Hardening Distortions of Serial Produced Gears

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Abstract

Hardening distortions are unwanted changes in shape and dimension that arise during hardening of steel components. Uncontrolled distortions induce random errors to the manufacturing process, and have a strong negative impact on manufacturing costs. The distortions must be minimized to obtain a robust and competitive manufacturing process. The distortions are not only caused by the hardening process, several factors from previous manufacturing steps including the component geometry itself contribute to varying extent. The aim of the current work is to investigate the main influencing factors on hardening distortions for serial produced gears. The thesis investigates factors from several manufacturing steps, all the way from the steel making to loading arrangement during quenching.

The investigations were done on two different types of gears for heavy-duty transmissions, crown wheels for the rear axle central gear and main shaft gears for the gearbox. The steel for the gears was produced using either continuous casting, producing rectangular, round or square strands, or ingot casting producing square ingots. For rectangular strands, the effect of disabling magnetic stirring of the steel melt during casting was investigated, finding a strong reduction of gear runout of crown wheels. Moreover, slender crown wheels gave high gear runouts for rectangular, continuous cast strands. For round and square strands, the effect of slenderness was small.

Segregations in crown wheels produced from the top and bottom of ingots were shown to go in opposite directions, producing opposite back-face tilts. The combination of ingot cast material and a step geometry in the back-face, gave a bimodal distribution of the back-face tilt which could not be found for continuous cast material.

For crown wheels quenched one at a time, influences of stacking level on the hardening tray were found, indicating an impact from small variations in the carburizing process, despite identical quenching conditions. For main shaft gears, collectively quenched by submerging the hardening tray in an oil bath, vertical and horizontal loading arrangements were studied. For vertical loading on bars, gears on the mid positions tended to have larger distortions. Local variations of oil flow in the oil bath corresponded to variations in surface hardness and, to some extent, also to the core hardness. Horizontal loading gave considerably less roundness and runout errors but increased flatness errors.

This thesis shows the complexity of the distortion phenomenon and how several factors interact and contribute to the final result. It is shown that factors with significant impact on hardening distortions for one component may be less important for another component. The results also show how important it is to consider the whole manufacturing chain if distortion problems arise. With this in mind, each type of component to be hardened should be produced by a manufacturing chain where each process step is carefully chosen, preferably at the design stage, with respect to minimizing distortions.

Keywords
hardening distortions, crown wheel, main shaft gear, gear runout, back-face tilt, macrosegregation, ingot casting, continuous casting, case hardening
List of appended papers

Paper 1


Paper 2


Paper 3

A. Olofsson, M. Köhn, S. Jonsson, “Identifying process parameters influencing gear runout”, To be submitted

Author’s contribution to the appended papers

Paper 1 Planning, major part of experimental work, evaluation and major part of writing.

Paper 2 Planning, experimental work, collection of data and major part of evaluation. Writing together with supervisor.

Paper 3 Major part of planning, experimental work and evaluation. Writing together with supervisor.
1. Introduction
The automotive industry produces a variety of high-precision steel-components for engine and transmission which are hardened and tempered. The requirements on finished parts are often extremely high, tolerances within a few micrometers are common. The stringent requirements are necessary in order to obtain transmissions with desirable characteristics, i.e. high efficiency, low level of noise, and high strength while also being lightweight and compact. Considering strength, the case hardening process is vital due to the improvement in mechanical performance of the steel, i.e. tensile strength, fatigue strength and wear resistance. However, an inevitable side effect of hardening is distortions which can have strong negative impact on performance and manufacturing costs if not being properly controlled.

1.1. Distortions
Distortion is defined in ISO 4885:2017 as “any change in the shape and original dimensions of a ferrous workpiece, occurring during heat treatment” [1]. In the latest version of the standard, the definition was complemented with the remark “the causes are manifold including not only the heat treatment process but also the workpiece geometry, steel inhomogeneity and the production conditions”. Hence, the causes for distortion are complex, and the traditional view of the heat treatment process, as the single contributing factor, has been nuanced. Today it is accepted that previous production steps also contribute to the distortions in varying extent. In this thesis, the term production conditions refers to conditions during the complete manufacturing chain, from steelmaking to hard machining.

The most common methods used in industry to minimise and correct distortions are press quenching, straightening and hard machining (e.g. grinding). Press quenching is mainly used for ring shaped components with large outer diameter to thickness ratio. It involves quenching in oil while simultaneously constraining the component to hold size and shape by the use of dies. For elongated components, e.g. shafts, prone to bend during hardening, 3-point straightening machines are normally used as a corrective measure. However, die quench equipment exists also for shafts. The idea is to rotate the shaft around its axis during quenching while simultaneously exerting pressure by fixtures matching the shaft profile. Although the above mentioned techniques are effective they may not be sufficient. Thus, grinding is often used as the finishing corrective measure. Although grinding offers high accuracy on final dimensions, it both adds costs and reduces the hardening depth since the process is abrasive. The use of grinding involves predetermined stock allowances that have to be tuned-in for the worst scenario, meaning excessive machining (over compensation) for most parts. Obviously, there are significant savings in minimising distortions and lowering its spread. This enables reduced stock allowance and thereby shortened process time, both in grinding and heat treatment. Other benefits that come with less distortion are elimination of non-value added activities such as; measuring of entire production batches, sorting parts by error size, reworking adjustable parts or scrap and replacing non-adjustable parts. Furthermore, since case hardening takes place late in the production chain, all scrap losses comprise value added from several machining processes.

1.2. State of the art
Due to the high costs related to distortions, extensive research has been conducted over a long period of time in order to avoid or minimise distortion. The research has been intensified during the last three decades due to the ever increasing demand of cost effective manufacturing. A comprehensive project was conducted at Bremen University in Germany, were the establishment of the Collaborative Research Center (CRC) was funded by the Deutsche Forschungsgemeinschaft (DFG) in 2001. The project involved scientists from several disciplines
(engineers, physicists and mathematicians). The project established the term “Distortion Engineering” which implies a methodical approach of treating distortions as a “system attribute” of the entire process chain [2]. The methodology consists of three levels of investigations. The first level identifies parameters and variables that influence distortions considering the entire manufacturing chain. The second level emphasises understanding of the mechanisms behind the distortions and relates them to the so-called “carriers of distortion potential”, identified as: component geometry, chemical composition/segregations, microstructure/grain size, residual stresses, temperature, and mechanical history, Figure 1. These carriers can be introduced and inherently stored in the workpiece during each production step, move along to subsequent process steps and increase/decrease in amount and direction. Some are introduced late in the process chain, like residual stresses due to clamping, and some are introduced early, e.g. segregations in the steel making. The third level aims for active correction by “deliberately introducing an inverse distortion” [3] counteracting the introduced “distortion potential”. This can be realised by controlled inhomogeneous heating/soaking and/or quenching. However, this requires, beside detailed information about the built in “distortion potential” linked to the workpiece, also fast in-process measurements and a fast control technique. Zoch [4] summarised the achievements within the CRC and concluded that the 11-year project contributed a lot to the understanding of distortion mechanisms and influencing parameters. He further stated that the compensation strategy could be proven successful for rings by the use of pre-set parameters; however the lack of fast in-process, high-resolution measurements did not allow for a fully controlled compensation.

![Figure 1](https://example.com/figure1.png)

**Figure 1  Carriers of distortion potential [4]. With permission from John Wiley and Sons.**

1.3. Outline and aim of the work

The aim of the current work is to investigate the main influencing factors on hardening distortions for serial produced gears. Data for analysis have been collected from test series performed on industrially manufactured components. This has allowed collection of a considerable amount of data enabling good statistical evaluation. The investigated factors have been limited to the existing production structure, however, with the possibility of enhanced traceability when considered necessary, e.g. all the way back to the steel plant casting process.

The studies are conducted on two types of components, crown wheels and main shaft gears. The crown wheels are of different size and geometry, the larger ones being press quenched while the smaller ones are free hardened. The main gears are free hardened. Both dimensional- and shape changes are analyzed. A summary of the investigated factors can be found in Table 1.
Table 1  Summary of investigated factors in the present study, studies conducted on crown wheels in paper 1 and paper 2, main shaft gears in paper 3.

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>LEVEL</th>
<th>PAPER 1</th>
<th>PAPER 2</th>
<th>PAPER 3</th>
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</thead>
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<td>Casting method</td>
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<td>x</td>
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<td>Casting geometry</td>
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<td>no. 1 / no. 2 / no. 3</td>
<td></td>
<td></td>
<td>x</td>
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<tr>
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<td>Stacking level</td>
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<td></td>
<td>x</td>
</tr>
<tr>
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<td>Position; Vertical / Horizontal</td>
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<td></td>
<td>x</td>
</tr>
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<td>Isothermal annealed / Controlled cooling</td>
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<td></td>
<td></td>
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<td>x</td>
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<td>x</td>
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</tbody>
</table>

The introductory chapter is followed by a chapter describing the manufacturing chain including some of the factors known from literature to have an impact on distortions. Chapter 3 describes the investigated components, the material, and the evaluated parameters. The results and discussions are found in chapter 4. The final chapter concludes the findings and suggests future research.
2. Manufacturing chain
The main steps in the manufacturing chain of most transmission components are: steel making, rolling, forging, annealing, soft machining, case hardening, and hard machining. Due to the vast difference required in both knowledge and equipment for the various manufacturing steps, the intermediate and final products are manufactured in three types of companies, i.e.; steel plant that casts the steel and rolls it into bars; forger that cuts the bars and forges the pieces into blanks followed by annealing; and finally a transmission manufacturer that machines the blanks into gear components, hardens them and finishes them by hard machining. Examples of end-products from each type of company can be seen in Figure 2.

![Examples of end-products from the involved manufacturing companies, a) steel bars produced at steel plant, b) blank produced at forger, and c) crown wheel machined and hardened at transmission manufacturer.](image)

2.1. Steel casting and rolling
Steel casting can be seen as the final step in the steel-making process. It is preceded by a primary- and secondary steelmaking. The primary step uses either pig iron, scrap, or a combination of them as raw material and involves melting and converting the raw material to steel by reduction of carbon. The secondary step involves thorough processing and control of e.g. alloying content, de-oxidation, inclusion removal, and degassing. The secondary steelmaking is also referred to as ladle metallurgy. Precise control of ladle metallurgy is related to producing steel grades with consistent and narrow chemistry. From a bottom hole in the ladle, the steel is teemed into the casting system.

The casting can be done by either ingot casting or continuous casting, Figure 3. The major difference between the casting methods concerns the solidification process. For ingot casting, the melt is teemed into a gating system, distributing the melt to several moulds, where the steel solidifies. For continuous casting, the melt is teemed into a tundish providing constant casting speed for further teeming of the melt into a water-cooled, vertical chill-mould, where a primary cooling occurs. This creates a steel shell, stable enough for further extraction to subsequent cooling zones, where a secondary cooling occurs. Additional melt is simultaneously teemed into the chill-mould from above forming a continuous strand of steel. The completely solidified strand, having passed all cooling zones, is then cut into desired lengths at the end of the discharge system.
In general, solidification of most alloys is accompanied by a phenomenon called macrosegregation. This could best be described as variations in local chemical composition, compared to the average composition [6]. Macrosegregation occurs at length scales near the dimensions of the casting, from centimetres to metres in the case of large ingots. The macrosegregation pattern is strongly influenced by the cooling conditions. Obviously, both casting technique and casting geometry will affect the cooling conditions and thereby have great impact on the macrosegregation pattern.

Illustrations and descriptions of macrosegregation patterns can be found in literature, e.g. by Lesoult [7]. He shows typical variations of carbon concentration for both ingot cast and continuous cast steel, Figure 4. For an ingot with nominal carbon content of 0.22 wt%, there is a “negative segregation cone” at the bottom centre of the ingot (0.16-0.18 wt% C) whereas the top centre has a positive segregation region (0.3-0.7 wt% C). The carbon content closer to the periphery, both at top and bottom, differs only slightly from the nominal value. For continuous cast material, Lesoult shows the carbon variation along the centre axis of a 1 m long steel slab. The content varies roughly between 1 and 1.5 times the nominal composition with an average of approximately 1.2, this type of segregation is referred to as centre line segregation. By comparing the two examples, one can see that both methods have big variations in carbon content. However, the ingot cast material has a more severe segregation going from strong negative to strong positive when moving from the centre bottom to centre top. The continuous cast material, has in general, a positive segregation at the centre throughout its length. Both casting methods show an enrichment of carbon in the last solidified parts.

A common method to reduce the centre line segregation for continuous cast material, is to apply electromagnetic stirring during casting. The stirring facilitates mixing of melt from the core, with melt from the two-phase region. The two-phase region consists of solidified steel, in the form of a dendritic network, and melt, sucked-in between the dendrites due to solidification shrinkage. The applied stirring, forces the melts of the two regions to mix. This keeps the melt more homogeneous during solidification, resulting in less macrosegregations.
An important factor for the outcome of hardening, connected to steel making, is hardenability [8-9]. Hardenability determines the steel’s ability to form martensite during quenching. It depends on the chemical composition and the austenitic grain size. Referring to Figure 1, it can be considered as a “carrier of distortion potential”. Hardenability is determined by experimental tests or calculations. The calculation formulas are based on regression analysis from empirical data. Basically, the hardenability is calculated by multiplying each alloying element with an individual factor, the same goes for the austenitic grain size, the sum of all terms gives the hardenability. It is easy to understand that variations in chemical composition, e.g. due to segregation, will also give variations in hardenability. If these variations persists through subsequent manufacturing steps, and still exist in the component to be hardened, one can easily imagine variations in hardness of the quenched component. Another aspect is the variation in hardenability between heats casted at different occasions. Thus, seen from a steelmaker’s point of view, hardenability is the most important factor to control from batch to batch in order to accomplish consistent distortion behaviour in heat treatment [10].

The cast products can have rectangular, square or round cross sections and be of various lengths, referred to as either blooms or billets. The dimension of the cross sections ranges from 150 up to 600 mm (seen diametrically or along the square/rectangular side). Ingot cast material are in general in the upper range, having larger cross sections. In an investigation by Gunnarsson [11], the influence of as-cast geometry on hardening distortions of press quenched crown wheels, made from continuously cast material with both rectangular and round form, showed that the as-cast shape had a dominating influence on the out-of-roundness of the central bore. The rectangular as-cast shape showed a larger ovality with higher variance in comparison to the round as-cast shape. However, another study by Gunnarson et al [12] on three free-quenched circular components, showed no coupling between the distortion and the as-cast shape.

Following casting, the blooms/billets are then re-shaped by hot rolling into smaller cross sections. This is also done by the steel plant, either directly after casting to make use of the stored heat, or later which then requires reheating. Hot rolling is beneficial for strength since cracks and pores are closed due to the high area reduction. For that reason, there is a minimum requirement for the reduction factor, i.e. the ratio of cross section area before and
after rolling, which in general should be at least 5. The rolling is done in several sequences and the finished bars are either square or round, irrespective of the initial shape. The dimension of the rolled cross sections range between 80 to 160 mm (seen diametrically or along the square/rectangular side).

2.2. Forging and annealing heat treatment

The next process step in the manufacturing chain is forging. The main benefits of forging are that complex-shaped steel-products can be serially produced obtaining high and consistent strength properties [13]. There exists several forging techniques, however, this discussion is limited to closed die forging, being the production technique used for the components in this study.

The first step consists of sawing the bars into pieces of predetermined lengths followed by induction heating to a temperature of about 1200-1300°C. The next step is pre-forming, which is done between two flat dies, simply reshaping the workpiece roughly in accordance with the needs of successive dies. Another positive effect is the removal of the oxide scale around the work piece. The workpiece is then placed in a die, which can be the first in a series. The forming is done by one or several hammer blows, forcing the metal to flow and fill the die cavity. This procedure is repeated for all succeeding dies. The excess metal, forming a flash, is then removed. The blanks are marked with a batch code, coupled to the forging occasion and steel heat for traceability.

The material flow connected to metal forming produces a banded pattern following the blank profile, which can be seen after etching. The banded pattern has its origin from the variations in local chemical compositions due to segregations from casting and the subsequent rolling, aligning the segregations in the rolling direction. The influence of these patterns on hardening distortion was investigated by Rentsch [14]. The study was conducted on gear wheel blanks and included both experiments and simulations. The experiments revealed a coupling between the material flow patterns, separated in two distinctive types, and distortion behavior. Simulations of material flow showed good agreement with experiments for one type but could not be reproduced for the other type, making it difficult to explain the cause for variation. However, simulations in a succeeding study suggested that asymmetric temperature over the billet height, e.g. due to hold time on the cold support, could be the reason for the variations in flow pattern [15]. Hence, a consistent and reliable forging process is important for keeping the temperatures stable and thus reduce the variations in the material flow pattern.

After the forging is completed, the blanks are cooled down, Figure 5. This can be done in a controlled way by adding a hold time at a set temperature in the range of 750-650 °C, before further cooling. This is referred to as controlled cooling and results in a mixed microstructure of ferrite and pearlite which is beneficial for the machinability. If the cooling is performed in ambient air without any control, the microstructure will result in a mixture of several phases (martensite, bainite, perlite and ferrite) being detrimental for machining. Thus, another annealing process has to be carried out, e.g. isothermally annealing. This involves reheating the workpieces above the austenitization temperature accompanied by a hold time to ensure uniform workpiece temperature. This is followed by forced cooling to ~650°C with isothermal hold time for at least 2-4 hours. Then, they can be further cooled in ambient air down to room temperature. The obtained microstructure consists of a ferrite-pearlite mixture which is finer that the one formed during controlled cooling as the extra austenitizing brings a finer microstructure to the steel. During hardening, this results in a smaller austenitic grain size with improved hardenability for the isothermally annealed blanks.
2.3. **Machining and case hardening**

The final part of the manufacturing chain involves soft machining, case hardening and hard machining. Soft machining comprises considerable removal of material. The machining is done in several steps of which turning and gear cutting remove most material. About 30-40% of the weight of the blank is removed during turning and milling for both crown wheels and main shaft gears. Crown wheels are also subjected to hole drilling, while main shaft gears are subjected to tooth shaping and pointing of clutch-teeth, and shaving of the milled helical gears. As the final step in soft machining, both components are deburred.

The case hardening process involves heating the parts to 940°C in a carbon-enriched furnace-atmosphere resulting in a carbon uptake at the steel surface. The high temperature implies a full austenitic transformation and thereby a faster diffusion of carbon into the steel from the carbon-enriched surface. After carburizing, the gears are quenched in oil, either one at a time in a press quench (crown wheels), or by submerging several gears simultaneously into an oil bath (main shaft gears), i.e. free hardening. During quenching, the carbon enriched surface will form martensite and thus become hard. The bulk material, not being enriched with carbon, will transform into a mix of structures, with bainite as the major component in the studied gears, leading to a tougher core.

The case hardening is performed in a pusher furnace, schematically shown in Figure 6. A brief description of the sequences at hardening are as follows. The gears are stacked on hardening trays (A), washed (B) and pre heated (C). The carburization is done in one of three furnace tracks (D), the movement forward is governed by pushing additional hardening trays into the furnace at a pace set by a predetermined cycle time. Depending on the quench method, the flows will be separated. The gears to be press quenched, are positioned at a picking station (E), picked one at a time by a manipulator (F), transported by an overhead gantry (G), every other placed in one of two quench presses (H), constrained by a fixture with pre-set pressures, oil-quenched, washed (I) and tempered (J). The gears to be free hardened on the other hand are, after passing the picking station (E), placed in an open elevator directly above the oil bath (K), and are swiftly submerged in the oil. After quenching, the free hardened gears are washed (I) and tempered (J).
Figure 6  Schematic overview of a pusher furnace including stacking station (A), washing zone no 1 (B), pre-heating zone (C), carburizing zone (D), picking station (E), manipulator (F), overhead gantry (G), three quench presses (H), washing zone no 2 (I), and tempering zone (J). Free hardened gears are quenched in oil bath (K) following the path A-E, KIJ. Crown wheels follow path A-J.

Quench pressing of crown wheels allows control of the inner diameter and the tilt of the back-face. In normal production, the press quench tooling consists of a solid lower die, a segmented central expander, an inner upper die and an outer upper die, as shown in the left-hand side of Figure 7. The expander, the inner and the outer dies are controlled independently by individually setting the corresponding pressure valve. The press forces from the outer upper die is distributed on two rings, enabling further distribution to the gear “toe” and “heel”, respectively. However, the outer and the inner pressures need to be adjusted relative to each other to avoid back-face tilting. Normally, both dies are pulsed every two seconds periodically releasing the pressure, allowing the part to contract freely as it cools without frictional contact to the lower die.

The right-hand side of Figure 7 shows another design of tooling. The main difference is the fixed mandrel onto which the inner diameter shrinks upon cooling. However, the back-face tilt is, as for the previously described tooling controlled by an inner and an outer die. Although, the position of the applied press forces differ, especially for the inner upper die.

**Quench press fixtures**

![Image of quench press fixtures]

Figure 7  Cross sections of two quench-press fixtures, left-hand side showing fixtures with a segmented central expander, right-hand side showing fixture with a fixed mandrel. Crown wheel indicated with bold contour.
Gears that are free hardened, can be stacked on hardening trays in various ways, e.g. in the two ways shown in Figure 8. The gears are simultaneously quenched by submerging the whole tray in an oil bath having forced upward oil flow due to agitation from an underlying, submerged piping system. Although the upward-flowing oil will enclose all parts, the quenching conditions will differ from part to part. This is due to a combined effect of the oil flow being inhomogeneous even before submerging the tray, the loading arrangement itself and its effect on the oil flow for various positions on the tray.

![Figure 8: Measured oil flow in quench bath with schematic positions of gears, a) vertical loading, b) horizontal loading.](image)

The influence of stacking conditions on distortions have been known for a long time, especially the importance of achieving a uniform heating of all parts and free access of furnace atmosphere to them [16]. Thus, a well-spaced stacking should be used. This will also favour similar cooling conditions from part to part since the interference between closely-stacked parts are reduced. However due to economic reasons in industry, well-spaced stacking conditions are seldom practised. A somewhat opposing solution is described in a recent study [17]. By introducing an extra mass at the bottom of the tray, under the stacked parts, both over-shrinkage and dishing of the bottom parts could be eliminated. The extra mass generated vapour bubbles by its massive thermal capacity which lead to a reduced early stage cooling, especially for the bottom stacked parts. Hence, the cooling conditions between parts, stacked at bottom and top of tray, became more equal.

The final machining is performed after hardening. This involves machining of the references, for crown wheels being the centre hole and back-face, for main shaft gears being the centre hole and hub-planes. During these operations, both components are clamped on to the gear teeth. An illustration for the main shaft gears is given in Figure 9. This operation finalises the manufacturing chain for this component. For crown wheels, on the other hand, grinding of gears finalises the manufacturing chain. During this operation, the crown wheels are clamped on to its references.
Figure 9  Illustration of clamping a main shaft gear during hard machining of centre hole and hub planes on both sides (grey).
3. Experimental
The studies were conducted on two types of components, crown wheels and main shaft gears. The crown wheels were of different sizes, being both press quenched and free hardened. The main shaft gears were free hardened. The material came from steel plants producing either ingot cast or continuous cast steel. The casting geometries were either square, round or rectangular. A limited number of forgers produced the blanks.

3.1. Materials
Both crown wheels and main shaft gears were manufactured from case hardening steels. The crown wheels from a steel similar to 17NiCrMoS6-4, while the main shaft gears were manufactured from a lower alloyed steel, 20NiCrMoS6-4, both given in Table 2.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Cu</th>
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<td>0.14</td>
<td>0.14</td>
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<td>0.40</td>
<td>&lt;0.35</td>
<td>&lt;0.05</td>
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</table>

3.2. Studied gears
3.2.1. Crown wheels
The crown wheels can be grouped in families according to their size, having the same inner- and outer diameter within the family, but slightly different heights and cone angles. Crown wheels from two different families are shown in Figure 10. Both of them have a large diameter-to-thickness ratio, making them distortion-sensitive. Thus, they must be press quenched. Crown wheels of type 2 can either have a flat back-face, lower part of Figure 10b, or a back-face with step, upper part of Figure 10b. Relating to Figure 1, the component (target) geometry can be considered as a carrier of distortion potential. Hence, the influence of geometry was investigated for crown wheels of type 1 with different cross-section area and for crown wheels of type 2 with flat- and step back-plane, respectively.

![Cross sections of crown wheels from two families](image)

The steel for the crown wheels originated from seven steel plants. The steel plants, identified as A-G, use different casting methods, as listed in Table 3, producing rectangular-, square- or round continuous strands or square ingots, respectively. The casting methods, either continuous casting or ingot casting, are denoted by CC and IC, respectively. Before delivery, the castings are re-shaped by rolling at the steel plants to a smaller cross section, except for C_{CC} and G_{CC} which are delivered as-cast. The degree of deformation due to rolling can be expressed as the reduction factor, given by ratio of cross section area before and after rolling.
Table 3  Process characteristics for the steel plants delivering steel to crown wheels, last column showing forger and steel plant connections.

<table>
<thead>
<tr>
<th>Steel plant</th>
<th>Casting method</th>
<th>Casting geometry</th>
<th>Reduction factor</th>
<th>Symbol</th>
<th>Forger</th>
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<td>Rectangular</td>
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<td></td>
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<tr>
<td>Bتعلق</td>
<td>Continuous</td>
<td>Rectangular</td>
<td>7 to 11</td>
<td></td>
<td>2</td>
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<tr>
<td>Aتعلق-NS</td>
<td>Continuous (not stirred)</td>
<td>Rectangular</td>
<td>5 to 7</td>
<td></td>
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<td>8 to 12</td>
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<td>6 to 11</td>
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<td>1; 2; 4</td>
</tr>
<tr>
<td>Cctor</td>
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<td>Square</td>
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<td>1; 3</td>
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<tr>
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<td>Continuous</td>
<td>Square</td>
<td>n/a</td>
<td></td>
<td>3</td>
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</tbody>
</table>

The hardening distortions for flat and step geometries for crown wheels of type 2, Figure 10 b, were studied for continuous and ingot cast material finding big variations for the combination of step geometry and ingot casting. To better understand the influence of ingot casting on distortions for the step geometry, a set of 86 crown wheels were investigated, linking information about each blank’s original position within the ingot (top, middle or bottom) to the experimental results. A summary of the investigated combinations with the number of investigated crown wheels can be seen in Table 4.

Table 4 Summary of tests comparing ingot cast and continuous cast crown wheels.

<table>
<thead>
<tr>
<th>Casting method</th>
<th>Heat No.</th>
<th>Crown wheel type</th>
<th>Ingot</th>
<th>Position in ingot</th>
<th>No. pcs</th>
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<td></td>
<td>H2</td>
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<td></td>
<td></td>
<td>Flat</td>
<td>*)</td>
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<td>38</td>
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<tr>
<td>Ingot</td>
<td>H3</td>
<td>Step</td>
<td>Ingot 1</td>
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<td>13</td>
</tr>
<tr>
<td></td>
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<td>14</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>bottom</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ingot 2</td>
<td>top</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>middle</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>bottom</td>
<td>16</td>
</tr>
</tbody>
</table>

*) A mix of several ingots
3.2.2. Main shaft gears
The studied main shaft gear is shown in Figure 11. The material originated from three different steel plants, all being continuously cast, but with different geometries being either square, round or rectangular. The round and rectangular strands were rolled into square cross sections while the square strand was rolled into a round cross section. The blanks were heat treated by either controlled cooling (CC) or isothermally annealing (IA). The material was then either stress relieved (SR), 650°C for 3h, or non-stress-relieved (NSR). The stress relief annealing, which is normally not included in the process, is carried out to reduce possible residual stresses in the blanks which can arise from inhomogeneous conditions during the annealing heat treatment. In order to see the effect from stress relieving, the Brinell hardness (HB 10/3000) of the blanks was measured.

![Main shaft gear](image)

Figure 11  Main shaft gear.

3.3. Distortion parameters
The base body dimensions were measured using coordinate measuring machines (CMM), Zeiss Contura or Zeiss Prismo. The gear geometries were measured using Klingelnberg P40 or P65. Moreover, a Faro Prime arm (portable CMM) was used for control of inner diameter and back-face tilt of press quenched crown wheels. This arm was used for measuring in soft condition, press quenched condition and tempered condition.

3.3.1. Crown wheels
Hardening distortions were analysed using three geometrical parameters: gear runout, inner diameter and back-face tilt. These distortions are schematically illustrated in Figure 12. The gear-runout measurement was performed by one-flank detection of every gear tooth flank using a spherical probe in a Klingelnberg P65 measuring machine. The back-face and inner diameter served as references during measurements. The gear runout can be described as wobble of the gear teeth and is illustrated in Figure 12a by warp. It should be emphasized that the gear runout after hardening was measured after hard turning of the inner diameter and the back-face but before grinding. The inner diameter and back-face tilt were measured with the Faro arm directly after hardening.
3.3.2. Main shaft gears

The hardening distortions for the main shaft gears were analyzed for the clutch teeth and the helical gears. The investigated parameters were concentricity, roundness and runout, the latter being a combination of the previous ones. The runout of both clutch teeth and helical gears are related to the centre hole, being the reference, see Figure 11.

The measuring procedure for runout, e.g. clutch teeth runout, can be explained with the aid of Figure 13. The location of the centre hole, being the reference, is measured and its geometrical centre point evaluated as a datum centre point (DCP). The clutch teeth positions are then measured, and described by the largest inscribing circle and the smallest circumscribing circle, both centred in the previously defined datum point. The radial distance between the circles is the runout.

As the clutch teeth and helical gear runout are affected by both concentricity and roundness errors, these parameters were closely followed after each production step. The interrelationship of these parameters during production can be theoretically discussed in relation to Figure 14. An ideal situation with zero runout shows no roundness errors and coinciding centre points for the centre hole and the clutch teeth Figure 14a. However, after hardening, both roundness and concentricity errors are found, Figure 14b. During subsequent machining of the centre hole, three helical gear teeth are used for clamping,
Figure 14c. Thus, the machining of the centre hole moves the DCP to coincide with the centre of the clamping points, Figure 14d. The hard machining will cause a random change of the runout of the clutch teeth, which will be either increased or decreased, depending on the concentricity between the helical gear teeth, centre hole and clutch teeth, respectively.

Figure 14 a) Ideal situation with zero runout, b) roundness and concentricity errors after hardening, c) clamping positions introducing datum point of post-machining, d) new datum centre point of centre hole.
4. Results and discussion
As pointed out in standard for heat treatment of ferrous materials, ISO 4885:2017, hardening distortions have their origin in steel inhomogeneity, workpiece geometry and production conditions. As a consequence, the results of the present work will be discussed in the same order. This means that results from crown wheels and main gears will be presented in parallel. Since a factor may have different impacts on hardening distortion in different directions, the influence of a factor on hardening distortion is closely linked to the direction of the studied geometrical feature. Thus, gear runout can be affected differently than back-plane tilt, for example, when something in the process chain is changed. As a consequence, the discussion must be based on a selected parameter.

4.1. Steel inhomogeneity
The effect of steel inhomogeneity is evaluated for two parameters, gear runout and back-face tilt.

4.1.1. Gear runout
The influence of steel inhomogeneity, i.e. macro segregations influenced by casting method and casting geometry, was investigated for two types of crown wheels, Figure 15 and a main gear, Figure 16. In both cases, but especially for crown wheels, the rectangular geometry gives the highest distortions. However, disabling the magnetic stirring during casting of rectangular strands, lowers the distortions of crown wheels down to the same level as round and square geometries. Admittedly, the results at this level do not vary much with respect to casting method (CC, IC), steel plant (C-G) and/or forging plant (1, 2, 3). Thus, these factors seem to have minor influence on hardening distortions while affecting the segregation pattern by enabling/disabling magnetic stirring, seems to have a strong influence. The influence of as-cast geometry on hardening distortions of various components has been discussed earlier [10]. In agreement with the present results, it could be seen that square or round as-cast shapes are beneficial over rectangular cross sections. In further agreement, it could also be seen that square and round strands produce similar results.

![Figure 15](image_url)

*Figure 15* Scaled runout averages, in relation to the worst group, for two types of crown wheels, shown above the two groups of bars. Each bar represents a steel plant, A-G, and a forger, 1-3. The shape of the symbols in the figure legend indicates the cast cross section. Error bars indicate 95% confidence interval.
For the main shaft gears, hardening distortions are expressed as roundness error after hardening, middle of Figure 16. The rectangular geometry gave the highest distortions, followed by round and square geometries. However, the difference is not at all as pronounced as for crown wheels. All material for the main gears was produced by continuous casting. Admittedly, two forging plants were used, one for rectangular and round strands and another one for square strands, making it difficult to conclude why the square geometry gave the lowest distortions. A comparison between controlled cooled (CC) and isothermally annealed (IA) blanks was also made. Only for rectangular strands, a slight difference was detected in favour for IA.

![Figure 16](image_url)

**Figure 16** Concentricity, roundness and runout for clutch teeth in percent of highest runout average. Two forgers were used, one for rectangular and round strands and another one for square strands.

### 4.1.2. Back-face tilt

The influence of casting method, continuous- or ingot casting, on back-face tilt was studied for crown wheels, Figure 17. The continuously cast material showed much less spread, which is very favorable for production control.

![Figure 17](image_url)

**Figure 17** Back-face tilt, a) showing all crown wheels according to running no, b) histogram of continuous cast with step design, c) histogram of ingot cast with step design, and d) histogram of ingot cast with flat design.
In order to understand the big variation in the ingot cast material, blanks were divided into three groups, top, middle and bottom, corresponding to their position in the ingot. Then, the test was repeated, Figure 18. Clearly, the top, middle and bottom groups separates into distinct groups of back-face tilts, with one exception. The first processed group, Ingot 1 Top (first green group) appears to have less back-face tilt than expected from the trends of the other data. This deviation could be caused by non-steady state conditions in the beginning of the test. The rest of the data, shows a very clear trend with back-face tilt decreasing from top to bottom.

Figure 18  Back-face tilt of top, middle, and bottom of ingot 1 and ingot 2 in machined and in quenched states.

The results from the two test series were compared by plotting the frequency distributions in the same diagram. The data from middle of Figure 17 (blue squares) and the data from ingot 2, Figure 18, (square symbols) were used as they combine the same casting method and crown wheel “step” geometry. When the position in the ingot is unknown, a bimodal distribution is found, solid line in Figure 19. When the position in the ingot is known, three distributions are found. The top and bottom, showing clearly separated peaks and the middle a flat, wide distribution. Combining the three groups, a bimodal distribution is found, dashed, thick line, just as in the first series.

Figure 19  Frequency graph showing bimodal distributions for ingot cast and step design of two heats (Ingot casting “step”, Figure 17c) and (Ingot 2, Figure 18).
In order to investigate the macro segregations, chemical analyses were made at three positions (A, B, C) in the cross section of the finished crown wheels. The results for carbon is seen in Figure 20, with a schematic illustration of the macro segregation in the ingot. The same trends, but with higher scatter, are found for the total alloying content (excluding carbon). Clearly, the top and bottom parts of the examined ingot show opposing trends from the center and outwards, the top with decreasing carbon content and the bottom with increasing.

The original locations in the ingot of the measured carbon concentrations were crudely estimated. Using Matlab, iso-carbon concentration lines were schematically constructed. These coincide very well with literature data on macro-segregations in examined ingots, refer to Figure 4, [7]. The carbon content in the C-positions are quite similar, indicating a small segregation. This correlates well with the early solidification in these points as they are close to the ingot wall where the solidification front starts. Naturally, the melt has not been able to form large segregations at this early solidification resulting in almost the same carbon content at these points. For the A-positions, the situation is quite opposite. They solidify late, especially the A-top position, giving time for much larger segregations. The top-A position has about 19% more carbon than the bottom-A position. Naturally, the carbon difference gives a corresponding core hardness difference. The HV30 core hardness goes from 395 at the bottom to 460 at the top, corresponding to an 18% increase. Considering these large chemical variations, it is not surprising that the back-face tilt of crown wheels differ, depending on the original position of the material in the ingot.

Figure 20  a) Average carbon content (average of 5 analyses) in three positions, A, B and C for top, middle and bottom, respectively. b) Schematic visualisation of the carbon content in an ingot, the crosses represent tentative positions of A, B and C, respectively.
4.2. Work-piece geometry
The influence of work-piece geometry was investigated for crown wheels with respect to gear runout and back-face tilt. The gear runout was investigated with respect to cross section area, whereas the back-face tilt was investigated with respect to the presence of a "step" in the back face. One design had a flat back face whereas the other had a step.

4.2.1. Gear runout
The gear runout was investigated for a family of crown wheels having the same inner- and outer diameters, a flat back face but different cross sections. The major difference between the crown wheels is the height of the gears. Thus, the difference is more-or-less expressed as slenderness, a larger cross section area corresponding to a more rigid crown wheel. The gear runout was plotted against cross section area, Figure 21. Clearly, a thinner cross section gives higher gear runout. The trends are more pronounced for the rectangular strands. The effect of disabling magnetic stirring is undisputable, compare A\textsubscript{CC-NS} with A\textsubscript{CC}. For round and square strands, the slenderness seems to be of less importance for the gear runout.

![Graph showing gear runout vs. cross section area](image)

*Figure 21* Scaled runout averages, in relation to the worst group, with regression lines, for crown wheels of type 1, all with outer diameter 424 mm, but with varying thickness. Error bars indicate 95% confidence interval. The crown wheels of type 1 in Figure 15, fall between 2.9 and 3.0x10\(^3\) mm\(^2\). Relation between steel plants and forgers, as in Figure 15.

4.2.2. Back-face tilt
The back-face tilt of two crown-wheel geometries were investigated, one having a step in the back face whereas the other was flat. The original data was presented in Figure 17a) with the corresponding distributions of the back-face tilt in c) and d), respectively. For clarity, the distributions are reproduced in Figure 22 together with the geometries. Both types have large spread in the data, but the distribution for the step design is clearly bimodal. For process control, the bimodal distribution is highly undesirable. In the present case, very few crown wheels will be produced without a back face tilt.

It is interesting to note that crown wheels with step design made out of continuously cast steel show a rather small spread, Figure 22a. This means that it is the combination of ingot casting and step design which is undesirable. The step design causes special challenges for press quenching as the step in the quench-press fixture is fixed whereas the step in the crown wheel varies with temperature and microstructure during quenching. Thus, for the same press settings, the height of the fixture may need to have different values for the ingot
top- and bottom material, respectively. For the flat geometry, on the other hand, where the contact between fixture and back face is always well-defined, the distribution is prevented from becoming bimodal, although the spread is still wide.

Figure 22  Distributions of back-face tilt for crowns wheels a) continuous cast with step, b) ingot cast with step and c) ingot cast with flat back-face. The geometry is indicated above each diagram.

4.3. Production conditions
Generally, influences from the production conditions are undesirable. It should not matter whether the product was soft machined in one or another line, carburized in one or another furnace, etc. However, sometimes, it is unavoidable that differences occur due to the design of the production facility.

For crown wheels, the influence of stacking level in the carburizing furnace on back-face tilt and inner diameter was investigated. For main shaft gears, the influence of loading arrangement on the hardening tray was investigated for the runout, roundness and concentricity. In addition, the effects on case depth, core hardness and surface hardness were investigated.

4.3.1. Press quenching
The influence of stacking level on the back-face tilt is seen in Figure 23. The data was taken from ordinary production representing several orders, heats, quench presses and press settings. In addition, the orders were processed at various periods of time. Despite this, it is possible to see a weak trend of decreasing back-face tilt from level 1 to level 5.

Figure 23  Back-face tilt of crown wheel type 2, split in groups of steel plant and stacking level. Error bars indicate 95% confidence interval.
The influence of material position in the ingot was previously presented in paragraph 4.1.2. Now the same data was further divided into material position and stacking level, allowing to analyze the influence of stacking level, Figure 24. A trend emerges, showing decreasing back-face tilt with increasing stacking level. The figure also demonstrates the importance of first dividing the results into groups of top, middle and bottom, and then to sub-divide these groups into levels. Although the trend is seen for the total group, second column in Figure 24, the separated data, columns 3-5 show much less spread and more clear trends. The same trend is also present for the continuous cast material, column1, supporting the finding of decreasing back-face tilt with increasing stacking level.

Figure 24 Back-face tilt of crown wheels from steel plants A_{CC-NS}, rectangular continuous cast, and steel plant F_{IC}, ingot cast. The ingot cast crown wheels are first shown in total and then separated into top, middle and bottom.

Another important parameter to control during press-quenching is the inner diameter. To some extent, it can be increased by increasing the pressure on the inner expander. See Figure 25 where three production orders and one test order are compared. The two first orders, quenched with an expander pressure of 17 bars, generally show larger inner diameters than the third one, quenched with only 1 bar expander pressure. However, in all cases there is a clear trend for increased inner diameter with increased stacking level.

Figure 25 Average inner diameter for three production orders and one test order vs. stacking level. The first and last orders are rectangular continuous cast while the two in the middle are quadratic ingot cast. Error bars indicate 95% confidence interval.
The last column in Figure 25 shows a test series, quenched in another quench press using a fixed mandrel. Clearly, there is no influence of stacking level when a fixed mandrel is used. Thus, there is a big difference between quench pressing crown wheels using a central expander or a fixed mandrel.

In order to investigate the influence of stacking level further, the temperatures of the crown wheels were measured before entering the quench press. The temperature difference from the calculated average was evaluated. Similarly, the inner diameter changes due to hardening were measured. The deviations from the average diameter change were plotted against the deviations from the average temperature, Figure 26. Clearly the levels form distinct groups. The trend through all data was compared with the calculated theoretical diameter change due to thermal shrinkage before placing the crown wheels in the quench press. The obtained trend has a slope, that is a bit smaller than the theoretical line. The difference may be attributed to the opposing effects by the expander and the phase transformations during quenching. Clearly, the temperature differences have no influence when quenching on a fixed mandrel which can withstand much stronger shrinkage forces than the expander.

![Figure 26](image-url)

**Figure 26** Deviations from average inner diameter change (soft to hardened and tempered) vs. deviation from average temperature before quenching. Colors indicate stacking level. The dotted-dashed line indicates the theoretical diameter change due to thermal shrinkage. The dashed line shows regression line for all data, with an $R^2$-value of 0.83.

### 4.3.2. Free hardening

Free hardened components are quenched by submerging the whole tray in an oil bath. The loading arrangement may thus have a great influence on distortions. In addition, each component has an individual position on the tray giving them individual quench conditions and possibly also different hardening distortions.

In order to investigate the influence of loading arrangement, main shaft gears were hardened in two loading arrangements. In the first one, 12 gears were vertically arranged on two bars and in the second one, 12 gears were horizontally arranged. The results, Figure 27, shows that the mid-position on both bars, position 3 and 9, tend to give higher distortions. The horizontal arrangement gives considerably less roundness errors leading to less runout errors as well. However, the horizontal arrangement also gives an increased flatness error (not shown in the figure).
The concentricity errors for helical gears and clutch teeth were evaluated for the vertical arrangement, Figure 28. As seen, the errors are small in the soft machined condition. After hardening, the error has increased for helical gears. In the final hard machining of the centre hole, three randomly selected helical teeth are used for clamping. As a result of this procedure, the concentricity error increases considerably for the clutch teeth. Even the concentricity error of the helical gears increases. During hard machining, the three helical gears used for clamping, determine the movement of the centre hole. This gives a random movement of the centre hole and thus a random relative motion between centre hole and clutch teeth. Generally, random displacements increase the spread. In this case, it increases the concentricity error for the clutch teeth. For the same reason, the random centre hole displacement gives an increase of the concentricity error for the helical gears themselves.

Returning to the roundness errors, they could be described as an oval with a given direction, Figure 28. For two thirds of the main shaft gears, the direction of the oval fell into one direction for the upper bar, and another one for the lower bar. As seen, the orientations are rotated relative to each other. It is plausible that the lower bar is located in an undisturbed, upright oil-flow, giving an oval orientation in line with the main oil flow and that the upper bar is located in a disturbed, partly heated oil flow with less cooling capacity near the lower bar. As a result, the oval on the upper bar is rotated.
Figure 28  

(a) Position of centre points (CP) of clutch teeth and helical gears, relative to the datum centre point (DCP) for the soft machined, hardened and hard machined conditions. (b) Orientations of clutch teeth oval roundness errors. For both figures; (x,y) = (tray direction, up).

The influence of position on hardening parameters, case depth, core hardness and surface hardness, Figure 29, was investigated. A clear trend of increased surface hardness can be seen along both bars, position 1-6 (upper) and 7-12 (lower). A similar trend is seen for the core hardness, but less clear because of higher scatter. The increased hardness values along the bars coincide with increased oil flow measured in the empty oil bath. Hence, the higher hardness can be attributed to better quenching.

The case depth shows no trend, but when it is evaluated for the lower (6 o'clock) and upper teeth (12 o'clock), there is a clear difference. The lower teeth have higher case depth than the upper ones.

Figure 29  
Hardening parameters for vertical positions, 1-3-6 and 7-9-12, for the whole vertical population, and for horizontal population.
The horizontal arrangement gives higher surface hardness and higher core hardness but lower case depth than the vertical arrangement. As the difference in case depth between the two loading arrangements is similar to the difference between upper and lower teeth for the vertical arrangement, the hardness profiles were investigated, Figure 30. As seen the hardness is generally higher for the lower teeth between 0.3 and 1.5mm giving a higher case depth. The surface hardness, on the other hand, is very similar for upper and lower teeth. Comparing the loading arrangements, the hardness profiles are very similar below 0.7 mm, the vertical loading having slightly higher case depth. The surface hardness is clearly highest for horizontal loading. It could be emphasized that it was not possible to link hardening distortions to the observed hardening parameters.

![Figure 30](image)

Figure 30 Hardness profiles for a) vertical loading of 18 gears evaluated for upper and lower teeth, average of all positions and b) vertical (upper and lower teeth on 18 gears) and horizontal (4 teeth on 4 gears) loading.

The influence of pre heat-treatment of blanks was investigated by applying an extra stress-relief annealing. The annealing lowered the hardness of the blanks, but had no influence on the clutch teeth runout, Figure 31. However, there is a trend of increased clutch teeth runout with increased hardness of blanks, but this trend seems to be caused by some other factor influencing both hardness and distortions. Thus, there is no direct coupling between hardness and distortions. In addition, there are no residual stresses in the blanks giving rise to hardening distortions. If residual stresses were important for hardening distortions in the studied case, the stress-relief would have had a clear effect.

From a production perspective, it would be of great importance if the distortions could be maintained at the level found for the square continuous strands with the lowest hardness. However, it is difficult to point out why the low-hardness blanks give low hardening distortions.
Figure 31  Clutch teeth runout after hardening, normalized to the worst group, vs. Brinell hardness of blanks. Non stress-relieved groups are connected by a solid line, stress relieved by a broken one. Filled symbols represents controlled cooling (CC) and open isothermal annealing (IA), respectively. The shapes of the symbols indicate the shapes of the continuous cast strands.
5. Conclusions and future work
The results of the present thesis are summarized in Table 5 by marking the distortion parameters significantly affected by various factors.

The casting method influences the back-face tilt of crown wheels because of segregations in ingots. The top and bottom parts of an ingot show opposite segregations and produce opposite back-face tilts.

The casting geometry affects the gear runout of both crown wheels and main gears and also the roundness of main gears. For crown wheels, continuous cast rectangular strands produce very high runouts but by disabling the magnetic stirring during casting, the differences to other casting geometries disappears. For main gears, the roundness is best for square strands and worse, but quite similar, for rectangular and round strands. The runout, affected by roundness, follows the same trend.

The influence of forger was investigated for crown wheel without finding any influence.

An effect of loading arrangement with respect to stacking level was indicated for the back-face tilt and could clearly be seen for the inner diameter of crown wheels. The effect for the inner diameter could be explained by temperature variations of the crown wheels, when placed in a quench press equipped with a central expander. However, replacing the central expander with a fixed mandrel, removes the effect of stacking level completely. This is natural as the fixed mandrel gives a precise inner diameter whereas the expander oppose shrinkage by a preset force, not corresponding to a fixed inner diameter. For the main gears, no differences could be found for upper and lower bars using vertical loading arrangement. On both bars, a tendency was found for the mid positions to give higher distortions. Switching from vertical to horizontal arrangement gave considerably less roundness and runout errors but increased the flatness error.

The effects of annealing heat treatment and stress relief annealing were investigated for the main gears. No significant effects could be detected.

The effect of component geometry was investigated for crown wheels. It was found that slender crown wheels are more prone to give high gear runouts for rectangular, continuous cast strands. For round and square strands, the effect of slenderness is small. It was also found that a step in the back face affected the distribution of back-face tilt for ingot cast material. A flat back face produced a normal distribution whereas a step geometry produced a bimodal distribution, both with wide spread. For continuous cast material, on the other hand, the step geometry produced good results with a normal distribution of considerably less spread. Thus, the bimodal distribution is due to a combination of ingot casting and step geometry.
Table 5  Summary of factors that, in the present study, are found to significantly affect hardening distortions.

<table>
<thead>
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<th>FACTORS</th>
<th>LEVELS</th>
<th>CROWN WHEELS</th>
<th>MAIN GEARS</th>
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<td></td>
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<tr>
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<tr>
<td></td>
<td>Step / Flat</td>
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</table>

In future work, the effect of segregations will be investigated. In an ongoing project (FFIFF, funded by Vinnova), cut billets from ingots and strands will be forged in different directions relative to the rolling direction. This will produce different segregation patterns in the blanks. The segregations will be characterized and linked to the observed hardening distortions.

Simulations will be used to investigate effects from various cooling conditions. It will also include directional variations of dimensional changes due to phase transformation. Experimental information will be collected by dilatometry experiments.

The effect of the vapor-phase during oil quenching will be investigated by applying different pressures over the oil bath. The activities are planned within the VBC consortium (Värmebehandlingscentrum) in collaboration with Swerea IVF.
6. Acknowledgements

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Anders Olofsson, Södertälje, May 2017
7. References


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