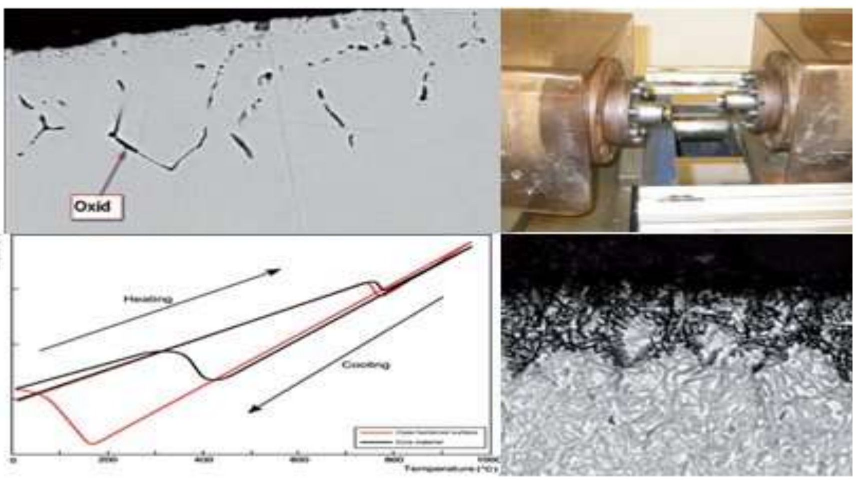
Improved fatigue properties of powertrain components by reduced internal oxidation and interrupted quenching (INTOX-Q)



INTOX-Q

Project within FFI Fordonsutveckling

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Content

1. Executive summary

The aim of the project has been to increase the fatigue resistance, by at least 25%, of carburized transmission components by introducing two methods; (1) interrupted quenching and (2) a modified heat treatment process in order to minimize a negative effect caused by internal oxidation at the surface in connection to atmospheric carburizing. A second aim was to understand the mechanisms of the connection between process improvements and change in fatigue properties.

By this powertrain components can be produced with lower weight, higher torque transmitted by the gear box or higher load capacity of the vehicle as well as prolonged service life. This would result in high performance components facilitating vehicles with lower fuel consumption and increased competiveness for the companies.

Within the project, the two methods were adapted and optimized for case hardening of specimens for rotating bending fatigue tests, and gears to be evaluated by pulsating fatigue testing. Three case hardening steels were included in the study. All heat treatment was carried out in industrial batch furnaces.

The maximum increase in fatigue strength, 16%, was obtained for steel 16MnCr5 by introducing the modified hardening process for minimizing the effect of the internal oxidation and controlled quenching. A rule of thumb is that a 10% increase in fatigue strength corresponds to a doubling of service lifetime. Strength increase 16% should therefore correspond to a triple service lifetime. Reference is the heat treatment process used today and normal quenching in the applied quenching oil.

2. Background

Two methods were used to increase the fatigue strength of hardened components:

- Introduction of interrupted quenching
- A modified carburizing process in order to reduce a negative effect of internal oxidation, generation of HTTP-structure that is obtained in atmospheric carburizing.

Interrupted quenching
Interrupted quenching is performed during hardening and means, in this case, that the cooling sequence is adjusted to be slower during martensitic transformation. The method

has mainly been studied for gas quenching applications. When quenching in gas, the cooling rate at the lower temperatures where martensite transformation occurs, is higher to that of a hardening oil, *Figure 1*. In previous experiments where the cooling rate is slowed down, in the lower temperature regions of the martensite transformation, up to 25% higher fatigue strength at pulsating testing of gears in steel 16MnCr5 has been achieved [2-4]. The proposed mechanisms for the increase in strength are increased amount of retained austenite and its stabilization combined with slightly higher residual compressive stresses. During crack propagation retained austenite is transformed into martensite, which provides compressive stress around the crack tip and prevents its growth. Reduced occurrence of micro-cracks at the grain boundaries has also been discussed.

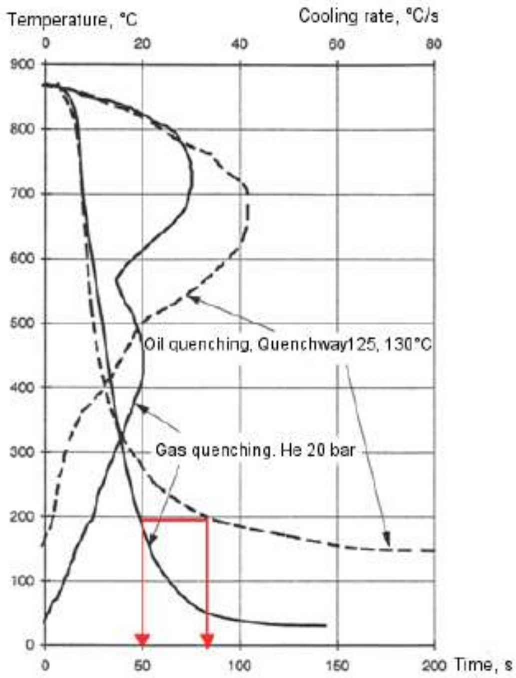

Figure 1 Cooling curves, measured with a steel probe, for quenching in gas, helium 10 bar, and a hardening oil. [1]

Reducing a negative effect caused by internal oxidation

At atmospheric carburizing, alloying element with a high affinity for oxygen such as Mn, Si and Cr, oxidize and form oxides in the grain boundaries, so-called internal oxidation, *Figure 2*. The forming of oxides leads to a depletion of alloying elements near the surface, that in turn causes a reduction in hardenability that may cause consequent transformation of the outer surface layer to ferrite, bainite and pearlite, called HTTP structure (High Temperature Transformation Products). Most likely both the oxides and the HTTP structure have a negative effect on the fatigue strength. Which one that has the greatest impact is not known and is most likely depending on the application. Oxide arms can act as initiation for cracking and HTTP structure has a lower strength than a

martensitic structure. The formation of HTTP structure occurs before martensite transformation resulting in very low compressive stress or even tensile stresses in the HTTP layer.
By introducing a modified casehardening process it is possible to increase the hardenability of the HTTP area [5].

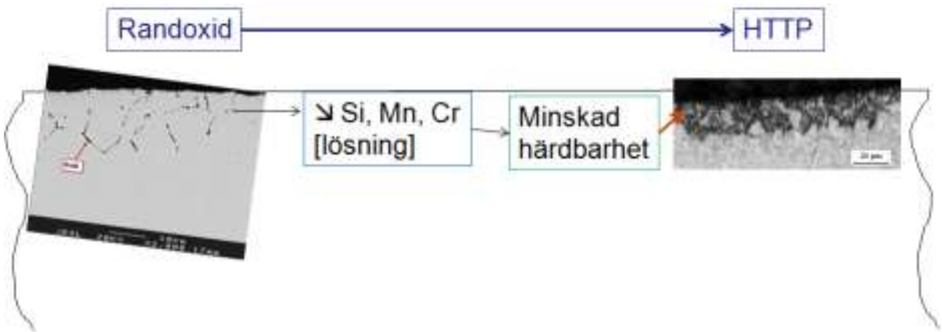

Figure 2 Formation of oxides and HTTP-structure at the surface of a steel during internal oxidation.

3. Objective

The aim of the project is to demonstrate the possibility to increase the fatigue strength of hardened components by introduction of two methods that can be implemented in atmospheric carburizing processes. In the application it was stated a goal of achieving at least 25% higher fatigue strength of case hardened transmission components through:

- Interrupted quenching
- Control of internal oxidation (by minimizing a negative effect caused by this)

The following questions were adressed:

- Theoretical
  - The mechanisms for increased fatigue strength
  - Correlation internal oxidation - HTTP – retained austenite
  - Calculations to determine when the interruption of the cooling is to take place, ie when the surface temperature has reached the temperature at which approximately 50% martensite is formed
- Practical
  - Implementation
  - Set and parameters for the oil quenching
  - Impact on the various positions in the load
  - Temperature uniformity - process window

4. Project realization

Interrupted quenching and the modified heat treatment process to control/suppress a negative effect of internal oxidation, i.e. the formation of HTTP structure, was performed on specimens and gears in steel 16MnCr5, V2158 and Ovako 158Q, *Table 1*. V2158 and 16MnCr5 are more traditional case hardening steels and 158Q is an Ovako steel designed to give no internal oxidation and thus no HTTP structure.

Table 1 Chemical composition of investigated steels.

Stål	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Cu
16MnCr5	0,19	0,27	1,2	0,014	0,035	1,17	0,19	0,06	0,008	0,020	0,14
V2158 ~20MnCrS5	0,19	0,21	1,3	0,013	0,033	1,26	0,18	0,04	0,005	0,022	0,20
Ovako 158Q ~20NiMo10	0,20	0,03	0,23	0,007	0,002	0,37	2,18	0,67	0,003	0,027	0,126

Rotating-bending tests were performed on specimens in steel 16MnCr5 and Ovako 158Q. Pulsating testing was performed on gears steel in Ovako V2158 and 158Q. The result is not included in this report, and is only available for the project participants.

Several experiments and calculations were made to optimize and adapt the methods for the steels and available equipment.

Interrupted quenching

Prior experiments with interrupted quenching the practical conditions concerning cooling characteristics of the available hardening oils were examined. Figure 3 shows the cooling curves for the hardening oil used in the final experiments.

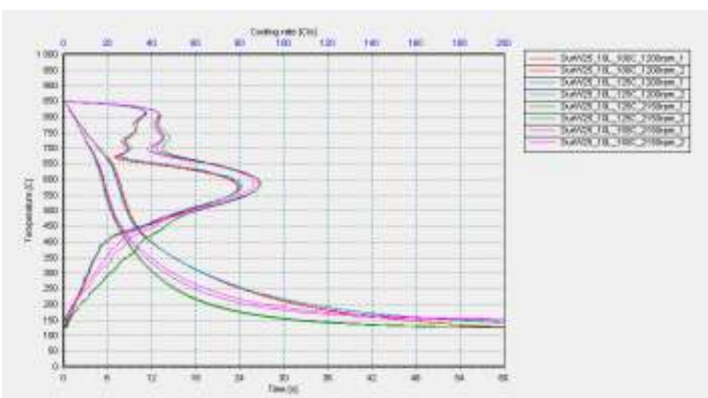

Figure 3 Cooling curves, according to ISO 9950, for hardening oil Durixol W25 at 100, 125 and 150 °C at two different agitation speeds.

The steels were evaluated by dilatometer testing for different cooling sequences with holding times at different temperatures in order to slow down the cooling rate; above Ms, at 30% martensite formed and at 60% martensite formed. Figure 4 shows dilatometer results of interrupted quenching at about 30% martensite for carburizing steel 16MnCr5.

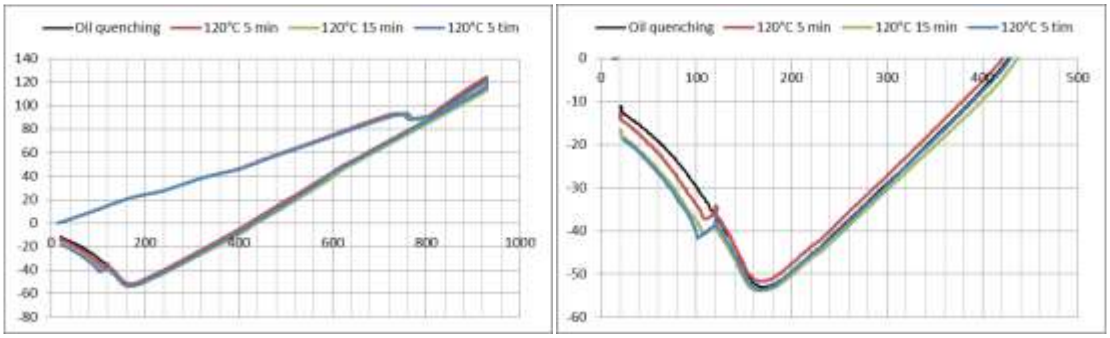

Figure 4 Dilatometer result for carburized steel 16MnCr5 with interrupted quenching at about 30% martensite.

Most analyzes were made for carburized steel, but also not carburized steel was evaluated. The studied steels, which were carburized at a carbon potential of 0.75% C, shown different temperatures for the start of martensite transformation, Ms, according to the dilatometer result;

- 16MnCr5: Ms 160 °C
- V2158: Ms 150 °C
- Ovako 158Q: Ms 210 °C

The above can be interpreted as that the effect of the interrupted quenching may be different for the different steels, i.e. for the same cooling sequence the martensite transformation takes place different. In particular Ms for Ovako 158Q deviates from the other.

The interrupted quenching was performed by lifting the charge from the cooling bath after various times as well as varying the oil temperature. A number of tests were made to evaluate different parameters in order to achieve the interrupted quenching: time in the bath and oil temperature was varied. From these, two variants for the heat treatment of bars and gears were selected. The reference was hardening in Durixol W25 at 100 °C and full-time in the bath.

Control of effects of internal oxidation

In the project a modified case hardening process was used to reduce the amount of HTTP structure. This minimizes the unwanted HTTP structure, but the oxides are still present. The process can be used for steel 16MnCr5 and V2158. Steel Ovako 158Q have been developed in order to provide no internal oxidation. However, the modified process was carried out even for this steel to verify that the modified process had no effect.

Various parameters for how the modified process would be carried out were examined. A final process was selected and used for all the heat treatments of the specimens for fatigue testing.

Experiments

All experiments were performed in industrial batch furnaces at Bodycote and GKN Driveline. The pre-tests were made at Bodycote and GKN. Heat treatments of test pieces and gears for fatigue testing were made at GKN.

Rotating bending fatigue testing were conducted on specimens in steel 16MnCr5 and 158Q heat treated with or without the modified process and with or without interrupted quenching, *Table 2*.

Table 2 Heat treatment of samples for rotating bending fatigue.

	16MnCr5		158Q	
	Normal carburizing	Modified process	Normal carburizing	Modified process
Normal quenching				
Interrupted quenching 1				
Interrupted quenching 2				

5. Results and deliverables

5.1 Project results

Table 3 shows the results of rotating bending fatigue of specimens in steel 16MnCr5 and 158Q heat treated with or without the modified process and with or without the two variants of interrupted quenching. *Table 4* shows the retained austenite and residual stresses in the surface.

Table 3 Fatigue strength and the change compared with reference process at rotating-bending test.

	16MnCr5		158Q	
	Normal carburizing	Modified process	Normal carburizing	Modified process
Normal quenching	768 MPa	846 MPa = +10%	839 MPa	800 MPa = -5%
Interrupted quenching 1		889 MPa = +16%	783 MPa = -7%	
Interrupted quenching 2			825 MPa = -2%	

Table 4 Retained austenite, RA, and residual stresses, RS, in the surface of the specimens in Table 2.

	16MnCr5		158Q	
	Normal carburizing	Modified process	Normal carburizing	Modified process
Normal quenching	RA 5-20% RS -50 MPa	RA 20% RS -200 MPa	RA 15% RS -150 - -250 MPa	RA 20-25% RS -150- -250 MPa
Interrupted quenching 1		RA 35-45% RS -100 - -200 MPa	RA 20% RS -150 MPa	
Interrupted quenching 2			RA 20 % RS -200- -250 MPa	

By minimizing the effect of internal oxidation, thus increasing hardenability in the HTTP structure, and interrupted quenching *steel 16MnCr5* showed an increase in fatigue strength. The fatigue strength was increased by 10% by introduction of the modified process. In this case, oxides are still present, which most likely have a negative effect on the strength. When interrupted quenching was also applied the strength increase was 16% compared to the reference. The main reason why the increase did not reach the target of 25% is that the reference was quenched in hardening oil, which means that the cooling rate around Ms is slower than for “direct” gas quenching. The target of 25% in the project proposal was based on experiences done with gas quenching, where the reference was direct quenching with a high cooling rate through the temperature range where the martensitic transformation takes place. It is also likely that the cooling sequence could have been further optimized, for example slowed down earlier, but this was limited for practical reasons.

The modified process had no influence on the fatigue properties for steel 158Q.This was also not expected since this steel does not provide internal oxidation. However, interrupted quenching gave no increase in the fatigue properties either. One explanation for this could be the higher Ms temperature for steel 158Q which means that the interrupted quenching has no effect since the temperature-equalization was too late for this steel. This shows the importance that the interrupted quenching is adjusted for the relevant steel grade. The retained austenite content was relatively similar for all variants of 158Q indicating that the interrupted quenching had no effect. One explanation that the strength even became worse, especially for interrupted quenching variant 1, is that the compressive stresses were lower in this case compared to the reference.

A result is a practically implementable process. Both the modified process and interrupted quenching has been applied in batch furnaces at Bodycote and GKN. For steel 16MnCr5 and V2158, the current process parameters can be used as they are, but for steel Ovako 158Q further optimization of interrupted quenching parameters are required.

It may be noted that steel Ovako158Q, which does not provide internal oxidation, gives 10% higher fatigue strength compared to 16MnCr5 for reference runs. By further optimization of the interrupted quenching it should be possible to further increase the strength of Ovako 158Q.

Within the project AGA presented solutions for how the modified process also can be applied in a pusher furnace.

5.2 Delivery to FFI-goals

The project has addressed the following goals of the program:

Goal	Contribution of INTOX-Q
Materials technology for more efficient vehicles	Enabling components with lower weight and longer lifetime through increased strength. An increased strength can also be used for increased torque, with the same space requirements and weight of the structure. A rule of thumb is that a 10% increase in fatigue strength corresponds to a doubling of service lifetime. Strength increase 16%, which was achieved in this project, should therefore correspond to a triple service lifetime. Reference is the heat treatment process used today and normal quenching in the applied quenching oil.
Methods and tools for vehicle	Increasing competitiveness when components

development	with increased performance and strength can be manufactured without requiring redesign of the components and the surrounding space. Time and cost saving.
Substantial (measurable) weight reduction	Can be obtained at implementation by the companies thanks to 16% higher strength
Substantial cost reduction	See above regarding reduced need for redesign. The techniques should not result in significantly higher costs, depending on the day's production, but some adaptation and quality assurance are required.
Considerably improved material properties	16% higher strength was obtained. The project also showed that Ovako 158Q gives 10% higher fatigue strength compared to 16MnCr5 for the reference heat-treatment process.
Ensuring that the Swedish automotive industry contributes to and have access to methods, tools and world-class expertise to enable rapid and efficient development.	The two methods are not used industrially today, but can be implemented at relatively low cost.
"Implement industrially relevant development measures" and "work to ensure that new knowledge be developed and implemented, and that existing knowledge is implemented in industrial applications"	Both interrupted quenching and the modified carburizing process can be implemented industrially.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Conferences and seminars where INTOX-Q has been presented:

- 4th Bodycote/AGA Heat Treatment Seminar, 30-31 maj 2012. Interrupted quenching for improved fatigue performance. Sven Haglund, Swerea KIMAB
- FFI Katrinehholm:
  - 2012:
    - Avbruten kylning. Sven Haglund, Swerea KIMAB
    - Inverkan av randoxidation på kontaktutmattning/böjutmattning. Jérôme Senaneuch, Swerea KIMAB
  - 2015
    - Inverkan av randoxidation och kylning på utmattningshållfastheten hos sätthärdade komponenter, Sven Haglund, Swerea IVF
- VBCs medlemsmöten 28-29 jan 2015, 29-30 jan 2014 och 30-31 jan 2013
- Impact of Internal Oxidation and Quenching Path on Fatigue of Powertrain Components. Stormvinter, A et al. ASM Heat Treat Society Conference & Exposition, 20-22 oktober 2015. Detroit, USA.
- Förbättrad sätthärdningsprocess för högre utmattningshållfasthet. Senaneuch, J; Haglund, S. Aktuellt om material- och värmebehandlingsteknik. SHTE. 22-23 september 2015. Västerås

6.2 Publications

- Conf. proceedings: Impact of Internal Oxidation and Quenching Path on Fatigue of Powertrain Components. Stormvinter, A et al. ASM Heat Treat Society Conference & Exposition, 20-22 oktober 2015. Detroit, USA.
- Improved fatigue properties of powertrain components by reduced internal oxidation and interrupted quenching – INTOX-Q. Sven Haglund and Jérôme Senaneuch, Swerea KIMAB; Albin Stormvinter and Eva Troell, Swerea IVF; Anders Åström, AGA Gas; Kim Wallin, GKN Driveline. VBC-report 2015

7. Conclusions and future research

Interrupted quenching can be implemented both in atmospheric and low-pressure processes. The project demonstrated that the technology allows a substantial increase in the fatigue strength. However, adaptation to different steel grades depending on Ms temperature is necessary to achieve maximum effect and maximum productivity. Calculations are a useful tool for this and it would also require further testing in practice to evaluate the possibility of, for example, other quenching oils, salt baths and gas quenching.

It still remains to be determined the mechanism for increased fatigue strength with interrupted quenching. Retained austenite and its stability is an interesting hypothesis. Further research is needed regarding interrupted quenching and impact on different steel grades. General studies of the effect of retained austenite and its stability on strength is of interest.

8. Participating parties and contact person

Company	Contact
Volvo GTO	Alexander Drott
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GKN Drivline Köping	Kim Wallin
Bodycote Heat Treatment	Annika Martinsson, Solmaz Sevim
Ovako Steel	Kristofer Eriksson
AGA Gas	Anders Åström
Scania	Therese Källgren, Ninos Hawsho
Swerea IVF	Eva Troell, Albin Stormvinter
Swerea KIMAB	Sven Haglund, Jérôme Senaneuch
KTH, ITM	John Ågren, Henrik Larsson