

Innovative Steel Design and Gear Machining of Advanced Engineering Steel

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The basis for high-fatigue performance in high-hardness steel originates in precise inclusion engineering. In addition, recent research shows that by changing the alloying strategy, an increase in the bending fatigue limit can be achieved similar to that of adding another shot-peening process. This paper describes the potential of clean steel for new approaches in transmission gearbox manufacturing and possibilities to meet the future demands for smaller, lighter and managing higher torque. An important factor is the bending fatigue performance of gear teeth where increasing fatigue strength is required. The paper discusses how shot peening might be eliminated in high-cleanliness, as-carburized steel components using an alternative composition. The full benefit of this new steel design can be obtained by using a high-quality steel with a decreased number of critically sized inclusions in the loaded volume. To address potential machining issues of clean steels, the paper also deals with the production process, including quantitative machining trials and the importance of tooling selection. The study is focused on the production of gears—primarily with turning and hobbing. Initial results show how these clean steels can be machined in full scale production in standard conditions with equal or better efficiency and cost.

Introduction

The increasing demands in the automotive industry for weight reduction, fuel efficiency and a reduced carbon footprint need to be addressed urgently. Up until now, widely used conventional steels have lived up to expectations. However, with more stringent emissions standards, demands on materials are increasing. Materials are expected to perform better, resulting in a need for increased fatigue strength. A possibility to increase torque on current generations without design changes can be achieved by selecting suitable materials.

With current and future generations of transmissions evolving towards higher loads as well as weight reduction, the material needs to support the step changes taking place, instead of limiting them. Better performing materials that can handle the higher stresses mean that loads on gear materials could be increased from 30% up to or above 100%, depending on the starting point, therefore providing new design opportunities. Today, single- and double-peening are methods frequently used to increase the fatigue strength for this type of loading. To meet increasing demands however, making use of the inherent potential of materials with improved intrinsic fatigue prop-

erties appears to be a natural way forward to handle the step changes taking place (Ref. 1). And with an innovative steel design, costly and undesirable processing steps, such as shot peening, might even be eliminated.

Steel parts need to keep going virtually forever as well as meet new regulatory requirements. When selecting the right

steel quality for highly loaded applications, it is not always easy to know all the functional properties and the cost and quality implications. It is important that suitable test and inspection methods are used to verify that the material fulfills the desired requirements. More precise methods, compared to the commonly used international standards, should be

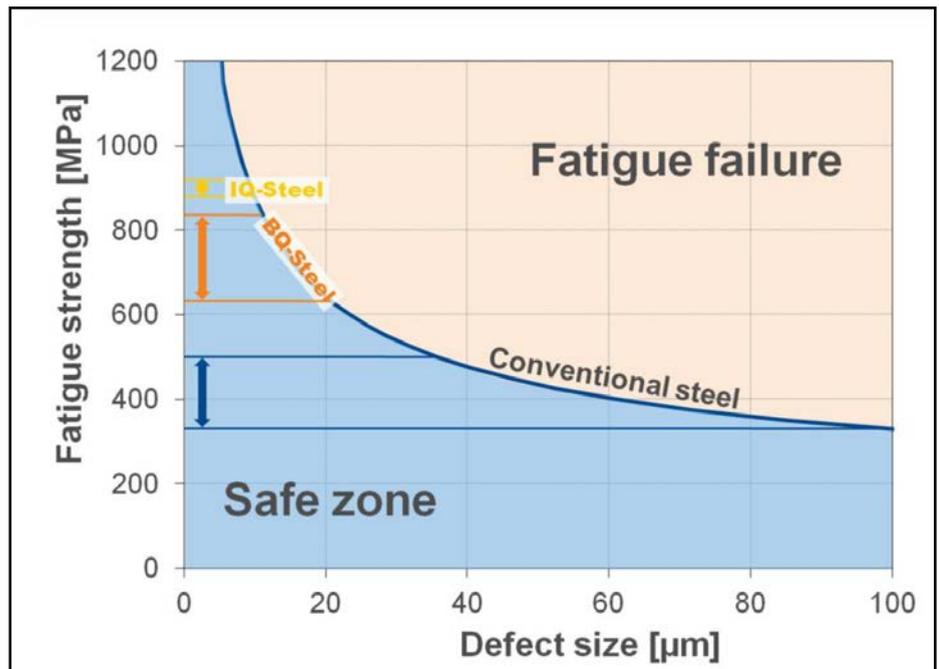


Figure 1 Relation between defect size and fatigue strength.

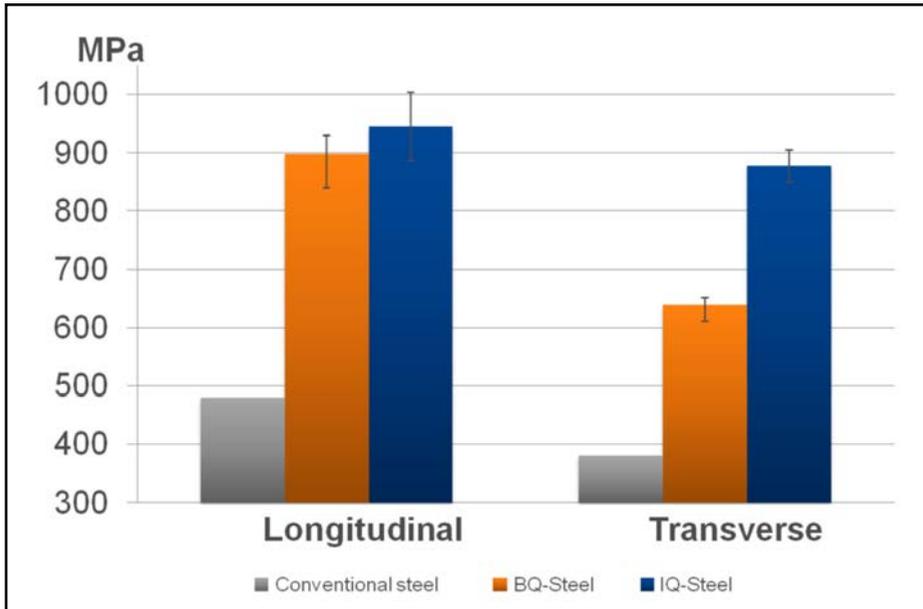


Figure 2 Rotating Bending Fatigue of conventional steel compared to BQ-Steel and IQ-steel in both longitudinal and transversal direction.

applied. In fact, such methods are already implemented for steel in highly stressed diesel injection components.

When moving from conventional steel to advanced engineering steel (clean steel), production issues like machining and tooling selection also need to be addressed before implementing material to production.

How Steel Cleanliness Affects Material Life

From experience, it is known that defects such as nonmetallic inclusions can initiate fatigue failures. Over the years, Ovako has focused on fatigue research and has now built up an impressive database of fatigue data. Steel quality has a huge

impact on the fatigue life of a steel component. A clean steel that contains smaller sized defects compared to a conventional steel gives longer fatigue life.

Improvements in steel cleanliness result in big design opportunities. That is good news for any designer who has relied on old standards, when in fact modern steel practices have opened up for a new level of performance. Because of the properties of Bearing Quality steel (BQ-Steel) and Isotropic Quality steel (IQ-Steel), which now close the gap to re-melted steels, it is possible to downsize gears, bearings, and other steel parts to meet new requirements. For instance, a gearbox can be made lighter, with higher power density, by using cleaner steel.

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

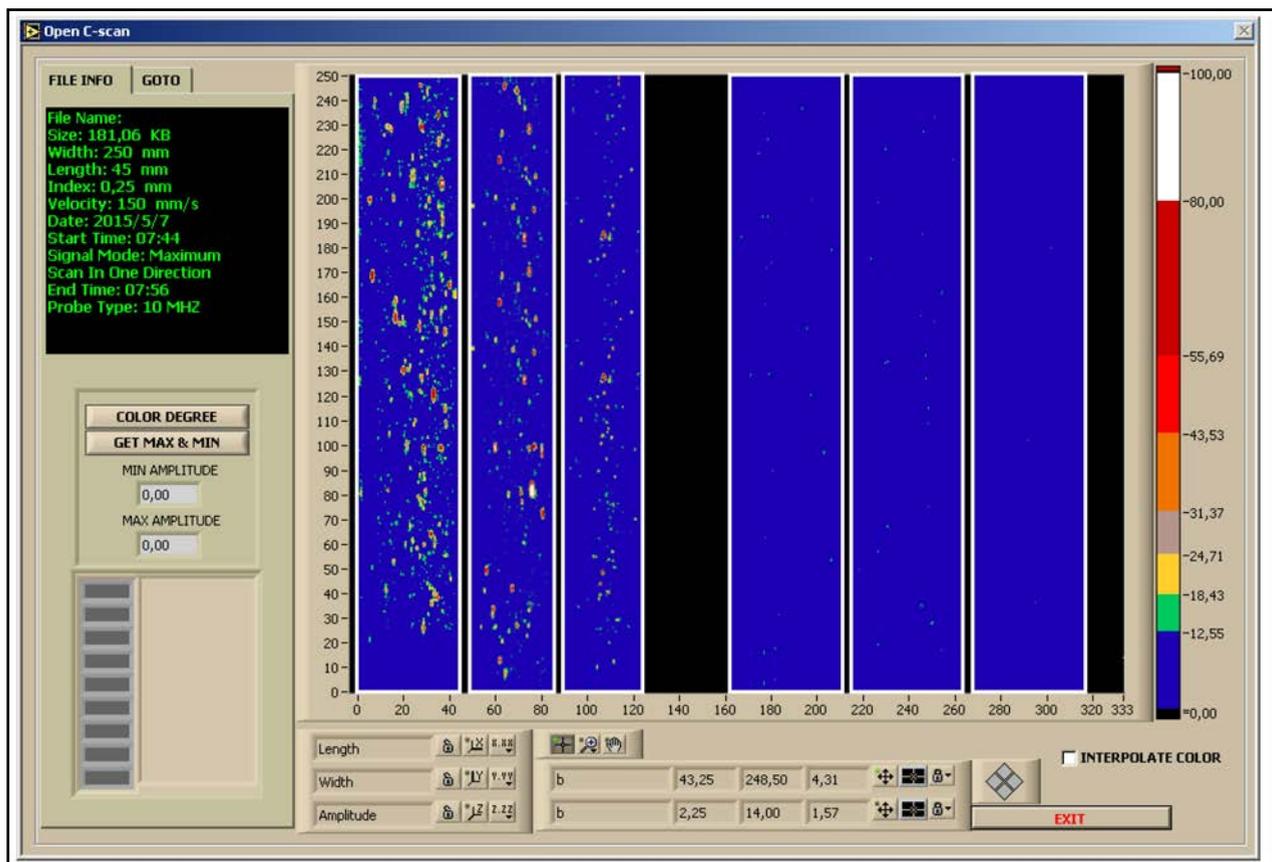


Figure 3 10MHz ultrasonic scans of six different steel samples from round bar ~ 70 mm.

IQ-Steels are 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 and therefore makes it suitable for complex load cases, such as those in gears.

In Figure 2, results from rotating bending fatigue 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 compared to conventional steel.

It is worth noting the typical sulphur content in the different types of steel mentioned in Figure 2. For conventional steel, a sulphur content of 200–400ppm is quite common, whereas for a BQ-Steel, the sulphur content will typically be around 80–100ppm. To achieve the desired properties of ultra-clean steel such as the IQ-Steel, the sulphur level has been reduced even more and is typically around 10 ppm.

Verifying Steel Properties

As has been shown, steel cleanliness is crucial when it comes to fatigue performance of high hardness steels; therefore, it is important to quantify the cleanliness in order to verify required fatigue performance of the final component (e.g., gear). Traditionally, macro-inclusions have been quantified by methods such as step-down testing and blue fracture testing. However, these methods give little or no information in regards to cleanliness, even for conventional steels of today.

For micro-inclusions, methods routinely used today, such as those found in ASTM E45, also give a very vague picture of the steel cleanliness, due to the small investigated area. For commonly used steels in the transmissions industry today, 10MHz ultrasonic testing has been proven 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, instead of investigating only a small area. In Figure 3 below, examples of ultrasonic testing on bars with a diameter of ~ 70 mm are shown.

Here, six samples have been evaluated by 10MHz ultrasonic testing; the three samples to the left are typical carburizing

steels used for gears in the transmissions industry today, and the three samples to the right are typical for clean carburizing steels (for example 20MnCr5) from the Ovako ingot route. The reason for the clearly visible difference between the different steels is how they are produced; the Ovako steel has an oxygen content of around 8ppm, whereas conventional steels have oxygen content in the range of 8–30ppm. Another important factor is the reduction ratio, which is much larger from this ingot route; commonly used conventional steels from continuous cast routes have a reduction ratio in the range of 8–25.

However, 10MHz ultrasonic testing is not an accurate enough method to separate the clean steels of today, due to inadequate resolution; in order to improve the resolution, higher frequency can be used.

Alloys for Gear Applications

The development and investigation of a modified gear application steel was initiated a number of years ago by a transmissions producer. Due to the current climate and changes in the automotive industry, this topic is now high on stakeholder agendas. A number of different studies have been performed; so far, all investigations point to this specific material showing very interesting properties in the as-carburized condition — meaning shorter production processes and the possibility of reducing or eliminating process steps.

Gas carburizing is a widely used process to enhance the properties of highly stressed components. Typically, case carburizing will create compressive residual stresses and a tough core. However, a disadvantage of the carburizing process is that the near surface of the components can exhibit poor structure and tensile stresses due to oxidation of alloying elements that reduce fatigue endurance. Therefore an additional process — such as shot peening — is often introduced to change the stress state on the surface from tensile to compressive. This increases the bending fatigue strength significantly, but also tends to degrade the surface quality, which can in turn lead to other failure modes such as surface pitting. In some applications fine grinding is introduced to improve the surface properties. However, since it is difficult to grind and get the necessary properties

Table 1 Typical chemical composition of Ovako 158Q compared to conventional steel for gear applications

	C	Si	Mn	Cr	Ni	Mo
Conventional 16MnCr5	0.18	0.10	1.30	1.25	0.15	0.04
Ovako 158Q	0.18	0.04	0.25	0.35	2.20	0.65

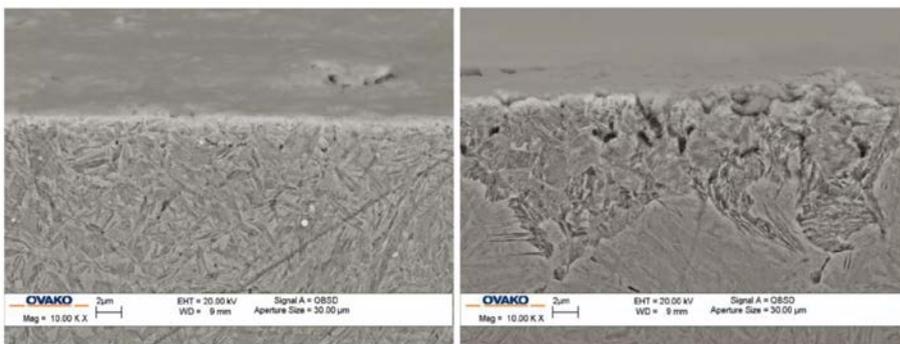


Figure 4 SEM micrographs of surface microstructure for Ovako 158Q (left); conventional 16MnCr5 (right).

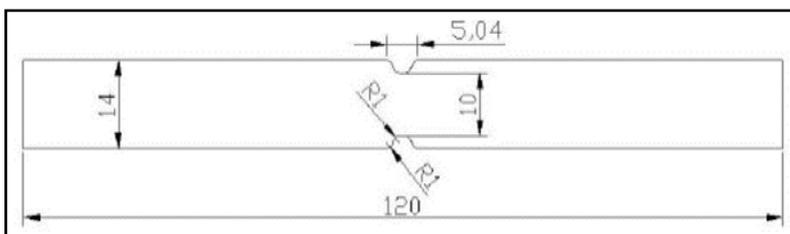


Figure 5 Notched specimen geometry for RBF testing.

in the root, subsequent shot peening is applied as well.

By using a different approach in the selection of the alloying elements, a steel — i.e., one that exhibits a dramatically reduced tendency for the formation of internal oxidation during conventional gas carburizing — can be produced. Silicon, manganese and chromium, the elements responsible for internal oxidation, have been reduced as much as practically possible, while yet maintaining the steel's hardenability by increasing the content of nickel and molybdenum (Table 1).

The result is a steel with a martensitic microstructure all the way to the surface, and thus the residual stresses remain compressive at the surface. Figure 4 shows the difference between a conventional gear steel and the 158Q in the as-carburized condition.

Fatigue Performance

To evaluate the fatigue performance of Ovako 158Q for as-carburized gear components, a thorough fatigue test program has been conducted. Rotating bending fatigue (RBF) tests, pulsator testing on gears, and surface fatigue testing in FZG-test rigs were performed.

Rotating bending fatigue tests were then conducted on a notched specimen to simulate the highly stressed root area of a gear tooth (Fig. 5).

The specimens were tested in an as-carburized condition with a fully reversed loading, i.e. — $R = -1$. The runout criteria were set to 107 cycles, and the applied load was changed according to the staircase test strategy.

Results of the RBF testing clearly indicate that Ovako 158Q exhibits an increase in the fatigue limit of >20%, compared to a conventionally used steel such as the 16MnCr5 (Ref. 2); (Fig. 6).

Bending fatigue testing done in pulsator testing rigs on gears shows similar results (Refs. 3–4), which verifies the reliability of RBF testing.

Contact Fatigue Testing

Gears made out of Ovako 158Q have been tested at the Royal Institute of Technology (KTH) in Stockholm to establish how this type of steel compares to conventional steel.

The tests were performed in an FZG back-to-back gear test rig with a pitting

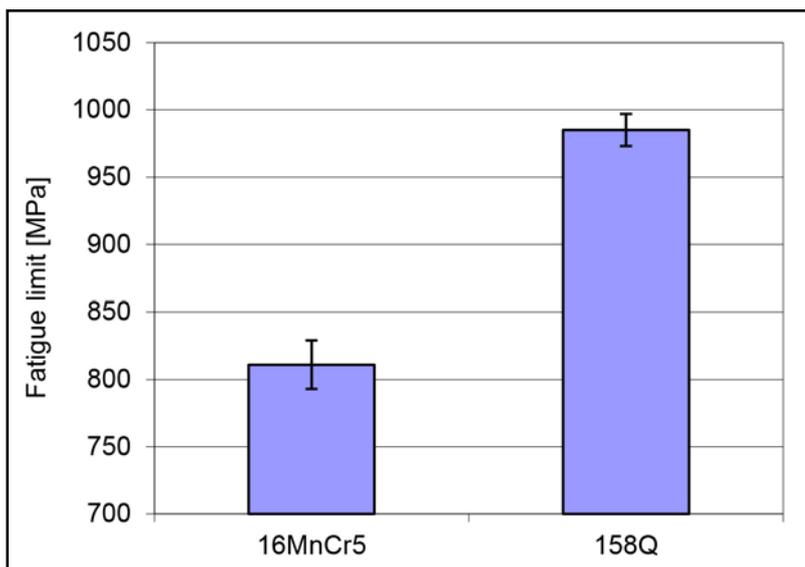


Figure 6 Fatigue limit for notched RBF samples of Ovako 158Q and reference 16MnCr5.

	Test 1, run time	Test 2, run time	Test 3, run time
Ref material (16MnCr5)	169h	118h	300h (run-out)
Ovako 158Q	300h (run-out)	300h (run-out)	300h (run-out)

Number of hours	118	169	300
Number of contacts of pinion	15e6	21.9e6	39.0e6

test set-up according to the FVA standard for pitting (Refs. 5–6), and in a first trial run at load stage 10. The gear profile with modified C-Pt geometry is common for this type of testing, although the tip relief is slightly altered. The gears have been produced through turning, gear cutting, case hardening, hard turning (inside) and grinding. No shot-peening has been performed on either material.

Before each test the gear case was flushed twice and a new gear pair cleaned and inspected for rust or any other damage, then mounted, loaded with the run-in load and the oil level set correctly and heated to 90°C. The gear pair was then run-in for four hours at a pinion torque of 94Nm (corresponding to load stage 5), which corresponds to a maximum Hertzian pressure of 0.92 GPa at the pitch. Once the running-in was done, the test rig was loaded to the test load of 372Nm for the pinion (load stage 10), corresponding to a maximum Hertzian pressure of 1.84 GPa at the pitch. Pitting failure in these tests is defined as having pitting over 4% of the flank, i.e. — 5 mm² of the C-Pt gears.

For the reference material, the results varied broadly. This is probably related to

a larger scatter in inclusion sizes that can be found in the reference material, combined with the surface conditions of these gears. For the gears made out of 158Q, the testing was stopped after 300 hours as defined by the test procedure (Table 2). Table 3 shows the number of contacts of the pinion at the maximum pressure of 1.84 GPa.

Machining Clean Steel

The aim of the machining trial was to understand how advanced engineering steel behaves in standard machining processes in comparison to conventional steel commonly used in gears. For this purpose the two steels tested were Ovako 158Q and a conventional 20NiCrMo2-2. Since the general consensus is that the sulphur content is one of the parameters affecting machinability, it is worth noting the sulphur content of the two materials; Ovako 158Q with an S-content of typically around 10 ppm, and 20NiCrMo2-2, with an S-content typically of around 200–400 ppm.

As a step in determining what impact clean steel will have on the total cost of production, quantitative trials have been performed to support machining

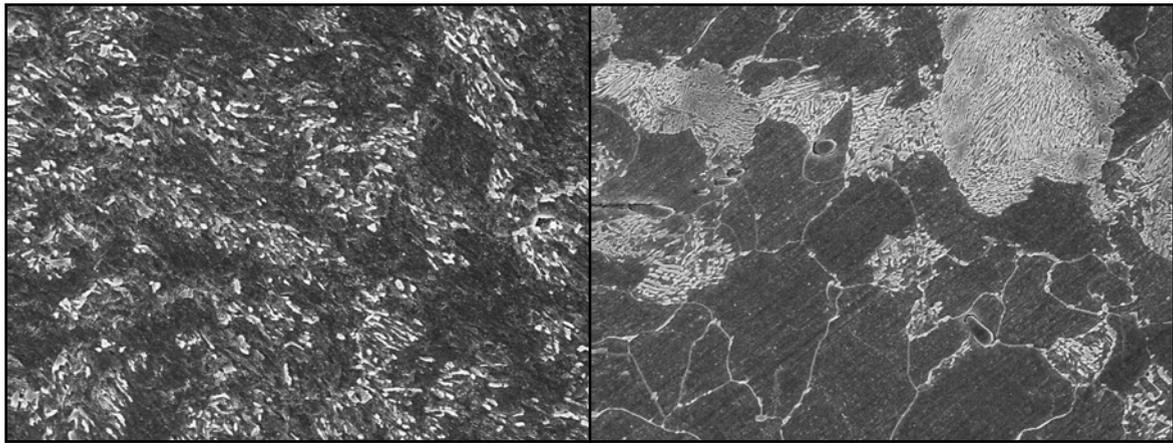


Figure 7 Microstructure photographed in SEM $\times 2,500$ magnification; Ovako 158Q (left); reference material, 20NiCrMo2-2 (right).

of this type of material. The key is optimization — i.e., finding the right set-up for this type of steel. It has been shown through testing done in collaboration with manufacturers of powertrain components and tooling, that producing gears according to current processes (such as turning and hobbing) can be achieved with cost neutrality, or in some cases even at a reduced cost. Simply by changing tool inserts to a more modern technology, clean steels machine just as well as, if not better than, conventional steels. One important factor is the consistent quality of the material; that variation, delivery to delivery, is very low. Correspondingly, ensuring a more advantageous microstructure than the uneven but standard ferritic perlitic structure, together with smaller inclusions that don't interfere in an adverse way, leads to a stable machining process.

Table 4 Material data

Material	Weight of blank (kg)	Weight after turning (kg)	Hardness (HB)	Inserts	Number of turned parts
20NiCrMo2-2	1.4	1.05	162	GC4325	404
Ovako 158Q	1.29	1.05	192	GC4325	404

Testing Procedure

The initial machining trials were based on the standard set-up at the transmissions component producer. The machinability test was carried out in ordinary production machines for a planetary gear, which in serial production is made from a forged blank of a steel close to the standard 20NiCrMo2-2. Gear data is $z=20$, modulus = 3.7 mm, and the same cutting data as in serial production was used for both materials.

The forged blanks in 20NiCrMo2-2 showed a ferritic/perlitic structure (Fig. 7, right).

The blanks in Ovako 158Q were cut from a rough-turned bar with a dimension close to the forged blank. The diameter was somewhat smaller compared to the forged blank, resulting in a slightly lighter blank. The structure was ferritic with cementite (Fig. 7, left).

Turning Trials

The weight of the blanks after turning was 1.05 kg, thus 0.35 kg was turned away from the reference material and 0.24 kg was removed for Ovako 158Q (Table 4). In serial production with forged blanks for reference material, the normal output is 290 gears-per-insert-tip — using insert tip type GC4225. By changing to a different insert type — insert type GC4325 with unidirectional crystal orientation — this number could be increased substantially. In the test 404 parts were turned with each insert tip for both types of material before the machining was stopped and the inserts analyzed. At that point the inserts had not yet reached their lifetime; the test was stopped before run-out.

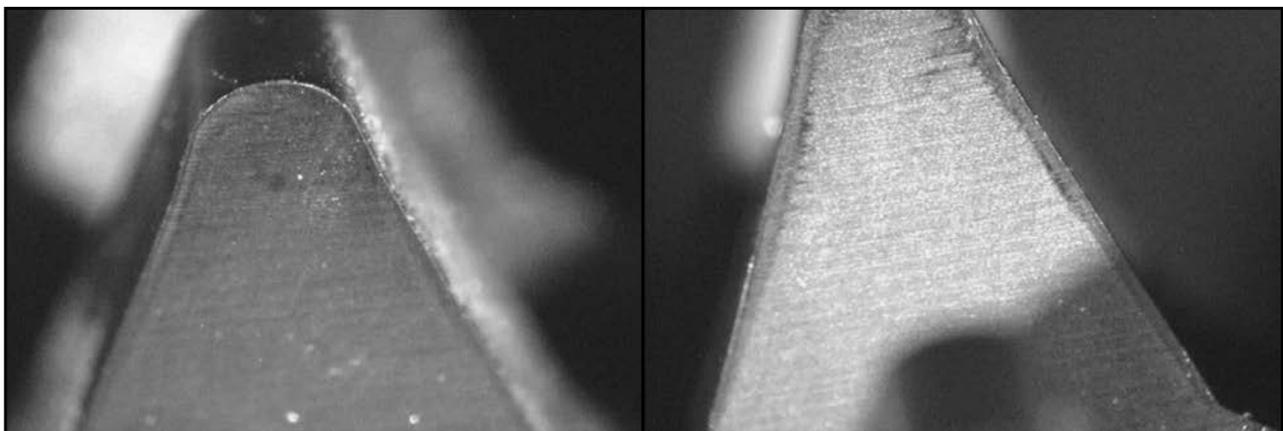


Figure 8 Hob tooth after 300 gears (magnification 30 \times) Ovako 158Q (left); reference material (right).

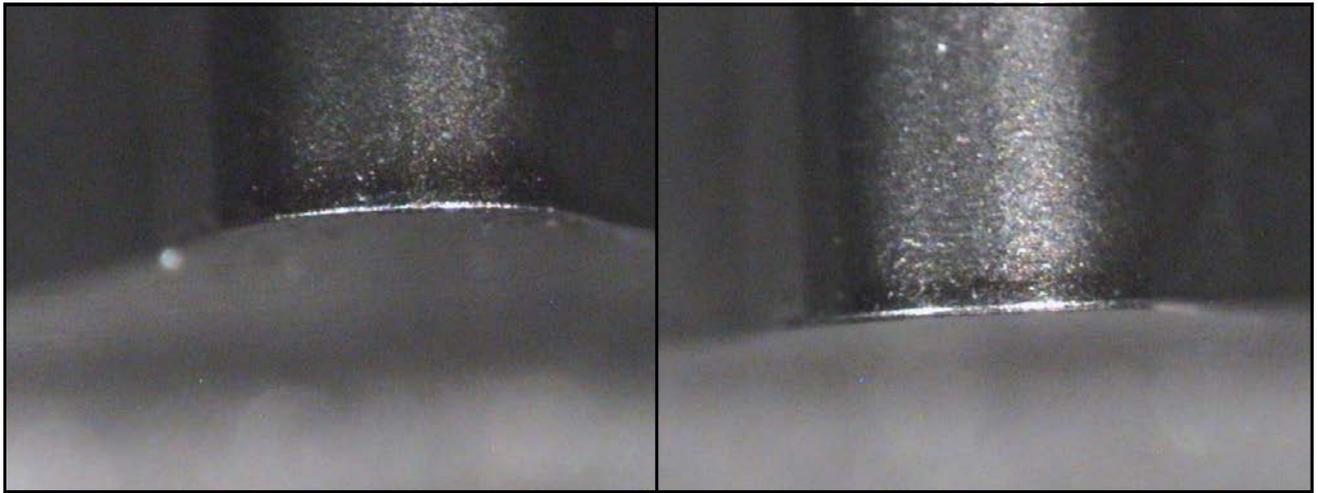


Figure 9 Hob tooth after 300 gears (magnification 63×) Ovako 158Q (left); reference material (right).

Gear Cutting Trials—Hobbing

A PM-HSS hob in S390, coated with Alcrona, was used for the test. The hob was sectioned in three parts with 35 mm effective shift distance for each section, in a dry hobbing process. Cutting speed was 150 m/min, and axial feed was 3.5 mm/rev with maximum chip thickness of 0.2 mm.

An increased hob temperature of 5–10°C was noted for Ovako 158Q, compared to the reference steel. The actual gear temperature for Ovako 158Q was measured to be 3°C warmer. The hob teeth were analyzed in a light optic microscope, but no significant difference in wear could be detected after the same number of parts was hobbled (Figs. 8 and 9).

The equivalent cutting length for each hob tooth was 9 m, which is considered to be very good.

Conclusions

It has been shown that by alloy design alone, the level of internal oxidation resulting from a ten-hour gas carburizing cycle can be reduced to less than 2µm. The steel grade 158Q with a reduced tendency to form internal oxidation shows an increase in fatigue limit of a minimum of 20%, when compared to commonly used conventional steel grades.

Machining trials for clean steel show a very similar behavior to conventional steels, regarding turning and gear cutting in a production set-up.

The results of the machining trials are the first part of two quantitative studies. The second part, which is now underway, will hopefully provide more conclusive

data in this area. So far, optimization of the production processes appears to be the key.

One important factor to take into consideration is of course microstructure. As mentioned for the machining trials, the microstructures of the two tested materials were different: one—more commonly found in the automotive industry—ferritic perlitic structure, and one ferritic with cementite. The fact that microstructure and material cleanliness play an important role in machining processes is supported by studies made by Swerea Kimab, an institute for applied research within the materials field (Refs. 7–8). 

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