Alloying Strategy Boosts Powertrain Performance

Patrik Ölund and Garry Wicks

The development of a new, gas-carburized gear steel, necessitated by a customer-driven specification, has not only increased the power density in an existing gearbox design, but has done so without requiring any significant change to production processes or heat treatment equipment.

Introduction

When a customer specified an increase in the power throughput of an existing gearbox design, they approached European steel maker Ovako AB with a request for a new-generation gear steel. Patrik Ölund, head of research and development at Ovako, and Garry Wicks, Ovako research engineer, demonstrate here how a novel approach to alloying strategy enabled them to increase the fatigue limit of the steel by 20 percent and still meet tough production constraints. Improvements in the surface fatigue strength of atmosphere-carburized steel gears have enabled a manufacturer to increase the power throughput of an existing gearbox design without any significant change to production or heat-treatment processes. Extensive testing of the gears revealed that when the load was increased, individual gear teeth were failing through fatigue fracture. The failure initiation points were in the area of maximum stress at the surface of the gear root (Fig. 1). Material and finishing defects were ruled out as the cause, but it was noticed that the surface of the gear root, which had no post-heat treatment finishing, showed clear evidence of internal oxidation resulting from the gas carburizing process.

Internal Oxidation

The level of internal oxidation of approximately 10 µm was in line with expectations, given the composition of the steel and the heat treatment process. However, it was known that internal oxidation could act as a stress raiser and initiate fatigue failure.

It was also known from published papers (Refs. 1 and 2), that internal oxidation could have a significant impact on the performance of steels tested under rotating bending fatigue conditions. The literature suggested that if the internal oxidation could be reduced to 2 µm, a potential gain of 100 MPa in the fatigue limit could be achieved (Fig. 2). The customer confirmed that if this increase in the fatigue limit could be achieved in the gear steel, the powertrain would be able to handle the increased power transmission levels.

The cause of the oxidation was depletion of the alloying elements near the surface during the carburizing process, which was reducing hardenability and fatigue resistance of the material by preventing a full martensitic transformation.

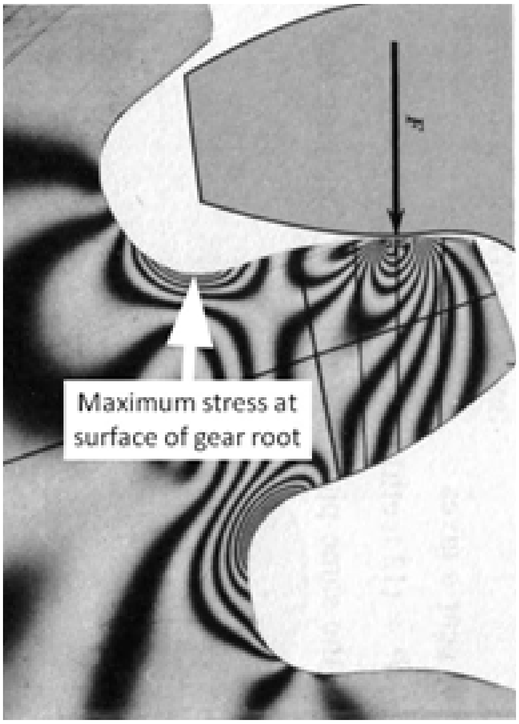

Figure 1 Failure initiation points.

Alloying Strategy

A strategy was developed to reduce the propensity of the alloy to form internal oxidation by lowering the Si content to a minimum, reducing Mn and Cr levels significantly and substituting Mo and Ni. The new alloy had to achieve both a hardenability and carburizing response equivalent to the existing steel grade. It was also decided to minimize the risk of failure from

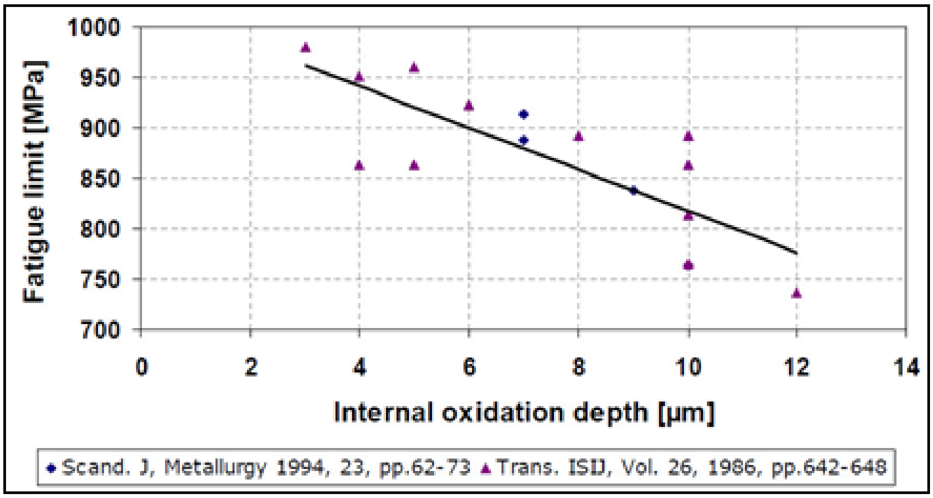

Figure 2 Internal oxidation and fatigue limit: literature indicated a potential gain of 100 MPa in the fatigue limit if the internal oxidation is restricted to 2 µm maximum.

sub-surface initiation by improving the cleanliness of the steel. This involved using the "IQ-Process" — i.e., a method of producing isotropic steels developed by Ovako. In "IQ steels," inclusions are reduced in number and size, producing a cleaner steel with improved structural fatigue properties.

This composition had to match the existing steel for hardenability and carburizing response, so a 50 kg test melt was produced and tested using a Jominy hardenability test. The results (Fig. 4) demonstrated that the new steel — Ovako 158Q — produced a favorable match on hardenability at depths up to 8 mm — i.e., sufficient to justify no further changes.

Response to heat treatment was measured alongside the current steel grade (Ovako 146S), and the widely used carburizing grade, EN 16MnCr5 (Ovako 234K). The chemical composition of the test materials is shown (Fig. 5).

The composition of the new steel was determined by using a predictive model, developed by Ovako, and by using real data collected over many years. The model uses actual heat analysis and measured hardenability values (Jominy) of a wide range of steel grades and chemical compositions; the results led to a nominal composition (Fig. 3).

Heat Treatment

The samples, machined from bar to a final dimension of 14 mm diameter with a length of 120 mm, were treated in a three-zone carburizing furnace for a total cycle time of 10 hours, after which they were directly quenched in oil, washed, and tempered in air at 170°C; the settings are shown (Fig. 6).

Following heat treatment, the hardness profiles of all three materials showed a very similar case depth of

	C	Si	Mn	Cr	Ni	Mo
Current grade - Ovako 146S	0.20	0.10	1.05	1.10	0.90	0.15
Proposed grade - Ovako 158Q	0.19	0.04	0.25	0.35	2.20	0.65

Figure 3 Nominal composition of existing and proposed steel grades (wt. %).

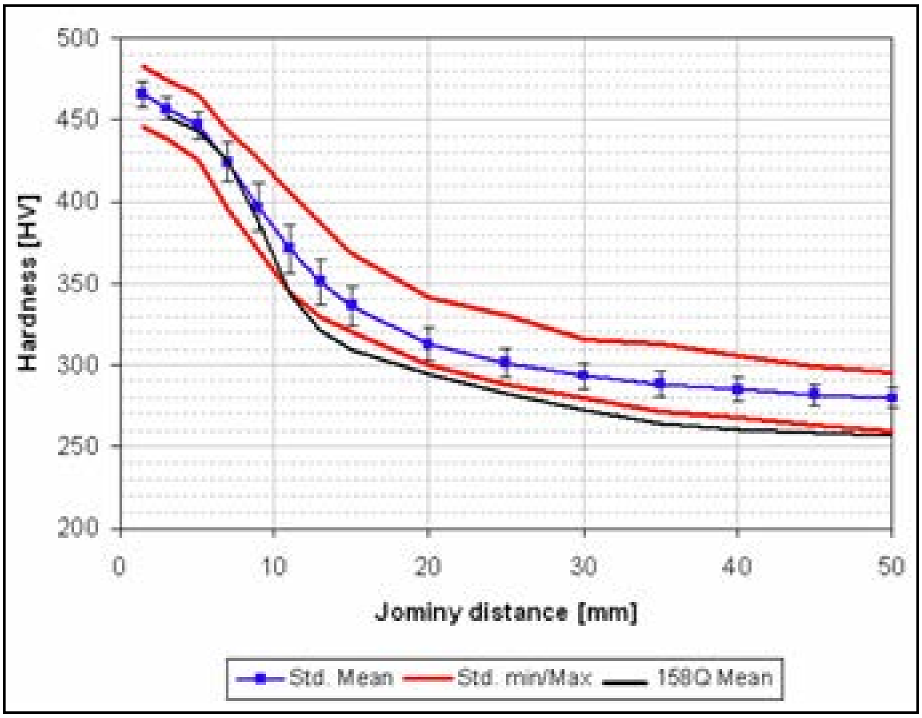

Figure 4 Jominy hardenability: measured hardenability of grade 158Q compared to existing grade.

	C%	Si%	Mn%	Cr%	Ni%	Mo%	
New grade	Ovako 158Q	0.18	0.05	0.25	0.39	2.28	0.69
Current grade	Ovako 146S	0.22	0.09	1.04	1.11	0.84	0.11
16MnCr5	Ovako 234K	0.18	0.24	1.20	1.02	0.13	0.03

Figure 5 Actual chemical composition of test materials (wt. %).

Zone	Temperature (°C)	C-potential (wt%)
1	820	0.95
2	940	0.85
3	860	0.75

Figure 6 Settings for the 3-chamber carburizing furnace.

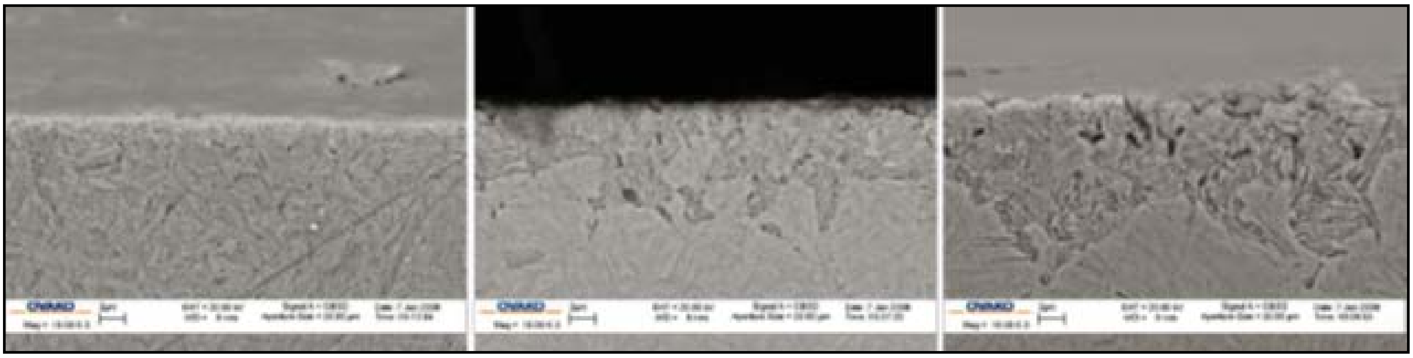

Figure 7 SEM micrographs of the surface microstructure — 2 percent nital-etched.

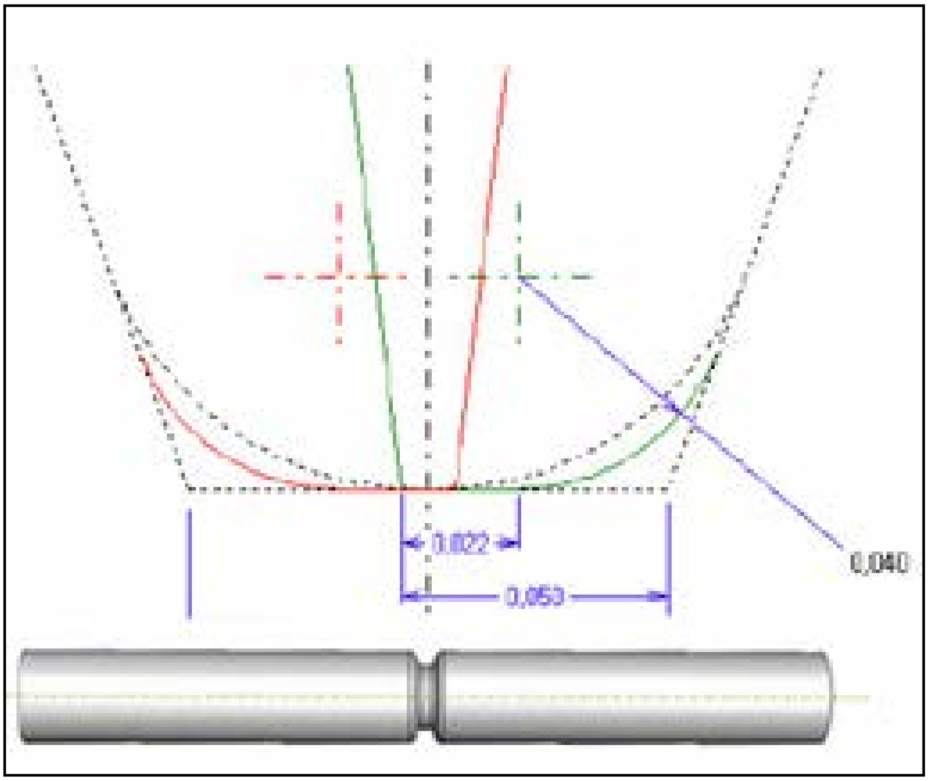

Figure 8 Notched test sample and gear root geometry.

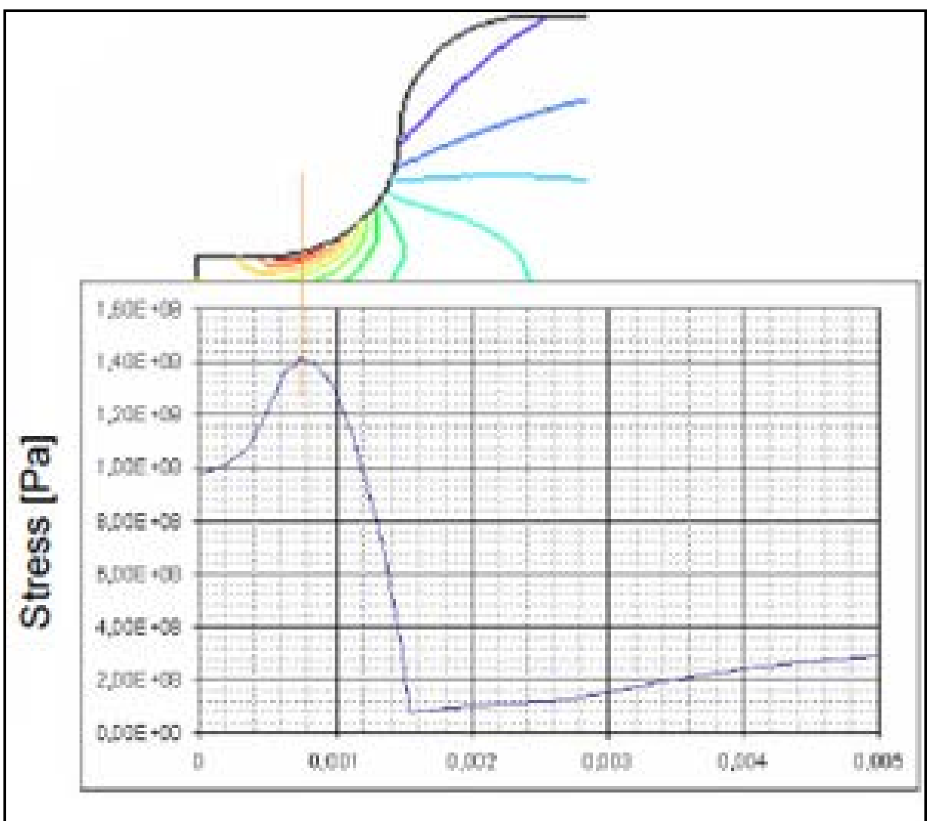

Figure 9 FEM calculation of highest-stressed region.

	158Q	146S	16MnCr5
Fatigue limit [MPa]	985	822	811
Upper 95% confidence limit [MPa]	997	852	829
Lower 95% confidence limit [MPa]	973	792	793
Number of results in evaluation	14	19	13

Figure 10 Results of RBF (radial basis function) testing.

0.60 mm (±) 0.05 mm. But the residual stress profiles showed a compressive residual surface stress for the new steel when compared to tensile stresses in the existing and carburizing-grade steels — indicating the presence of internal oxidation.

This was confirmed by examining the near-surface microstructures in high-resolution FEG-SEM (field emission gun-scanning electron microscopy). The micrographs (Fig. 7) show that the surface layer of non-martensitic material extends to 10 µm in the existing steel, and to 15 µm in the carburizing steel. The new steel, in which the surface residual stresses remained compressive, displayed a microstructure that was fully martensitic, right up to the surface.

Fatigue Testing

Rotating bending fatigue tests were carried out using samples of all three steels on four-point, rotating bending machines running at 3,500 rpm. The stress ratio was fully reversed- loading; i.e., $R = -1$, and the survival criterion was set to 10^7 cycles, or about 50 hours testing per sample. The applied load was changed according to the staircase test strategy.

The notches on the samples had been machined to the same geometry as the root of those gear teeth that had demonstrated fatigue failure. The stress concentration factor (Kt) for this specimen geometry was calculated to be $Kt = 1.7$. FEM calculations were used to determine the likely stress distribution and location of maximum applied stress (Figs. 8 and 9).

Results

The fatigue limit for Ovako 158Q was shown to be significantly higher than either the original Ovako 146S steel used in the powertrain, or the carburizing grade steel — 16MnCr5 (Figs. 10 and 11).

When the internal oxidation of the three samples, to the measured fatigue limits, was compared to the published data that had shown the correlation between the depth of internal oxidation and fatigue limits, the results were a good match (Fig. 12).

This clearly demonstrated that reduction of the internal oxidation depth can significantly impact fatigue limits, as published papers (Refs. 1 and 2) had proposed, and that the depth of internal oxidation resulting from a 10-hour gas carburizing cycle can be significantly reduced by a careful selection of alloys.

The end result was a steel grade with a reduced tendency to form internal oxidation and a fatigue limit 20 percent greater than the steel grade currently being used. **PTE**

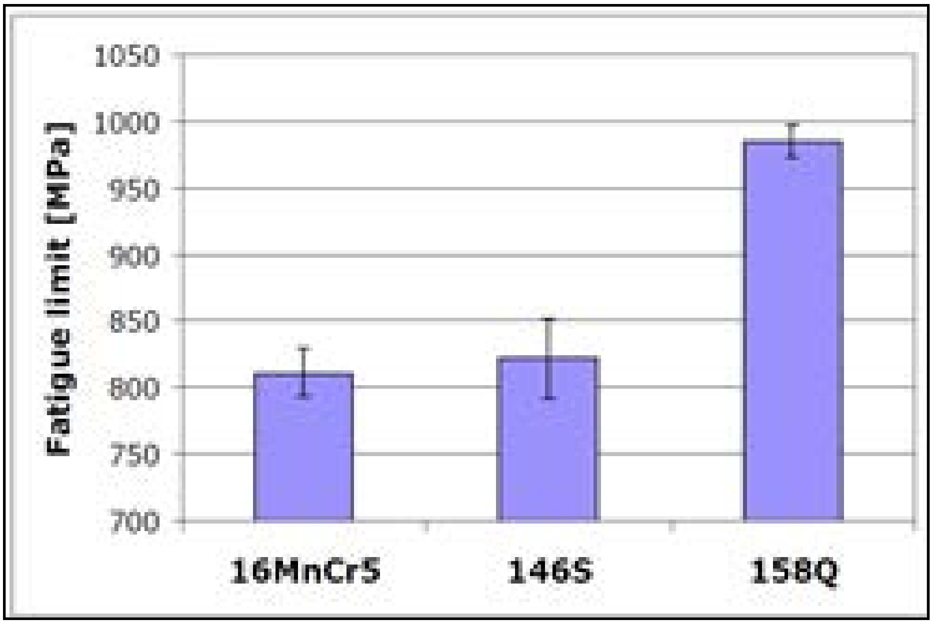

Figure 11 Fatigue limit for notched RBF samples; error bars show 95 percent confidence.

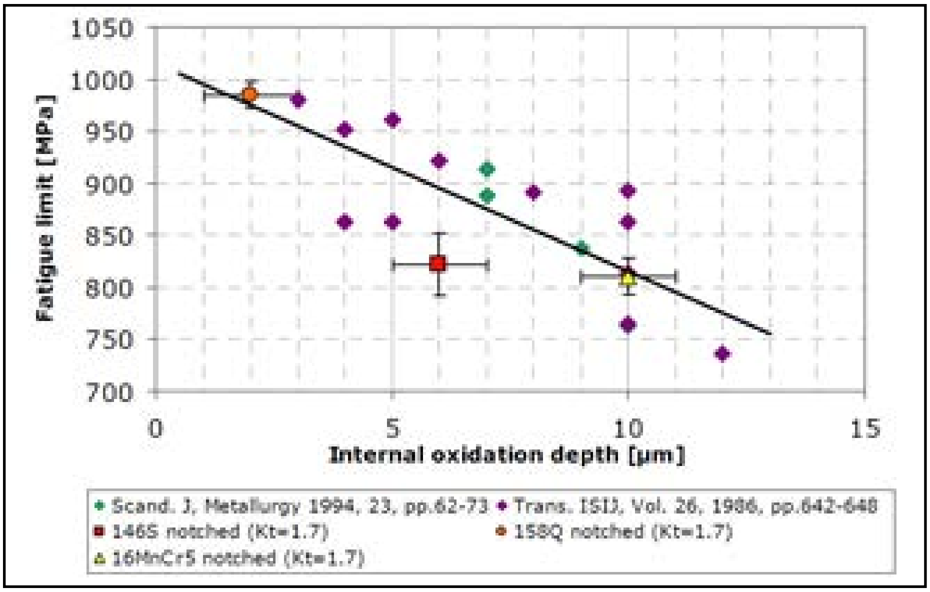

Figure 12 Effect of internal oxidation on the fatigue limit.

References

1. Namiki, N. and K. Isokawa. "Effects of Alloying Elements on the Rotating Bending Fatigue Properties of Carburized Steels," *Transactions of the Iron and Steel Institute of Japan*, Vol. 26, No. 7, 1986, pp. 642–648.
2. Larsson, M. et al. "Fatigue Properties After Carburizing: Influence of Core Hardness and Notch Geometry on Fatigue Properties of Case-Hardened Steels," *Scandinavian Journal of Metallurgy* 94, Vol. 23, pp. 62–73.

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. Most recently, Ölund was this year's winner of the Kami Prize, presented to a distinguished scientist whose research has become the basis of a technical development within the Swedish steel and metal industry.