing offers both a higher detectability and allows testing of a more significant volume of material, as shown in Table 1.

	ISO 3763 Blue fracture	**Ovako 10MHz UST**
Minimum feature detected	Length ≥ 1.0 mm Thickness ≥ 0.1 mm	FBH* ≥ 0.120mm
Coverage	Surface	Volume
Amount of material investigated1)	Approximately 2000 mm^2	Approximately 1054 cm^3
Number of tested specimen	2	3

Table 1 - Detectability and amount of tested material
* FBH –Flat bottom hole.

To illustrate the improved detectability, blue fracture samples were manufactured from an ultrasonic test piece that, when scanned, showed a high number of imperfections, see Figure 8. The scanned sample had a large number of defects exceeding 0.2 mm FBH (see next section) due to the large number of imperfections. Yet when blue fracture testing was carried out no indication of any defect could be found on the fracture surface, as shown in Figure 8.

Ultrasonic testing produces an output like that shown in Figure 10. The different amplitude sizes correspond to defect sizes. The class >100 % Full screen height (FSH) will correspond to an artificial defect exceeding 0.2 mm FBH.

Ovako has used this practical experience to create a standard based on setting a limit to the number of defects found in divided by the investigated volume. Physically, this relates to the maximum number of defects larger than 0.2 mm per unit volume. The data in Fig 9 is then further processed according to the method in Table 2.

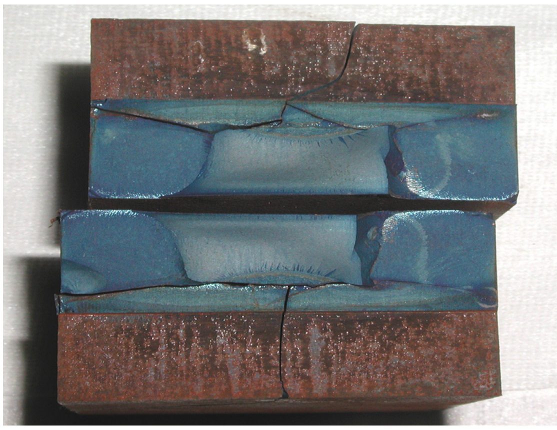


Figure 8 – Blue fracture test showing no indication of any inclusion

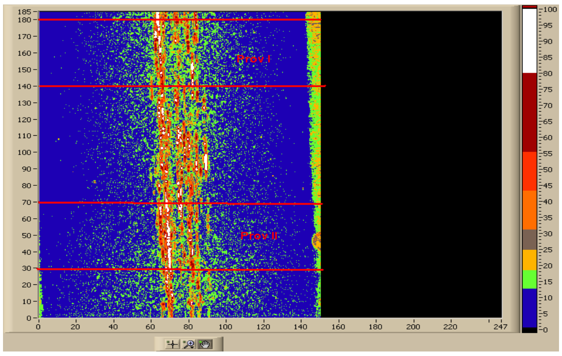


Figure 9 – Ultrasonic scan showing the positions where blue fracture specimens were selected.

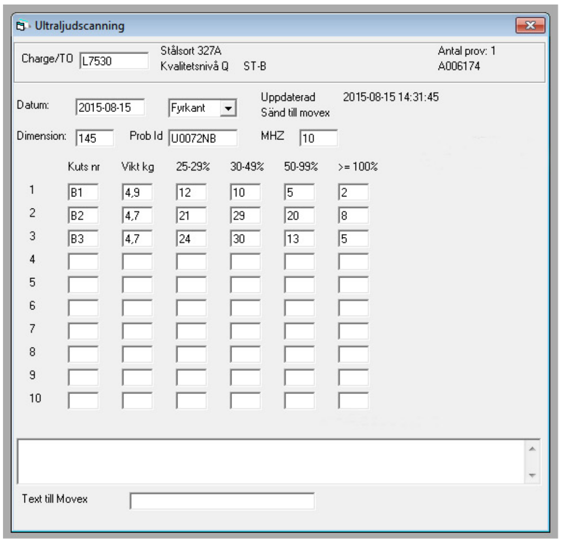


Figure 10 – Ultrasonic testing output from a medium carbon steel.

The number of defects larger than 0.2 mm FBH	2+8+5	15
Total inspected mass in kg	4.9+4.7+4.7	14.3 kg
number of defects larger than 0.2 mm FBH/ kg	15/14.3	1.05 #/kg
number of defects larger than 0.2 mm FBH /dm^3	1.05 x 7.8 (density)	8.2 #/dm^3

Table 2 - Calculation of number of defects larger than 0.2 mm FBH /dm3

The standard sets the proposed limits shown in Table 3.

The test conditions are

- Billet 80 to 250 mm round or square
- Samples from bottom part of the ingot (minimum 1.2 weight % crop)
- Average of minimum 3 samples
- Ovako testing procedure OFL047
- Additional evaluation as described in the example above i.e. number of defects larger than 0.2 mm FBH / dm^3

The standard makes it possible to set design parameters that correlate with the properties of clean steel – typically this could be an improvement of some 30% in the fatigue limit.

The standard has already been applied with considerable success for demanding components in bearing and diesel injection applications. It is now being applied for powertrain components.

Ovako has developed the standard along the same lines as established international standards. So while it is primarily intended for our own use Ovako is making it freely available for customers to take to any steel supplier.

Quality	< 0.4 % C	≥ 0.4 % C	Comment
BQ	< 60 (UST)	< 30 (UST)	Guaranteed values based on statistically testing
IQ	< 10 (UST)	< 5 (UST)	Tested values

Table 3 - Proposed limits for various quality classes and carbon contents.

5 — Practical example

In order to examine the effect of steel cleanliness on the fatigue properties, two different steel bars (70 mm in diameter) with a major difference in steel cleanliness were investigated. The steel grade was a carburizing steel (18CrNiMo7).

Assessment of steel cleanliness was performed by three different methods: micro inclusion rating by ASTM-E45; ultrasonic evaluation; scanning electron microscope.

Ultrasonic and SEM-evaluation revealed a major difference in cleanliness between the two steels, whereas the traditional micro inclusion rating method did not reveal any significant difference. The results from ultrasonic evaluation can be seen in Figure 11.

Fatigue samples were manufactured from the two investigated steels. These samples were prepared in a transverse direction to the rolling direction of the bar, as this is the most critical direction (inclusions are elongated in the rolling direction of the steel bar).

The results of the fatigue testing gave a fatigue limit of approx. 540 MPa for Steel A and 800 MPa for Steel B, see Figure 12.

	Steel A	**Steel B**
Steel grade	18CrNiMo7	18CrNiMo7
Casting Process	Continuous cast	Ingot Cast
Area Reduction	~10	~65

Table 4 – Investigated Steels.

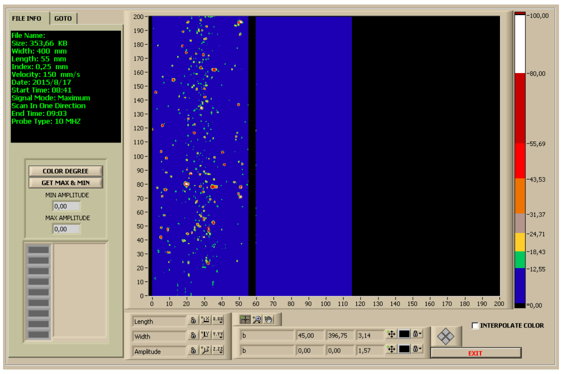


Figure 11 – Ultrasonic C-Scan (10MHz), Steel A (left) and Steel B(right).

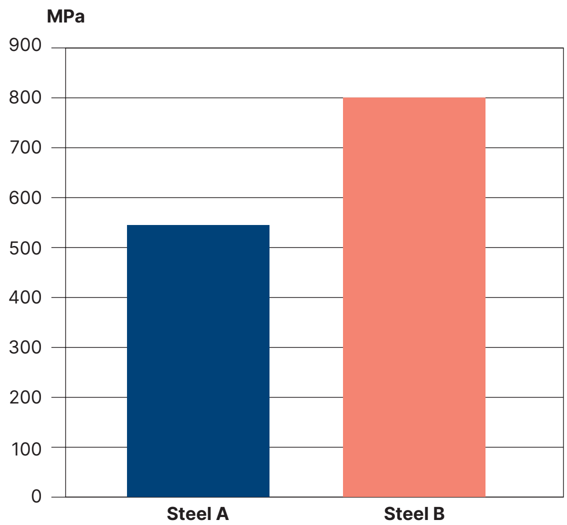


Figure 12 – fatigue limits from the two investigated steels.

6 — Summary

Non-metallic inclusions are the critical factor that determine the fatigue life of steel. The use of modern production techniques has resulted in a new generation of clean steels in which the size and distribution of inclusions is closely controlled.

Using clean steels for powertrain components can offer a significantly enhanced fatigue life – up to 50% in some cases.

Currently, powertrain designers are not able to fully exploit the advantages offered by clean steels as today's international standards do not provide the opportunity to specify them. The main reason for this is that the techniques outlined in current standards that have been applied historically for conventional steels are not sufficient to quantify the much smaller and more dispersed inclusions in clean steel.

Ovako has responded to this quantification challenge by developing a new approach based primarily on 10 MHz ultrasonic testing to correctly identify the size and nature of inclusions.

This method of quantification is codified in Ovako's standard that now enables powertrain designers to utilize the advanced fatigue properties of clean steel to optimize their components.

7 — References / Further reading

Patrik Ölund - Ovako Technical Report. The IQ-process – the Ovako isotropic quality process.

Patrik Ölund – Replacing blue fracture testing according to ISO 3763 with Ovako 10MHz immersion ultrasonic testing.

Standards for gear life calculations ISO 6336 and ISO/DTS 19042-1.

Appendix: Detection of non-metallic inclusions in steels with high cleanliness demands such as case- or through hardening bearing steels by the ultrasonic method, can be downloaded at Ovako.com

Erik Claesson, Lily Kamjou and Patrik Ölund – Ovako Technical Report. Clean steel – living up to power density challenges.

Gear Technology Magazine – 09/2015 – Page 58 – Article by FZG (PDF)

8 — About the Authors

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).

Joakim Fagerlund
Joakim Fagerlund is a Senior R&D Engineer in Ovako's R&D department. In his current role, he focuses on development related to steel cleanliness and fatigue. He has been with Ovako for more than 10 years and is based at the company's headquarters in Stockholm, Sweden. He has a master's degree in materials physics from KTH Royal Institute of Technology.

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.

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.

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

+46 8 622 13 00
ovako.com