Effects of manufacturing chain on mechanical performance

Study on heat treatment of powertrain components

JOHAN FAHLKRANS
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Abstract

The increasing demands for lightweight designs with high strength call for improved manufacturing processes regarding heat treatment of steel. The manufacturing process has considerable potential to improve the mechanical performance and to obtain more reliable results with less variation.

The goal of this thesis is to establish new knowledge regarding improved manufacturing processes in industrial heat treatment applications. Three research questions with associated hypotheses are formulated. Process experiments, evaluation of the mechanical performance, and modelling of the fatigue behaviour assist in answering the questions.

The gas quenching procedure following low-pressure carburising differs from the conventional procedure of gas carburising and oil quenching. It is shown that the introduction of a holding time during the low-temperature part of the quench has a positive effect on mechanical properties, with some 20 percent increase in fatigue strength. This is attributed to increased compressive surface residual stress and stabilisation of austenite.

Tempering is a common manufacturing process step following hardening in order to increase the toughness of the steel. However, the research shows that the higher hardness from eliminating tempering from the manufacturing process is beneficial for contact fatigue resistance. The untempered steel showed not only less contact fatigue damage but also a different contact fatigue mechanism.

Straightening of elongated components is made after heat treatment in order to compensate for distortions. The research shows that straightening of induction hardened shafts may lead to lowering of the fatigue strength of up to 20 percent. A fracture mechanics based model is developed to estimate the effects of straightening on fatigue strength.

Keywords
Heat treatment, case hardening, carburising, induction hardening, gas quenching, tempering, straightening, fatigue strength, contact fatigue, fracture mechanics
Sammanfattning

Ökande krav på höghållfasta lättviktskonstruktioner kräver förbättrade tillverkningsprocesser för värmbehandling av stål. Det finns stor potential att förbättra mekanisk prestanda och att erhålla mer tillförlitliga resultat med mindre variation genom att förbättra tillverkningsprocessen.

Målet med denna avhandling är att etablera ny kunskap kring tillverkningsprocesser inom industriella värmbehandlingsapplikationer. Tre forskningsfrågor med tillhörande hypoteser formuleras. Processexperiment, utvärdering av mekanisk hållfasthet och modellering av utmattningsbeteende bygger upp besvarandet av frågorna.

Gaskylning som följer lågtrycksuppkolning skiljer sig från det konventionella förfarandet med gasuppkolning och släckning i olja. Resultaten visar att en hålltid i den nedre delen av kylningsförloppet har positiv inverkan på utmattningshållfastheten. Orsaken till förbättringen hänförs till ökade tryckrestspännningar samt stabilisering av austenit.

Anlöpning är en vanlig tillverkningsprocess som efterföljer härdning för att öka stålets seghet. Forskningen visar däremot att den högre hårdheten för oanlöpt stål är fördelaktig för motstånd mot kontaktutmattningshållfasthet. Oanlöpt stål visade mindre mängd kontaktutmattningsskador och även en annan skademekanism.

Riktning av långa komponenter görs efter värmbehandling för att kompensa för de formförändringar som uppstår. Forskningen visar att riktning av induktionshärdade axlar kan leda till sänkning av utmattningshållfastheten med upp till 20 procent. En brottmekanisk modell som uppskattar effekten av riktning på utmattningshållfasthet presenteras.
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Finally, Anna, Stella, and Vilhelm,

I love you

Stockholm, March, 2015

Johan Fahlkrans
List of appended papers

Paper I
Gas quench rate after low pressure carburizing and its influence on fatigue properties of gears / Einfluss der Abschreckgeschwindigkeit nach Niederdruckaufkohlung auf die Schwingfestigkeit von Zahnrädern.

J. Fahlkrans, A. Melander, S. Haglund.

Published in

Paper II
Influence of tempering on contact fatigue.


Published in

This paper is a revised and expanded version of a paper presented and included in proceedings at conference New Challenges in Heat Treatment and Surface Engineering, Cavtat, Croatia, 9–12 June 2009.

Paper III

J. Fahlkrans, A. Melander, J. Gårdstam, S. Haglund.

Published in
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1 Introduction

Steel is the most widely used engineering material and will probably remain so for the foreseeable future. The benefits of steel in comparison to other materials are for example low production costs, the sustainable and environmentally adapted use with a high degree of recycling, and further its performance per cost and weight unit regarding strength and toughness.

Heat treatment of steel components within the manufacturing industry is an important manufacturing step. Heat treatments are performed in a late stage of the manufacturing process. The value of the input component is high, and the heat treatment process adds high value given the process’ increase in specific strength.

It is estimated that roughly half of the heat treatment made in Sweden and Germany is carried out in the manufacturing industry on machine components and other parts. Examples of heat treating processes in the manufacturing industry are case hardening, induction hardening, or nitriding processes. The other half is carried out on semi-finished components by the steel manufacturers. Annealing is the most common form of heat treatment of semi-finished products such as tube, wire, flat-rolled steel, bar, and plate. This form of heat treatment is not considered in this thesis [1].

The financial value of heat treatment in the manufacturing industry is difficult to estimate. The only official statistics available concern sales within the sub-contract heat treatment sector in some countries. The total refinement value of all the heat treatment in Europe (excluding steel manufacturer’s heat treatment) for 2010 was roughly estimated to 40-50 billion euro. The same figure for Sweden was about 2.5 billion euro [1]. Further, it is estimated that the automotive industry, including its sub-suppliers, accounts for about 60% of the heat treatment of the
manufacturing industry, and that about 5% of the manufacturing cost of a car is for heat treatment [2]. The automotive industry accounts for more than 10% of Swedish export [3].

The mechanical properties of a steel component are to a large extent dependent on the heat treatment process applied. There is no doubt that many components would have a much shorter service life than they have today if they were not hardened, case hardened, nitrided or heat treated in any other way. Some would not even serve their purpose at all. Without efficient heat treatment processes, many components would be much heavier since hardening increases the specific strength of the steel. This is the reason why about 50% of a car’s total weight consists of heat treated steel [1]. Examples of components heat treated within the automotive industry are crankshafts, camshafts, gear wheels and other transmission components, axles, and shafts.

1.1 Research motivation

The demands on lightweight designs with high strength are constantly increasing within the automotive industry. Increased performance, for example in a powertrain component of a truck, can be utilised to increase the product performance such as engine power or to reduce weight.

The production process can be modified for a number of reasons. Increased knowledge of the relationship between the production process, the material, and the mechanical performance of the finished component are essential in reaching goals regarding optimum properties and minimum processing cost. Reduced variations in mechanical performance allow for improved design of components; design criteria must most often consider the weakest component of the production batch. The relationship between the production process, the material, and the design of the component is schematically shown in Figure 1.1.
The focus of this thesis is to modify the process in order to obtain increased mechanical performance. The present research comprises three different process steps within the manufacturing chain of heat treatment of steels, the steps being:

- Cooling after low-pressure carburising
- Tempering and its effect on fatigue resistance
- Straightening after hardening

The process improvements of each of the steps all aim at improving the quality and possibly also at lowering the cost of the component. Common denominators are the aim of increasing the fatigue strength of the component and reducing the variations in mechanical properties.

Low-pressure carburising with subsequent gas quenching is a relatively new process compared to conventional gas carburising with oil quenching. The process offers many advantages such as part cleanliness after the process, the absence of internal oxidation on the surface, reduced distortions, and shorter process times. Early studies of low-pressure carburised and gas quenched components showed reduced fatigue strength compared to conventional gas carburising and oil quenching [4], [5]. There have been indications that the gas quenching process can be optimised to obtain higher fatigue strength [6]. Thus, the
motivation for the present research is to obtain a gas quenching process that delivers similar or increased mechanical performance compared to ‘standard’ gas quenching and also compared to conventional oil quenching (after gas carburising).

Tempering is a part of the heat treatment process that is nearly always performed. One part of the thesis explores the possibility to eliminate this process step for selected applications. Eliminating tempering reduces processing time, manual handling of components, energy consumption, and there is no need for investing in tempering furnaces. This procedure could also be beneficial in terms of performance for components subjected to contact fatigue loadings. Thus, the motivation for this research is to establish during which conditions eliminated tempering is beneficial.

The heat treatment process results in distortions. For this reason, straightening after heat treatment is often necessary for elongated components. However, the effect of straightening on the mechanical performance is not known. Straightening comprises localised stresses higher than the yield strength. For this reason, it can be argued that the straightening might reduce for example fatigue strength. Thus, the motivation is to establish the effects of straightening on the mechanical performance of shafts.

The motivation for the thesis is to, related to the processes presented above, describe and model the mechanisms affecting the mechanical performance. Further, the process’ influence on these mechanisms and ways to improve the processes are presented. This is achieved experimentally by process experiments and fatigue testing, by evaluation of the related physical phenomena, e.g. residual stresses and fracture surfaces, and by modelling the fatigue behaviour.

1.2 Research questions and hypotheses

Three questions are investigated within the frame of this research work. For each question, a hypothesis is formulated.

The first question concerns the process of low-pressure case carburising followed by gas quenching. The process has many apparent benefits
compared to traditional processes. However, it has been observed that the process characteristics have considerable influence on the mechanical performance of components, with lower fatigue strength than from conventional case hardening. For this reason, the first basic question to be answered in this work is formulated as:

**RQ1** Can the performance, measured as fatigue strength, of gear wheels be improved by optimisation of the gas cooling sequence?

The hypothesis of this question is related to the rate of gas quenching compared to oil quench rates. Gas quenching is faster than oil quenching in lower temperatures, below 400°C, which affects the for example temperature homogeneity of the quenched part, and in turn possibly also the relationship between martensite formation in the centre and the surfaced. Thus, the hypothesis is:

**H1** The introduction of a holding time during the gas quenching sequence, in the correct temperature range, and with the appropriate duration, increases the fatigue strength of the component.

The second question is related to contact fatigue resistance. Contact fatigue is a common failure mode in applications with high contact pressure and rolling or sliding surfaces. Tempering after carburising case hardening is commonly made within the industry, in order to increase the toughness of the steel. The additional process step involves costs in terms of process time, handling, equipment and energy, and may not always be beneficial for performance. The question is formulated as:

**RQ2** Is it beneficial from a rolling contact fatigue point of view to omit the tempering process after case hardening?

Untempered steel has higher hardness than after tempering. However, tempering increases the toughness of the steel, and it is often stated that untempered steels are too brittle to be used in components. Contact fatigue applications, however, could benefit more from the increased hardness than the negative effect of reduced brittleness. The hypothesis of the research question is:
The higher hardness of the untempered steel results in larger resistance to contact fatigue.

The third question regards post processing of heat treated components. Straightening is a common action to compensate for distortions that occur during heat treatment. Deformation above the yield stress is necessary to achieve the straightening effect. Cracking of the component must not occur, and there are detection systems available for that purpose. However, the effect of the mechanical performance of a straightening operation that is considered successful is not known, which leads to the third question:

RQ3 Does straightening after surface hardening have any negative effects on the performance, the fatigue strength, of elongated components?

The hypothesis to this question is related to the residual stress state before and after the straightening operation. During the loading operation, tensile stresses are created in some parts of the cross section and compressive in other areas. For a case hardened component, even with simple geometry such as a shaft, the resulting residual stress state after straightening is not intuitive. Simplified two-dimensional models cannot describe the stress state after straightening. The maximum reduction of compressive residual stress can occur in other parts of the cross section than the part of highest tensile load during straightening. The third hypothesis is:

H3 The residual stress state in the entire cross section of the component is critical to its performance.

1.3 Research framework

To be able to answer the research questions, a research framework has been established. The theoretical background for the framework is obtained from research made in several fields, ranging from manufacturing technology, metallography, fatigue, modelling, and statistics. Scientific papers, journals and books have been studied to create the theoretical base of the thesis. The results were based on experimental work combined with modelling of the fatigue behaviour.
1.4 Outline of the thesis

Following this introductory chapter, a chapter on material states follows, including theoretical aspects on the influence of the material in the production process and the effects on component performance. A presentation of the manufacturing chain related to heat treatment processes is made in chapter 3. The chapter includes theoretical phenomena behind the included processes and short information regarding their influence on mechanical properties. Chapter 4 summarises the results of the appended papers. At last, the thesis includes conclusions of the results and suggestions for future research in chapter 5.

1.5 Introduction to the papers

Appended to this thesis are three papers from peer-reviewed journals. The papers treat the subject of process optimisation of different steps of the manufacturing chain and include the results of the thesis.

Each of the papers is briefly introduced below with a description on how they answer the research questions introduced earlier. The author’s contribution to each paper is also presented.

1.5.1 Paper I: Gas quench rate after low pressure carburizing and its influence on fatigue properties of gears

The cooling process after low-pressure carburising was studied in a systematic approach. The influence of different cooling procedures on the mechanical performance was evaluated experimentally, with the help of a design of experiments test matrix set up. The physical mechanisms behind the results were discussed, which intended to answer research question 1.

The author’s contribution to the paper was design of experiments, set up and analysis of heat treatments, dilatometer testing, fatigue testing, fractography, analysis of the results, and writing of the paper.
1.5.2 **Paper II: Influence of tempering on contact fatigue**
The second paper investigated component performance for untempered test rings. Omitting tempering in manufacturing can in some cases offer increased mechanical performance. The correlation between the amount of damage in fatigue testing and surface hardness was discussed, answering to research question 2.

The author’s contribution to the paper was design of experiments, evaluation of fatigue testing, fractography, analysis of the results, and writing of the paper.

1.5.3 **Paper III: Straightening of induction hardened shafts – influence on fatigue strength and residual stress**
The paper used a simplified FEM model to illustrate the influence of straightening to residual stresses. The results were used to set up the experimental tests. A physical model for the fatigue strength based on the change in residual stress invoked by the straightening operation was set up. This model assisted in answering research question 3.

The author’s contribution to the paper was analysis of results from FEM modelling, design of experiments, evaluation of fatigue testing, fractography, analysis of the results, set up of physical model for fatigue strength, and writing of the paper. The FEM model was made by Johannes Gårdstam.
2 Material states and component performance

Materials in general, and steels in particular, undergo many different states during the production process chain. Depending on the position in the production process or properties related to the component in use, different states are desired. In general, the different states can be divided into two groups: 1) states during manufacture and 2) states in the end product.

The state of the material is to a great extent depending on the manufacturing process performed last. Further, the state is also dependent on the material itself. The design process is thus important in order to select materials that are suitable not only for the component in service conditions, but also suitable for the production process.

![Diagram](image)

Figure 2.1 Material state depending on design and process.

2.1 Material states in the manufacturing process

Steels are defined primarily by chemical composition. For structural and heat treatable steels, carbon is an essential alloying element; thus steel may be defined as an alloy of iron and small amounts of carbon and other elements [7].
Steel can be processed to produce a great variety of microstructures and properties. The microstructure is an important state of the steel. The microstructure consists of one or many phases. A phase is defined by a certain arrangement of the atoms.

Pure iron can occur in two phases depending on temperature: ferrite that has a body-centred cubic (BCC) crystal structure, and austenite with a face centred cubic (FCC) crystal structure. Steel may have other phases, and several phases can exist at the same time. Examples of phases are ferrite, austenite, and martensite. Examples of microstructures are pearlite (ferrite and cementite) or bainite [8].

The iron-carbon equilibrium phase diagram is the foundation on which all heat treatment of steel is based. This diagram defines the temperature-composition regions where the various phases in steel are stable, as well as the equilibrium boundaries between phase fields. However, the iron-carbon diagram is limited to equilibrium phases. Some heat treatments, such as the martensite formation, produce non-equilibrium structures [9].

Desired states of steels are often accomplished by heating in temperature ranges where a phase or a combination of phases is stable, followed by cooling (or heating) between temperature ranges in which different phases are stable. The traditional method of hardening of steel is first to heat it to austenitic state and then to cool it rapidly. Upon cooling from the austenitic state, several different phases may form [7].

Figure 2.2 shows a continuous cooling transformation (CCT) diagram of a low alloyed steel (0.42 % C, 0.78 % Mn, 1.79 % Ni, 0.80 % Cr, and 0.33 % Mo). Rapid cooling from the austenitic state produces martensite. Too slow cooling should be avoided since other phases or structures, such as ferrite, pearlite, or bainite may form.

Martensite is a hard phase with favourable strength properties. The hardening effect derives partly from the complex internal structure of the martensite, and partly from the solution hardening effect of carbon. The solubility of carbon is greatly exceeded when martensite forms rapidly and diffusionless. With higher carbon concentration of the martensite, more interstitial sites are filled. Thus, for low alloyed steel, the hardness of the martensite increases with increasing carbon content [10].
2.1.1 Hardening

The most common process for improving the component’s mechanical performance (tensile strength, fatigue strength, or wear-resistance) is hardening. Hardening is the collective name for thermal methods of creating a martensitic (or bainitic) structure in steel. Hardening is performed by some heat treatment process in combination with quenching. Hardening processes can be divided into through hardening and surface hardening processes.

Through hardening is performed by thermal processes where the microstructure is changed throughout the component, or at least in a large part of the cross section. Examples of hardening processes are austempering and quenching and tempering (martensitic hardening). These processes are not in focus of the present work.

2.1.2 Surface hardening

Surface hardening operations are beneficial for components that require high strength and wear resistance at the surface in combination with toughness in the centre of the component. Typical application can be shafts, axles, and transmission components such as gear wheels [11].
Surface hardening creates a gradient in properties from the surface towards the centre of the component. The gradient can be achieved through thermal or thermo-chemical processes.

Thermal processes imply changing the properties of the steel by subjecting it to a thermal sequence. Only the surface to be hardened is heated and quenched. Examples of thermal processes are induction hardening, flame hardening, and laser hardening.

Induction hardening is the thermal process studied in the present work. The process involves induction heating to austenite followed by quenching that causes the austenitised volume to transform to martensite. The method is quick and energy effective since only the volume to be transformed is heated. Hardening depths can be from one or a few millimetres up to half the radius of e.g. a shaft. The process results in compressive residual stresses at the surface that is favourable for fatigue strength [12]–[16].

Thermo-chemical processes involve a thermal sequence in combination with a chemical reaction with the external environment, often an atmosphere. The chemical composition is thus changed at the surface, commonly by addition of carbon, nitrogen, or both. Examples of thermo-chemical processes are carburising case hardening, carbonitriding, nitriding and nitrocarburising.

Case hardening is the thermo-chemical processes studied in the present work. The process increases the carbon content of the steel surface by carburising in an atmosphere or under low pressure (LPC) at a temperature of typically 850-950°C. The carburised layer is typically 0.1 to 1.5 mm deep but can be up to several millimetres. The surface carbon content is typically 0.7-1.2 % and decreases gradually towards the core carbon content. Carburising is followed by quenching typically in oil for atmospheric carburising or in high-pressure gas for low-pressure carburising. Figure 2.3 shows a schematic example of a low-pressure carburising process. While quenching, the carburised layer transforms to martensite with hardness determined by the carbon content. Case hardened components have a hard surface with a softer and tougher core, as well as a compressive surface residual stress state, which is a beneficial combination for high strength, wear resistance, and toughness [1], [17].
2.1.3 The tempering process

After hardening to a martensitic structure, the steel has relatively low toughness. Tempering, heat treatment in the temperature range of 160 to 650°C, improves the toughness of as-quenched martensitic microstructures but lowers strength and hardness.

The temperature range for tempering can be divided into two more specific ranges: low-temperature tempering, up to 300°C, which modifies the characteristics of the quenched structure, and high temperature tempering, in the range of ~550-650°C, which removes many of the characteristics of the quenched structure [17]. Paper II treats the subject of low-temperature tempering below 200°C.

The tempering temperature and time have an effect on the microstructure and mechanical properties of the steel. During tempering of a case hardening steel, the core and the case material will react differently. At tempering temperatures between 80 and 200°C, there is coherent precipitation of carbides and transformation of retained austenite in the case to lower bainite. The case experiences softening. The core material is somewhat affected by slight softening and carbide precipitation. Above 200°C, the martensite loses its tetragonality and the case as well as the core material experience noticeable softening. [17].

Figure 2.3 Example of low-pressure carburising and gas quenching process (pressure not to scale). Details correspond to experiments in section 4.1.
At the same time as the toughness increases, relaxation of residual stresses and softening occurs during tempering. For this reason, it is important to find the optimum tempering temperature and time to balance between strength and toughness. Ultimately it is the balance of hardness (or strength) and toughness required in service conditions that determines the optimum tempering temperature and time of tempering for a given application.

The temperature range in between low-temperature and high-temperature tempering should be avoided due to different embrittlement mechanisms [7].

2.1.4 Residual stresses

Residual stresses are internal stresses in a component. Two types of physical changes cause the residual stresses produced during cooling of heat treated parts. Thermal stresses that occur while cooling (or heating) in the absence of a phase transformation, and stresses from phase transformation of austenite to less dense microstructures such as martensite, ferrite, or cementite.

Thermal stresses are dominant for subcritical cooling, i.e. when phase transformation does not occur. The volume expansion due to austenite transformation is the dominant factor in any heat treatment that involves cooling from austenite [1].

Thermal stresses arise when temperature gradients occur in the material. Immediately on initial cooling, temperature differences between the surface and centre occur and the surface contracts more rapidly than the centre. The contraction of the surface is confined to the greater volume of the centre material, and tensile stresses occur in the surface. Normally the tension exceeds the yield stress, and plasticisation occurs. On further cooling, the cooling and contraction of the centre is greater than that of the surface that results in a compressive residual surface stress state at the end of cooling [18].

The positive volume change from phase transformation of austenite to martensite is in the range of 4% for a steel with 1% carbon content (4.64 – 0.53 %C) [1]. For carburised steel, the carbon gradient from the surface will affect both the volume change and the Ms temperature on which the martensite starts to form.
Another source of residual stress is non-uniform plastic deformation. The deformation itself, as well as stress-induced martensite formation, creates residual stresses. The mechanism is utilised for example in shot peening where compressive residual stresses are created at the surface [19].

Residual stresses have considerable influence on the mechanical properties of a component. The residual stress may be considered as a superpositioned stress on the applied stress during service conditions. Thus, compressive residual stresses reduce the stress that the material experience during fatigue loading, and on the opposite, tensile stresses increase the experienced stress of the material [20].

The compressive residual stress state near the surface of surface hardened components is thus beneficial for mechanical properties during service conditions.

2.1.5 Defects and non-metallic inclusions

Steel cleanliness is crucial for components for demanding applications where high fatigue strength is required.

Inclusions are non-metallic phases, generally oxides and sulphides, introduced during making and refining of liquid steel, casting, and precipitation within solid steel. The number of inclusions and their size is to a large part governed by the steel making process [21].

Some inclusions are not desired. However, the production of clean steel, i.e. steel with low inclusion content, is demanding and reducing inclusions to a minimum can imply large costs. There are metallurgical processes for minimising the number of inclusions and their size in steel. Examples of such processes are electro slag remelting, calcium treatment, or deoxidation [1].

Some inclusions are deliberate. Manganese sulphides are sometimes beneficial for facilitating machining through the incipient fracture in the chips and also through providing certain lubrication. However, manganese sulphides generally have negative effect on the strength properties [10].

During hot rolling or forging of steel, hard inclusions such as aluminium oxides are crushed, while soft inclusions such as manganese sulphides are elongated and flattened. After these process steps of the manufacturing
chain, the possibility of changing the number or size of inclusions in steel is very limited or non-existing [10].

The effect of inclusions on the mechanical performance of steel components as the inclusions may act as initiation points for fatigue cracks. An inclusion may be considered as a pre-existing crack that can be treated by linear fracture mechanics models, described briefly in section 2.2 [22].

2.2 Mechanical performance of components

The majority of failures of engineering and automotive components is related to fatigue. Fatigue implies that the component is subjected to a varying load and fails although the maximum applied stress is lower than the ultimate tensile strength.

Many automotive components are subjected to cyclic loading in bending, rotating bending, torsion, in tension-compression, in surface contact, or a combination of the load cases. The fatigue strength is often limiting to the component’s service life.

As mentioned, heat treatment alters material states such as the hardness. The fatigue strength of a steel is closely related to its hardness. Figure 2.4 shows a linear correlation between hardness (in Vickers, up to a certain limit hardness, see further below) and fatigue strength (stress amplitude at stress ratio R=-1, rotating bending). Murakami [22] presents the empirical equation:

\[
\sigma_{\text{fat}} = 1.6 \cdot HV \pm 0.1 \cdot HV
\]  

(2.1)

For this relationship, the intrinsic fatigue strength can be considered to be limiting to the fatigue strength. That is, the relationship describes the theoretical strength of steel free from defects, such as non-metallic inclusions, pores, or surface roughness. The equation is valid up to a certain hardness, in the absence of defects or inclusions of critical size. For modern, ultra-clean steels, this critical hardness can be up to approximately 700 HV.
Above the critical hardness, for hard steels with high intrinsic fatigue strength, defects such as non-metallic inclusions or surface defects are limiting to the fatigue strength. In this case, the fatigue strength can be estimated by linear elastic fracture mechanics models [23].

From the Kitagawa diagram, information can be obtained regarding criteria for crack growth and crack arrest versus crack size and nominal stress, see Figure 2.5. Two lines constitute the Kitagawa diagram; the intrinsic fatigue limit $\sigma_0$ and the linear elastic fracture mechanics criterion for long crack growth [24].

The linear elastic fracture mechanics criterion is obtained from the stress intensity of the present defect, $K$, together with a threshold stress intensity, $K_{th}$. The stress intensity at the crack-tip depends on the shape of the crack, the nominal stress, and the location of the crack [25]. Above the intrinsic fatigue strength, $\Delta\sigma_0$, fatigue crack growth will occur through other mechanisms than those described by linear elastic fracture mechanics [22].
Figure 2.5 contains two different intrinsic strengths, for two martensitic steels of different hardness. Martensitic steels have roughly the same stress intensity threshold value. Provided that the hardness is the only difference between the steels, the inclined line for the fracture mechanics criterion will be identical for the two steels. The intrinsic fatigue strength, $\Delta \sigma_0$, depends to a large extent on the hardness of the martensite. The level of $\Delta \sigma_0$ will, therefore, vary between the steels. Lower hardness results in lower intrinsic fatigue strength. As a result of the lower intrinsic fatigue strength, the critical crack size becomes larger. One can, for this reason, say that the low hardness steel is more defect tolerant than the high hardness steel.

The regimes for crack growth as a function of $\log \Delta K$ (range of stress intensity) are shown in Figure 2.6. Regime I is associated with the existence of a threshold stress intensity range, $\Delta K_{th}$. Below this threshold, cracks either remain dormant or grow at undetectable rates. Cyclic loading up to this threshold can progress infinitely without fracture. Regime II shows a linear variation of $\log da/dN$ with $\log \Delta K$, which is denominated the Paris power law relationship. The fatigue crack grows...
stable until regime III where crack growth rates rapidly increase until $K_{IC}$ is reached causing catastrophic failure [24].

The fatigue modelling in this work is based on linear elastic fracture mechanics and assumes that growth of a fatigue crack only occurs if the stress intensity range at its tip exceeds the threshold value, $\Delta K_{th}$. In this case, an inclusion or defect may be considered as a pre-existing crack. The threshold value is a material property. For martensitic steels, the threshold has been found to be approximately 4 MPa$\sqrt{m}$ [26].

![Figure 2.6 Schematic illustration of crack propagation rate as function of stress intensity.](image)
3 Manufacturing chain

A typical heat treated automotive component, e.g. a gear wheel in the transmission of a car or truck, undergoes many steps in the manufacturing chain. The chain comprises both processes to create the desired shape and processes to give the component the required mechanical properties.

Heat treatment is applied to components to provide the steel with desirable properties. Depending on the component’s position in the manufacturing chain, different properties are desired. They can be divided into 1) properties during manufacture, and 2) properties in the end product.

Properties during manufacture include properties that facilitate different production processes such as machining. Often, this type of heat treatment is made by the steel manufacturer. Various kinds of annealing resulting in optimum hardness and microstructure for machining operations are examples of such processes. Stress relieving annealing to reduce residual stresses that arise during machining operations is another example. These processes are not described further in this thesis.

The most common process for improving the component’s mechanical performance, (tensile strength, fatigue strength, or wear-resistance) is hardening as described in sections 2.1.1-2.1.2.

Heat treatments to ensure that the component possess the properties needed for its final use are made in a late stage of the manufacturing chain, which implies that the value of the component is high. Given the increase in mechanical properties, or specific strength, caused by heat treatment, the added value of heat treatment is also high. Many heat treated components would have a much shorter service life than they
have today if they were not heat treated. Some would not even serve their purpose at all.

The process steps after heat treatment are mainly hard machining operations in order to obtain the correct shape or surface finish. Most often, only minor hard machining remains after heat treatment if any processing at all. Some components are also surface coated by, for example, thin film coatings (PVD coatings of e.g. TiN or amorphous carbon) in order to further improve wear and friction properties.

Examples of process steps within the manufacturing chain, and of sub-processes within the heat treatment category, of a typical surface heat treated component, are shown in Figure 3.1. Some processes may also be combined to achieve required properties; quenching and tempering followed by induction hardening or nitriding or carburising case hardening followed by induction hardening are examples. The primary focus of each research question is marked in the figure. All papers deal with the relationship between the production process and the final mechanical properties of the component.

Figure 3.1 Examples of sub-processes within the heat treatment category. The process flow in the top of the figure represents the manufacturing process for a typical heat treated component.
In the next sections, the process steps related to the papers will be described more in detail, and the state of the art within the fields will be presented.

### 3.1 High-pressure gas quenching of low-pressure carburised steel

Carburising case hardening is common in order to improve the performance of automotive powertrain components. It is mostly carried out at atmospheric pressure, followed by oil quenching. Low-pressure carburising (LPC) processes in combination with gas quenching offers many benefits: the parts emerge clean, bright, and dry, and are less distorted than oil quenched components, due to better control and uniformity of gas quenching compared to oil quenching. The quench gas flow can also be alternately reversed in order to improve the quench uniformity [27], [28]. Furthermore, the varying heat transfer mechanisms for fluid-based quenching agents (from film boiling to bubble boiling to pure convection) are avoided [29]. Thus, there is little need for cleaning or machining of the parts after LPC and gas quenching [30]. For this reason, smaller scatter in distortion is expected in the results of the gas-based processes. The low-pressure process also has the possibility to carburise drillings or blind holes. Another significant benefit of LPC is the absence of internal grain boundary oxidation, which is normal for gas carburising to depths up to 25 µm. Hard oxides act as sharp notches and initiation points for fatigue cracks [31], and related non-martensitic structures have a negative effect on the fatigue strength [17].

Advantages related to the production process are possibilities for integration into the production line, energy and gas is consumed only when needed so there is no idling losses, and that low-pressure carburising reduces processing time compared to conventional gas carburising since the carbon transfer is more efficient and the solubility limit for carbon in austenite is reached after only a few minutes [32], [33]. Further reduction of the processing time is also possible by increasing the process temperature. In general, the processing temperature is increased approximately 30°C in low-pressure carburising compared to gas carburising. Increased temperature in conventional furnaces is often not possible in practice due to increased wear of the fixtures and furnace
lining [34]. Micro alloyed steels might be needed at higher carburising temperature (1000-1050°C) in order to avoid grain coarsening [35].

It should be mentioned, however, that this process requires higher initial capital equipment cost than atmosphere carburising equipment. Higher alloyed steel might be needed since the cooling rate of the gas is lower than for oil quenching. Moreover, there is a risk of formation of soot and tar or carbide networks due to high carbon availability and process control limitations. A gas cooling chamber is schematically shown in Figure 3.2.

![Figure 3.2 Schematic view of gas cooling chamber [36].](image)

The cooling procedure has considerable influence on the final properties, such as fatigue properties and distortions, of a case hardened component. One advantage for high-pressure gas quenching is the possibility to adjust the cooling characteristics during quenching. Further, the cooling characteristics of gas or oil as quenching media are different: at high temperatures, 500 to 700°C, high-pressure gas quenching is slower while it is faster than oil quenching at temperatures below 400°C [1]. The different cooling characteristics of oil and gas quenching are illustrated in Figure 3.3.
Low quench intensity is beneficial in the low-temperature region to reduce thermal gradients, distortions and risk of cracking [37]. A compulsory condition is however that the cooling rate is fast enough in the high-temperature region to avoid unwanted phase transformations.

The objective of the present work is to evaluate the effect of modified quench rate on the fatigue strength of low-pressure carburised and gas quenched steel and to find the physical mechanisms for the effect.

State of the art

One would expect better fatigue properties for LPC and gas quenched parts than for conventionally heat treated components, due to the above-mentioned benefit of absence of intergranular surface oxidation.

However, increase in fatigue strength was not obtained in practice. Low-pressure carburising of a variety of steels has been compared to conventional gas carburising in many papers. Multiple detrimental mechanisms cancelled the benefit of the oxidation free surface.
The formation of carbide networks had an adverse effect on the tooth root fatigue strength of gears of several case hardening steels [4]. Further, intercrystalline fractures indicated that grain boundaries were, in some way, negatively affected. The weakening of grain boundaries was by Wise et al. claimed to be related to phosphorous segregations [5]. Clausen [31] stated that the weakening of grain boundaries was caused by the formation of grain boundary carbides, and by the effusion of manganese. Manganese effusion occurs during the low-pressure carburisation process, and the low levels of manganese near the surface lead to locally lower hardenability. Further, the surfaces of vacuum carburised parts were similar to thermally etched surfaces with deep grooves that acted as notches during fatigue loading [31].

Zimmerman et al. [38] showed that low-pressure carburised and gas quenched AISI 8620H obtained higher maximum compressive residual stress than gas carburised and oil quenched, and the carbon content went deeper into the part for a given case depth. The higher compressive residual stresses of LPC specimens were related to the steeper slope of the carbon profile.

As reported above, many of the negative effects were related to the characteristics of the low-pressure carburising process. However, this cannot be the sole explanation of the physical phenomenon. Since and Irretier [39], however, showed improved mechanical properties of low-pressure carburising with stop quench gas quenching compared to “direct gas quenching”, brief discussions on the cause of the improvement concerned the effect of auto tempering during the quench stop and temperature homogenisation.

If the observation made by Since and Irretier is correct, the reduced fatigue strength after low-pressure carburising is related to the cooling process characteristics of the gas quenching process. Much of the literature regarding quench rate of gas quenching is related to adjustment of the gas quenching rate at higher temperatures, above the core $M_s$ temperature, such as described by Atraszkiewicz et al. [40]. The purpose of this operation is to reduce distortions by temperature homogenisation. Several furnace manufacturers use this technique under various trade names [27], [41], [42].
The effect of quench rate in lower temperature ranges, around or below the surface $M_s$ temperature, and in relation to mechanical strength, has not been studied to large extent. Donachie and Ansell [43] reported that the as-quenched hardness of martensite was not affected by quench rate, but that the morphology of the martensite may be changed. However, the quench rate was varied only in the austenite region.

### 3.2 Tempering after surface hardening

Today most carburised and induction hardened components are subjected to low-temperature tempering after hardening. The underlying reason is that it is commonly believed that untempered martensite is far too brittle for actual service conditions. Tempering can also be essential for dimensional stability. Others argue that tempering is merely a corrective measure and that if the heat treatment is executed properly tempering is not necessary. The eliminated tempering process is shown in Figure 3.4.

![Figure 3.4 Process diagram for case hardening with and without tempering.](image)

Tempering of steel implies an additional process step and involves considerable costs in form of process time and energy consumption as well as costs due to handling of goods and investments in tempering furnaces etcetera. Furthermore, the energy consumption from the additional furnace treatment has negative environmental impact.
Eliminating tempering from the heat treatment process could lead to increased productivity, reduced energy consumption, and cost savings. In some cases, improved mechanical performance of the component can also be expected.

The objective of the present work is to determine the effect of eliminating tempering from the heat treatment operation. The effect is measured as contact fatigue resistance.

State of the art

In a gear wheel, failure can occur from either contact fatigue on the gear flank or bending fatigue of a gear tooth. These two load cases have been the focus regarding the effect of tempering.

If tempering is to be eliminated from the heat treatment process, it must not have negative effect on mechanical properties. There are several reports on the positive influence of tempering on fatigue properties. However, the literature presented here is focused on those who observed positive or at least neutral influence of untempered components. The literature is scarce, however, especially regarding contact fatigue applications.

Under pure rolling conditions, in the low-cycle high load regime (<10⁷ cycles), tempering decreased contact fatigue life [17]. A possible reason for the negative effect of tempering was described as transformation of retained austenite to bainite by tempering. Ahn et al. [44] did not find any difference in contact fatigue resistance between untempered and tempered carburised steel specimens in the Hertzian stress range of 3 to 4 GPa.

The surface hardness has been indicated to be an important factor for contact fatigue resistance. Widmark and Melander [45] report of linearly decreasing amount of damage with increasing surface hardness of carburised steels. Melander et al. [46] found no evidence for that the amount of retained austenite or surface carbon content had either positive or negative influence on resistance to fatigue damage generation.

The bending fatigue strength of several case hardened steels was unaffected [47], or even decreased [48] by 180°C tempering. The surface hardness decreased as well which was the probable explanation. The
resistance to impact stress and ultimate bending stress increased, however. For small case hardened gears, the bending fatigue strength decreased by some 20% after 200°C tempering. Also, the surface hardness decreased by tempering. Similar results were found in other studies [49]–[52].

The reason for the contradicting results regarding the influence of tempering on bending fatigue strength may be answered by the influence of the case depth.

The interaction between fatigue resistance and residual stresses can be described as tempering leads to decreased residual stresses, both compressive near the surface, and tensile on the core border. For small hardness depths, tempering has beneficial influence on fatigue strength since the core border is limiting. For large hardness depths, however, tempering has an adverse effect on fatigue strength since the surface is limiting [53], [54]. This is illustrated in Figure 3.5.

Another possible reason for negative effects of tempering may be the formation of bainite that can be an undesired microstructure.

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**Figure 3.5** Effect of tempering on fatigue strength during bending load. Positive effect of tempering for shallow hardness depths.
3.3 Straightening after surface hardening

Distortion from heat treatment is the combined effect of changes in dimensions and changes in shape. There are many causes of distortions in heat treatment. Many of them originate from the manufacturing process steps before heat treatment, or from the material itself. Examples of factors affecting distortions are presented in the fishbone diagram in Figure 3.6.

Distortion from hardening originates primarily from two phenomena: 1) the martensite that forms during cooling is greater in volume (i.e. less dense) than the original soft phase, which results in a degree of expansion during hardening, and 2) the necessary rapid cooling of the steel creates thermal stresses, which may cause distortion in the part.

To a certain degree, it is possible to reduce or eliminate distortions from the hardening process. Systematic changes related to the materials, such as volume change, phase transformation and heat stresses can be compensated for in the design of the part. Machining before heat treatment can be made to create less residual stresses. Non-uniform
heating or cooling can be reduced by optimising the processes or the design. The heat treatment batch sizes can have effects on distortion. Variations can be reduced by specifying the hardenability of the steel in narrower bands. The forging texture can be optimised, for example by changing billet shape or better control of segregations in the forged part.

However, distortion to some degree still occurs after hardening operations. Process deviations regarding furnace temperature uniformity or non-uniform diffusion will always be present to some degree. The same applies to segregations in the material.

Elongated components such as shafts typically have camber, obtain an hourglass shape, become oval or change in length. Distortions in other geometries have different characteristics.

There are various ways to correct for distortions. For gear wheels and rings etcetera that are not elongated grinding or machining to compensate for distortions is possible, which implies that the surface of the component is partially removed. It must be considered however that the material removal is not evenly distributed in relation to the hardness depth and the residual stress pattern. An asymmetric stress pattern and varying hardness may occur.

Camber for elongated components is corrected for by straightening. Straightening implies that the material is loaded to sufficient stress that local plastic deformation occurs. This affects the residual stress state in the component. Simplified arguments in the literature state that, due to the elastic spring-back after straightening, areas that are plastically deformed in tension obtains compressive stresses, and compressively deformed areas obtain tensile stresses. An automatic straightening machine is shown in Figure 3.7.
The work done in this thesis shows that simplified explanations of the residual stress state after straightening are not sufficient. Further, to be able to design components of sufficient mechanical properties, it is important to quantify the effect of this manufacturing process on the resulting mechanical performance. The contribution of this work is to quantify the effect of straightening on the fatigue strength of induction hardened shafts.

State of the art
The literature on the subject of straightening is scarce. Particularly straightening and its effects on the performance of the component, such as the fatigue strength, is little treated in the literature.

Automatic straightening equipment is often equipped with acoustic crack detectors. In that way, even small cracks from straightening can be discovered. Cracks that likely would not have been detected by manual straightening or following non-destructive testing [56].
Jönsson showed that an untempered test piece of carburised case hardened steel can be straightened with less force and less risk of fracture than a tempered [57]. One of the reasons for reduced risk of fracture of untempered components is that the difference between yield strength and ultimate tensile strength is larger before tempering. The process order of straightening before tempering is not very common, probably because of logistic reasons. However, for some components that are difficult to straighten without cracking, this process flow is utilised.

For carburised case hardened shafts, it was found that the residual stress state was asymmetric after a straightening operation. However, the fatigue strength in three-point bending was not affected by straightening [58], [59]. Plastic deformation (axial stretching) reduced the fatigue limit in rotary bending of nitrided test bars of steel Ck45 [60]. However, it was possible to restore the fatigue limit by shot peening.

Mitze [55] schematically presented stresses during and after straightening, and also schematic curvatures obtained by different straightening procedures. This illustration was only two-dimensional and anticipated tensile residual stresses where the straightening force was applied and compressive stresses on the opposite side. It was also concluded that several small straightening strokes with small rotation or movement in the axial direction is an effective way of crack prevention during straightening.

The present work will show that more comprehensive three-dimensional models are needed to anticipate the residual stress state of a straightened component.
4 Results and discussion

To answer the research questions in chapter 1.2, a number of studies have been performed. The results of these studies are summarised in the following chapter. Detailed descriptions of the studies are included in the appended papers.

4.1 High-pressure gas quenched gear wheels

The experimental investigation regarding gas quenching after low-pressure carburising was made by process experiments and fatigue testing of gear wheels. The cooling cycles were also modelled in dilatometry in order to get an understanding of the phenomena that occurred.

The experiments were set up in order to answer research question 1. The hypothesis to RQ1 regards a holding time during the gas quenching sequence. Thus, only the last part of the quenching cycle was studied.

The design of experiments included three parameters, which lead to seven test series in total. The first test series was a reference of 100 % gas quenching (direct gas quench). The others were defined in the final part of the quench process by a high and a low value of each:

I. The temperature of the start of reduced quench rate
II. The duration of the reduced quench rate
III. The final quenching rate after the holding time

Generally, a three parameters high/low design of experiments contains eight test series. However, in this case two test series had to be eliminated. Due to the heat recovery system in the quench chamber, slow cooling occurred during the holding time, and it was impossible in practice to obtain all test series.
The quenching was interrupted temporarily in various ways, near the martensitic starting temperature (Ms) [61], by a reduction of fan power and quench gas pressure. The quenching sequences are illustrated in more detail in Figure 4.1.

![Figure 4.1](image_url)  Schematic illustration of test series in the last part of the quench sequence. Gas quenching from 880°C to quench stop with 20 bar pressure and 100% fan power.

Figure 4.2 shows the fatigue strength from staircase fatigue testing [62], expressed as $F_{max}$. The load distribution programme (LDP) calculated the quotient between the tooth root bending stress and the applied force in fatigue testing and to approximately 17 MPa/kN [63].

All test series with quench stop had significantly (95%, [64]) higher fatigue strength than the reference test with direct gas quenching. From 13 to 14% higher (s2-s5), up to 21 to 22% higher (s6, s7) than the reference.

The test series with the highest fatigue strengths did have the slowest cooling at low temperatures and did not have any final quench after the holding time.

The parameters from the design of experiments showed that slow cooling after the quench interruption resulted in approximately 5 kN higher fatigue strength. The influences of the temperature and duration of the holding time were insignificant.
The residual stress state of the direct quench test series was clearly less compressive than the other series. The amount of retained austenite at the surface was measured to approximately the same value, 21%, for all test series. Any possible variation between the test series was smaller than the measurement uncertainty of approximately two unit percent.

Figure 4.3 shows the dilatometry curves for the direct gas quench test series and test series number 7. The two test series are the ones that resulted in the largest (ref) and the smallest (s7) expansion at the end of quench. An additional quenching sequence of isothermal quench stop at 30% martensite formation is also shown. It was clearly demonstrated that the isothermal hold led to stabilisation of the austenite. Approximately 15°C undercooling was needed to recommence martensite transformation at resumed quenching. The stabilisation of retained austenite could not have been chemical, due to the low diffusion coefficient for carbon in austenite at this temperature, and was therefore assumed to be mechanical.

The dilatometer tests showed correlation between the final volume (dilatation value at 80°C, end of cooling) and the fatigue strength measured. Small volume expansion of the case material resulted in the highest fatigue strength, Figure 4.2.

Physical mechanisms for the observations above are discussed in the following:
Figure 4.3 Dilatometer curves of a) the test series with the largest (direct gas quench) and the smallest (series no 7) final volumes, and b) effect of 5 min isothermal holding time at 135°C compared to direct gas quench. Specimens of surface carbon content.

Temperature homogenisation

During interrupted quenching, temperature homogenisation may explain the increased compressive residual stress: more of the core is allowed to transform into martensite (or non-martensitic phases). At resumed quenching, there is less expansion of the core during the final cooling, compared to direct gas quenching. Core expansion after martensitic expansion of the case reduces compressive residual stresses in the case [1]. Thus, temperature homogenisation by interrupted quench may result in more compressive residual stress.

Dilatometry testing only tested the case material in hollow thin samples, and the effect of volume expansion was still observed. The effect of temperature homogenisation on the relationship of martensite transformation between surface and centre could not fully explain the differences in volume expansion during quenching.

However, it is also likely that temperature homogenisation allows for rearrangement of local stresses and strains, leading to lowering of transformation induced plasticity and increased final, global, compressive residual stress state.
Stabilisation of austenite

Lower volume expansion could also be related to the amount of retained austenite. It is known that interrupted quenching leads to stabilisation of austenite [65], and that slow cooling leads to stabilisation of the austenite [66], [67]. Hollomon and Jaffe relates stabilisation to stress relaxation [68].

Some argue that there is an optimum austenite content regarding fatigue strength of approximately 35 % for case hardened test bars [69]. Stress-induced transformation of austenite to martensite leads to crack retardation or arrest [70], [71], thanks to hardening in front of the growing fatigue crack. Thus, a higher amount of retained austenite increases the effect of crack retardation during fatigue loading.

The effect of retained austenite is a possible explanation for the improved fatigue strength of interrupted quench specimens. However, the measurements of retained austenite were inconclusive, and it was not possible to verify experimentally different contents of retained austenite.

Other mechanisms

The effect of auto tempering could not be related to any mechanism explaining the observed results from fatigue testing. The effect of microcracking was not plausible.

Conclusion

It was thus concluded that the increased fatigue strength of the test series with slower final quench, Figure 4.2, was a result of the combined effect of 1) increased compressive surface residual stress, and 2) mechanical stabilisation of austenite during quench interruption.

Modification of the quench rate is made by turning off the fan and in some cases also to alter the pressure of the quench gas. Thus, the technique does not require costly investments and may be relatively easily implemented. It may also be possible that the effect is generic, i.e. valid for all steels and heat treatments [72]. Whether the effect is generic or not is not studied in the present work.
4.2 Tempering and fatigue properties

The experimental investigation regarding the performance of untempered parts was made by rolling contact fatigue testing of case hardened rollers, in order to answer research question 2. The hypothesis to RQ2 regards the hardness of the untempered steel and that this is related to increased resistance to contact fatigue. For this reason, a correlation between contact fatigue resistance based on hardness was developed.

Rollers of two different steels were case hardened according to Figure 4.4. Tempering was made for three hours at 190°C for Ovako 253 and one hour at 180°C for 20NiCrMo2. The tempering step was eliminated from one test series of each steel to compare tempered and untempered steel in contact fatigue.

The fatigue testing was executed by pressing and rolling the test roller against an EN100Cr6 bearing steel roller, in lubricated conditions without relative motion in the contact surface to 10 million revolutions of the test ring. Rockwell hardness test, HRC, indentations on the load ring acted as artificial damages. The fatigue damage, in the form of spallations, was measured after testing, Figure 4.5.

![Figure 4.4 Schematic process descriptions for case hardening of the two steels.](image-url)
The surface hardness dropped from 740 HV to 650 HV by tempering for Ovako 253, and similarly, from 800 HV to 750 HV for steel 20NiCrMo2.

The total amount of fatigue damage for each roller within each test series is summarised in a Weibull plot in Figure 4.6. Steel 20NiCrMo2 showed less rolling contact fatigue damage and hence larger fatigue resistance than steel Ovako 253. For each steel, the tempered test series showed damages both larger in size and more numerous than the untempered series.
The pile up around the HRC indents in the load ring led to plastic deformation of the surface of the test rings. Figure 4.7 shows the difference in plastic deformation for tempered and untempered steel 20NiCrMo2. The depth scale in the Z direction is six µm for both images. The tempered ring obtained a clear circular indent (approximately 2 to 3 µm deep) while the plastic deformation was not possible to distinguish from the roughness of the surface profile for the untempered ring. Ovako 253 had depths from approximately 5 to 6 µm for tempered rings while approximately 2 to 2.5 µm for untempered rings. Figure 4.8 shows the surface profile from the images in Figure 4.7. It is also evident that the untempered test ring kept more of the surface structure from grinding than the tempered one.

Figure 4.7 Plastic deformation in test ring from HRC indents in the load ring. Untempered test rings (left) nearly unaffected while tempered (right) obtained substantial deformation.

Figure 4.8 Surface profiles from Figure 4.7.
Different crack initiation sites were found for tempered and untempered test rings. The surface structures of untempered test rings remained similar even after rolling contact fatigue testing, Figure 4.9. Thus, the damages were initialised in grinding marks on the surface, evenly distributed over the contact pattern. This homogenous fatigue crack initiation mechanism is very much related to probability. Thus, quite large variations in the results are expected.

Tempered test rings obtained induced indents from the load ring HRC indents during rolling contact fatigue testing, Figure 4.7 and Figure 4.9. The fatigue crack initiation mechanism was heterogeneous and concentrated to these indents. The variation of the results is thus smaller. Further, larger individual surface damages were found on tempered test rings.

Figure 4.9  Surface structure and fatigue damage of Ovako 253. Left: untempered, and right: tempered.

Figure 4.6 shows that the variation (slope of the line) for the untempered test rings is the same for the two steels. In analogy, the tempered test rings have the same variation. Considering the findings presented above, this implies that the same fatigue mechanisms prevail in untempered test rollers regardless of steel type, as well as for tempered test rollers for the two steels.

Thus, it is concluded that eliminating tempering from the production process is beneficial from a contact fatigue point of view. It should be mentioned however that components that are simultaneously subjected to several different load cases may not benefit from eliminated tempering. Bending applications generally benefit from eliminated tempering for low
hardness depths, Figure 3.5. If brittleness is limiting in for example bending, or overloads in contact fatigue, untempered components may fail by other mechanisms.

Further, different fatigue mechanisms were found, and, even though, the same total amount of fatigue damage was found for the rings, the individual damages were larger for the tempered rings. The smaller and more evenly distributed fatigue damages of the untempered rings may not be as severe for a component in service conditions.

4.3 Straightened surface hardened shafts and their fatigue properties

The experimental investigation constituted straightening experiments of induction hardened shafts, fatigue testing, and modelling of the stress behaviour during straightening. The experiments were set up in order to answer research question 3. The hypothesis to RQ3 regards the residual stress state of the component after straightening. As mentioned in chapter 3, the literature mentions simplified two-dimensional models [55]–[57], [60]. This work shows that the residual stress state in the entire cross section must be considered.

The finite element simulation was made similar to the experimental setup, in order to approximate the residual stress state after induction heat treatment with subsequent straightening. The material data for the model was simplified in that the hardened layer was assumed homogeneous.

Figure 4.10 shows the longitudinal stress and equivalent plastic strain during maximum load of straightening, in the cross section at half length of the shaft. Tensile stresses and plasticisation occurred in the lower region while compressive stresses occurred in the upper region. Figure 4.11 shows the axial residual stresses after a complete straightening operation. The residual stress state of the entire cross section was affected by straightening. The force application occurred on the top at this cross section (0°). Tensile residual stress at the surface can be observed at the 0° and the ±120° orientations.
RESULTS AND DISCUSSION

Figure 4.10  Axial stress at maximum straightening load and the equivalent plastic strain. Blue areas indicate axial compressive stress. Red and yellow areas indicate tensile stress.

Figure 4.11 Axial stress after straightening, cross section at the axial position of straightening. Blue areas indicate axial compressive stress. Red and yellow areas indicate tensile stress.

Fatigue testing in three-point bending towards the areas of tensile residual stresses represents the weakest links in a rotating application. Fatigue testing was therefore made on straightened shafts in the orientations of ±120° where the highest tensile stresses occurred.

Straightening was made with two different forces representing two test series of severe and less severe straightening. Figure 4.12 shows the induction hardening process and schematically the fatigue testing and straightening procedure.
Three series were fatigue tested using the staircase method [62]:

I. Reference, no straightening
II. Straightened high force, fatigue testing towards 120°
III. Straightened low force, fatigue testing towards 120°

Figure 4.12  Experimental setup, induction hardening and schematic illustration of straightening and fatigue testing.

Figure 4.13 shows the surface residual stress along the circumference of shafts straightened to 80 and 97 kN. The unstraightened reference and the FEM model (Figure 4.11) are also shown. At the 120° position, the residual stresses are less compressive after straightening. The higher of the two straightening forces led to most reduction of compressive residual stresses. The FEM model exaggerates the stress states both for more and less compressive stresses than before straightening. However, the FEM model is qualitatively correct.

The fatigue strength was lowered by 7% by straightening to 80 kN (1.3 mm/m), and by some 20% by straightening to 97 kN (3.5 mm/m). The differences between the fatigue strength of the reference and that of both straightened test series were statistically significant [64].
Fracture mechanics model of the fatigue behaviour

To explain the results of the fatigue testing experiments a fracture mechanics model was adopted. It was assumed that fatigue cracks grew from initial defects of the specimen surface during fatigue loading. The fracture mechanics model assumed growth or arrest of pre-existing cracks, and that growth only occurred if the stress intensity at its tip exceeded the threshold value, $\Delta K_{th}$. The threshold value is a material property. For martensitic steels, the threshold has been found to be approximately in the range of 4 to 5 MPa√m [23], [26].

In the present study, fractures were found to have initiated at the surface and from former austenitic grain boundaries. For the fracture mechanics approach, the weak grain boundaries may be considered as pre-existing cracks. The three-point bending stress at the opposite side of the punch is approximated as purely tensile around the crack.

Based on the critical stress intensity at the crack tip, and the geometric functions, the critical stress range for crack growth was estimated to 762 MPa. However, it was necessary to incorporate the effect of residual stresses into the model. The effect of residual stress was considered as a superpositioned mean stress during fatigue testing [22].
A criterion for superpositioning of the residual stress was that the modelled R-value coincided with the experimental R-value used in testing. Another criterion was that only the positive part of the true stress range (including residual stress) was considered to contribute to crack growth. Negative parts (compressive) of the stress range were not considered to lead to crack propagation due to crack closure [24].

The model showed good correlation with the experimental results. Figure 4.14 shows the modelled minimum and maximum stresses in comparison to the experimental stress range from fatigue testing. The ranges of the model results are dependent on the range of the threshold stress intensity values found in the literature (4 to 5 MPa√m). The calculated stress intensities at the crack tip were 4.31, 4.58, and 4.36 MPa√m for unstraightened reference, straightened 80 kN, and straightened 97 kN respectively.

This concludes that the model used to characterise the conditions for fatigue crack growth and arrest is valid. Further, it may be used to predict the fatigue strength of straightened induction hardened shafts, provided that the residual stress state is known.

![Figure 4.14: Experimentally obtained stress range and modelled minimum and maximum stress regarding the range.](image)
It has been shown that the straightening force has an effect on the angle of the point of most negative effect on residual stress. Higher force moves the point up towards the punch, which was related to the amount of plasticisation that occurred during straightening. Further, straightening in several steps, with some degrees of rotation between the steps has been shown to have less negative effect on the residual stress state. [73]
5 Conclusions and future research

Material states during the manufacturing process are important to the mechanical performance of the end product. It is important to realise that changes in the manufacturing process have considerable influence on material properties that may be required at a later stage than for that particular process. The answers to the research questions and their respective hypothesis are presented below.

5.1 Conclusions

Research question 1
The increased fatigue strength of the test series with slower final quench, Figure 4.2, was a result of the combined effect of two mechanisms: 1) increased compressive surface residual stress and 2) mechanical stabilisation of austenite during quench interruption. The stress state was an effect of temperature homogenisation and rearrangement of local stresses while the stabilisation of austenite had a beneficial effect on crack retardation during fatigue loading.

The research has shown that it is possible to improve the mechanical performance of gears by manufacturing process modifications, which is also the answer to research question 1. Hypothesis 1 was shown to be true; the introduction of a holding time during the gas quenching sequence increases the fatigue strength of the component. And to be more precise regarding H1, slow cooling (DoE parameter III) after the quench interruption had significant effect on resulting properties while the influences of temperature and duration of the holding time (DoE parameters I and II) were insignificant.
Research question 2
The research has shown that it is possible to improve the mechanical performance in contact fatigue by eliminating tempering from the manufacturing process, which is also the answer to research question 2. Hypothesis 2 was shown to be true; the higher hardness of the untempered steel was beneficial for contact fatigue resistance. Different contact fatigue mechanisms were found between two different tempered and untempered steel alloys.

It should be mentioned however that components that are simultaneously subjected to several different load cases may not benefit from eliminated tempering. Bending applications generally benefit from eliminated tempering for low hardness depths, Figure 3.5. If brittleness is limiting in for example bending, or overloads in contact fatigue, untempered components may fail by other mechanisms.

Research question 3
The answer to research question 3 is that a hardened shaft can experience reduced fatigue strength due to straightening. The residual stress state in certain parts of the cross section is negatively affected. The hypothesis to RQ3 was thus true; the residual stress state in the entire cross section of the component is critical to its performance.

Whether the adverse effect of the residual stress state has negative effect on the performance of a component depends on its load case. A shaft subjected to torsional load or rotating bending load is however loaded over the entire cross section and will fail at its weakest point.

5.2 Future research
The thesis presents knowledge regarding the effect of the manufacturing chain on the mechanical performance of heat treated steels. The results from the thesis also identified future work for research.

For the first part, regarding gas quenching, an important question to investigate is whether the observed effects in this theses are generic. That is, to investigate if beneficial effects arise during interrupted quenching for different steels and other processes and quench methods.
To further study the physical mechanisms that occur during interrupted quenching would be of interest to better understand their effect on mechanical properties and how to optimise manufacturing processes.

Regarding tempering of steel, elimination of the process step has showed potential for increased fatigue strength. However, fracture toughness and brittleness are critical properties that must not be inferior to those of tempered steels. The experimental testing showed promising results, but brittleness tests and fatigue testing with overloads would be of interest.

For the part regarding straightening, the numerical modelling showed good correlation with experimental results. The fracture mechanics model considered the surface residual stress state for the cross section. The next step could be to develop a comprehensive model that considers the residual stress state and hardness distribution of the depth of the cross section, for any hardness depth.
6 References


Paper I
Paper I

Gas quench rate after low pressure carburizing and its influence on fatigue properties of gears / Einfluss der Abschreckgeschwindigkeit nach Niederdruckaufkohlung auf die Schwingfestigkeit von Zahnräubern.

J. FAHLKRANS, A. MELANDER, S. HAGLUND

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Paper II

Influence of tempering on contact fatigue.

J. FAHLKRANS, A. MELANDER, K. JOHANSSON, S. HAGLUND, S. B. HOSSEINI.

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Paper III
Paper III


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