FFI

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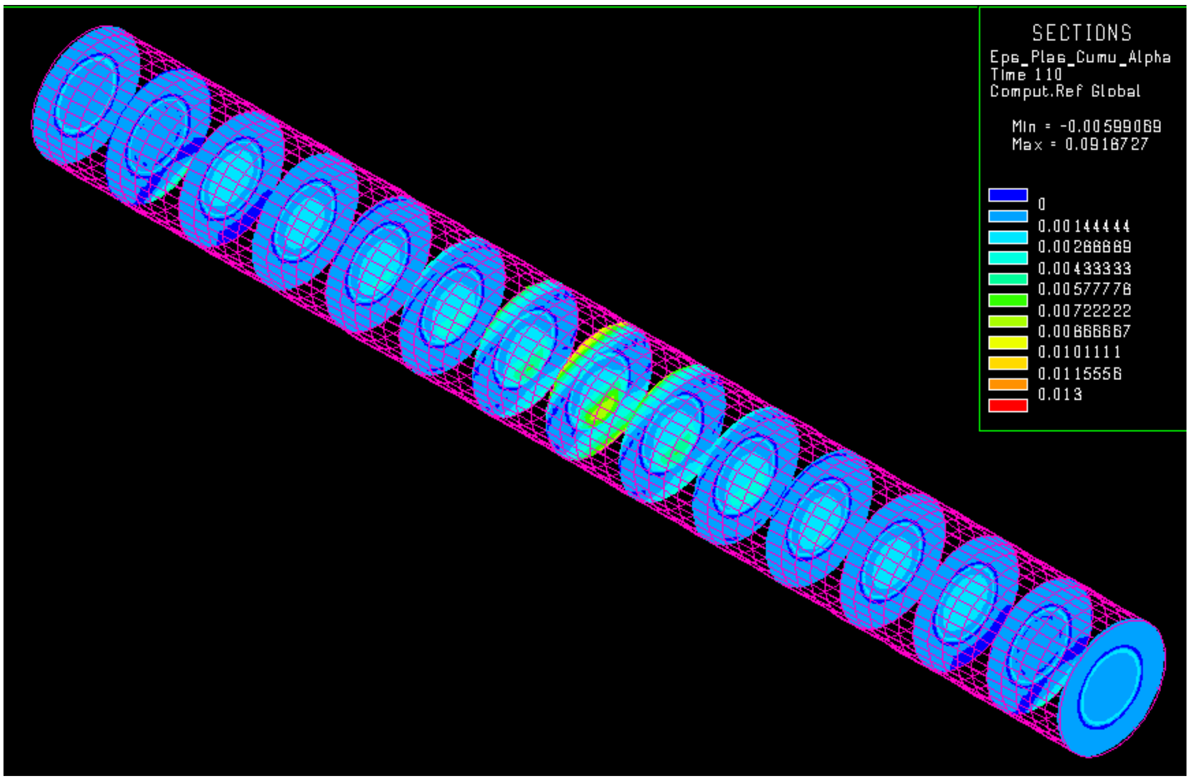

Project within FFI Vehicle and drive line production

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently

there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**
For more information: www.vinnova.se/ffi

Executive summary

Straightening of components after heat treatment is a common procedure in the industry. Typically, elongated components such as shafts and bars are distorted after heat treatment in such a way that straightening is necessary to obtain the desired shape. The straightening operation leads to local plasticisation of the component. This has an effect on for example the residual stress state and the hardness, parameters with strong influence on the fatigue strength of the component.

The objective of this study was to evaluate the influence of straightening on bending fatigue properties, the residual stress state, microstructure and hardness of induction hardened test bars. Straightening was made using three point bending on cylindrical shafts. The residual stress state and hardness were evaluated, before and after straightening. Fatigue testing was performed in three point bending, after rotating the shaft 60° after straightening, i.e. towards 120° direction. In addition to this FEM-simulations of straightening has been performed in order to formulate guidelines for straightening. The simulations were performed on a virtually induction hardened shaft of the same dimensions as used in the experiments.

It was concluded that straightening affects the residual stress state along the entire circumference of a component. The fatigue strength at 120° was 7 % lower after straightening with 80 kN load and 20 % lower after straightening with 97 kN load.

Residual stresses were affected differently around the perimeter of the shaft. At the point of straightening force application (0°) the compressive residual stresses after heat treating turned to tensile. At the opposite side at 180° the residual stresses turned more compressive than before straightening. At 120° and 240°, the stresses were negatively affected and the residual stresses turned less compressive. The higher of the two straightening forces had even more negative effect on residual stresses.

The simulations showed similar changes in residual stresses as were experimentally found. It was concluded that reversed straightening should be avoided and that at higher forces used with combined straightening operations at an angle compared to the desired straightening direction is preferable if larger corrections needs to be done.

The simulations performed in the project have been important for understanding and explaining the influences of a straightening operation, especially the differences between carburised and induction hardened components.

Background

The influence of straightening of case hardened test bars has been studied in previous projects within VBCentrum. The influence of straightening on mechanical properties has been studied and a minor investigation was made on the influence of straightening on the residual stress state on the perimeter (0°, 90° and 180°) of test bars [1]. The results were however somewhat ambiguous. Possible reasons for this were that residual stress measurements were made on the case hardened surface, and that the straightening force was difficult to control in the straightening equipment used.

The literature study showed that little research has been done on the effects of straightening on mechanical properties and especially fatigue properties.

Fahlkrans et al [2] studied the influence of straightening on case hardened shafts in three point bending fatigue tests. The shafts were straightened in three point bending mode and then fatigue tested either in the same direction, (0°), or in the opposite direction, (180°) to the straightening direction.

It was shown that the residual stress state was altered by straightening. Compressive residual stresses increased at the point of applying the load (0°) and at the opposite side (180°). However, compressive residual stresses were negatively influenced at the position representing 120°.

Fatigue testing showed that the fatigue strength increased after straightening, if testing was made to yield maximum load at 0°.

Fatigue testing was to apply maximum load towards 120° was not initially part of the project. However, a short test series was made with remaining shafts. The test series indicated that fatigue testing in this direction lead to decreased fatigue strength, by 4-5 %.

Objective

The first objective of this study was to evaluate the influence of straightening on bending fatigue properties, the residual stress state, microstructure and hardness of induction hardened test bars. The second objective was to formulate guidelines for the straightening procedure based on FEM-simulations.

Project realization

Shafts of diameter 25.7 mm were used. The length was 250 mm. The material was SS2244 (EN 42CrMo4). The shafts were induction hardened by scanning induction heating and quenched in a polymer solution. The induction hardening depth (DI) was 6.5 mm at 400 HV1. The straightening procedure was imitated using a MTS machine with a 100 kN load cell. Fatigue testing was performed in the same MTS machine as for the straightening procedure. Three point bending fatigue with 200 mm between the supports was applied. For fatigue testing, a roll was used for load application (instead of the tool used for straightening). The setup is shown in Figure 1.

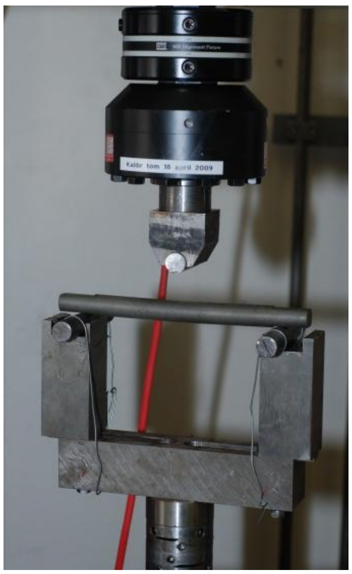

Figure 1 Experimental setup for fatigue testing

FEM-simulations

The shaft used for testing the bending fatigue properties after straightening has also been simulated using FEM (software: Sysweld from ESI). Material data was for the steel grade 42CrMo4 from the internal Sysweld database. In most of the calculations the standard model for isotropic hardening was used. The effect of transformation induced plasticity (TRIP) was also included in the calculation with the standards settings recommended by Sysweld. A full 3D-modell was used, see figure 2, utilizing 67200 element 57871 nodes.

The simulation of the induction hardening process was made by a surface power heat source which was tuned to give a hardened zone depth of half the radius after quenching without exceeding a surface temperature 1050 °C. The definition of the hardening depth was the depth where the martensite volume fraction exceeded 40%. The whole surface was heated at the same time which means that the heating was according to single shot approach. Quenching after heating was performed by using a set of surface temperature dependent heat transfer coefficients with a maximum value of 12 600 W/m·ºC at 500°C. *[3]*

The straightening was simulated by implementing nodal forces in a pattern resembling the tool used in the real experiments. The action of the anvils was simulated by locking nodal movement of the nodes representing the real anvils in the x- and y-direction.

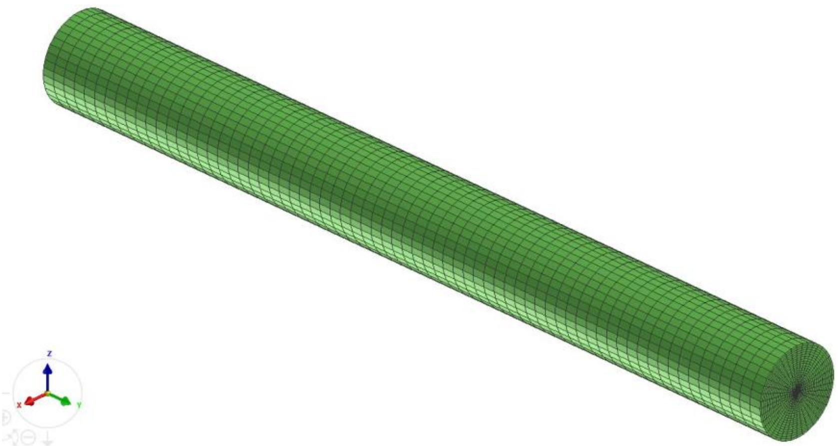

Figure 2 Meshed geometry for the simulated shaft with 67200 element/57871 nodes

In *figure 3* the martensite distribution after heating and quenching is shown for the case were the hardness depth is half the radius. In *figure 4* it can be seen in the axial cross-section how the calculated stress state appears in the axial, tangential and radial directions before straightening

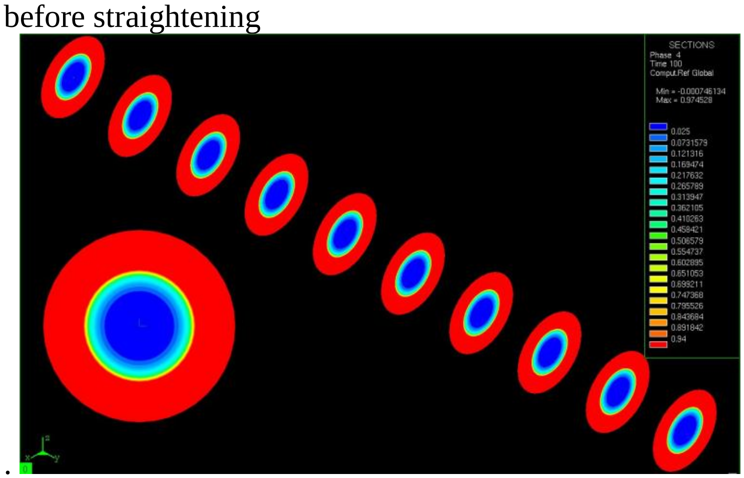

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Bild 3 Martensite distribution in the shaft in axial direction. In lower left a magnification of the distribution in the z-x-plane is shown

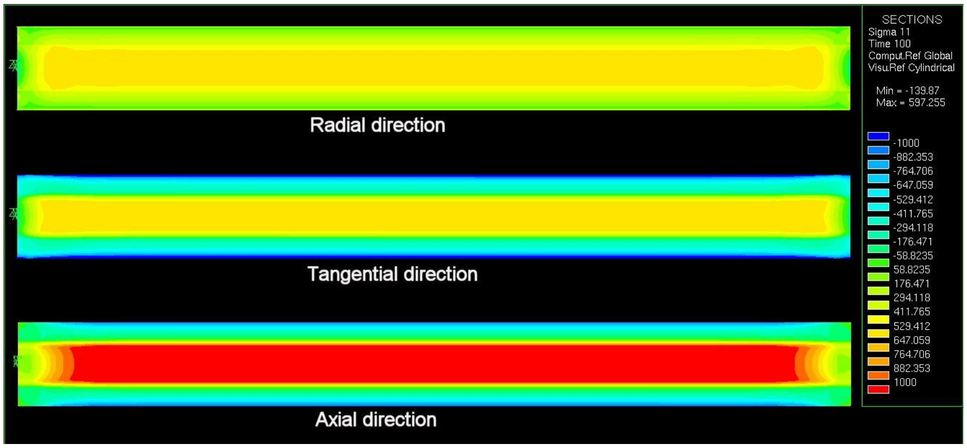

Bild 4 Calculated residual stresses after heating and quenching

Results and deliverables

Fatigue properties after straightening

The fatigue strength was determined by using the staircase test method. The results are shown in *figure 5*. The fatigue strength was lowered by 7 % by straightening to 80 kN, and by some 20 % by straightening to 97 kN.

The differences between the fatigue strength of the reference and that of both straightened test series were statistically significant using a t-test. Also the difference between straightened test series was considered statistically significant.

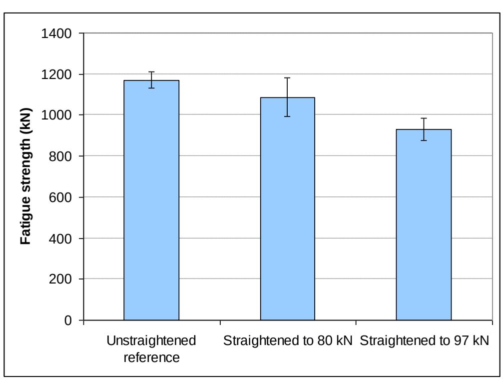

Figure 5 Results from fatigue testing

Residual stresses after straightening

The residual stresses were measured at a depth of 25 microns below the surface by means of x-ray diffraction before and after straightening. Before straightening (after heat treatment) the residual stresses were approximately -300 to -350 MPa and -350 to -450 MPa in axial and tangential directions respectively.

Several stress measurements were made in order to evaluate the influence of straightening on residual stress around the circumference of the shafts. *Figure 6*Figure shows schematically the location of the measurement positions. The stress was measured at every "hour" of the shaft from 0 to 180°. An additional measurement was made at 9 o'clock for verification. In order to avoid uncertainty of measurements, each measurement was made after etching to about 25µm. The depth of 25 µm was considered sufficient based on the stress profile above.

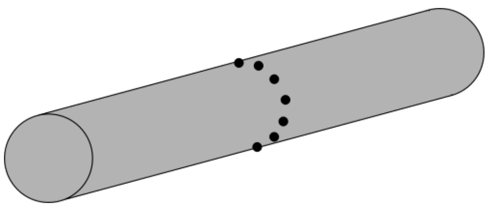

Figure 6 Schematic illustrations of measurement and etching locations

Figure 7 shows the residual stresses along the circumference of the shafts. The blue solid line shows the unstraightened reference. Straightening resulted in lowering of compressive stress at the position of 120°, just as previous investigations and simulations have shown. At 120° straightening led to a decrease in compressive residual stress from -350 MPa to -215 MPa at 80 kN straightening force and to -100 MPa at 97 kN straightening force.

At 150° to 180° the stresses increased substantially after straightening. The reason was the elastic recovery after releasing the straightening force. For 0° to 30° the stresses were tensile after straightening. This is due to the contact pressures from the tool during straightening.

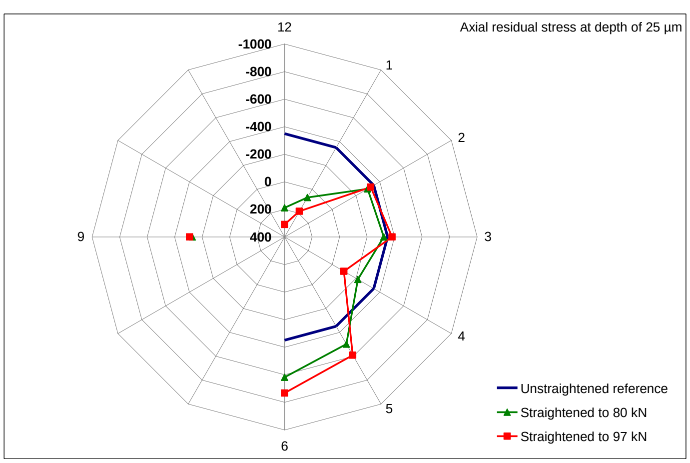

Figure 7 Polar plot of axial residual stress at 25 µm

Results from straightening simulations

Below shows the influence of the different straightening procedures as the changes in axial residual stresses in the area that has been mostly affected i.e the radial cross-section at the half of the length of the test specimen. The figures show the stresses around the circumference starting from the top where the straightening load is applied, eg. at 0°. In order to illustrate the permanent deformation achieved after straightening the residual deformation in the negative z-direction for the node in the centre of the node group used for the straightening tool was used.

Straightening with different loads

The effect of different straightening force on residual stresses when the straightening force was applied in the 0° direction is shown in *figure 8* and on residual deformations is shown in *figure 9.* Note that the residual stress change is larger for higher load and largest in the 0° direction. Also in the 120° and 240° there are peaks in residual stress change. This is exactly in line with the experimental findings for induction hardened samples, see *figure 7*. The residual deformations after unloading are in the same range as the experimental findings.

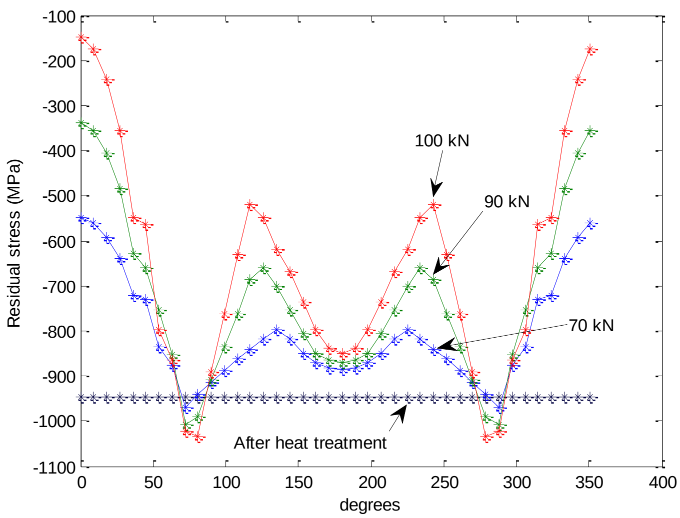

Figure 8 The effect of different straightening force on residual stresses.

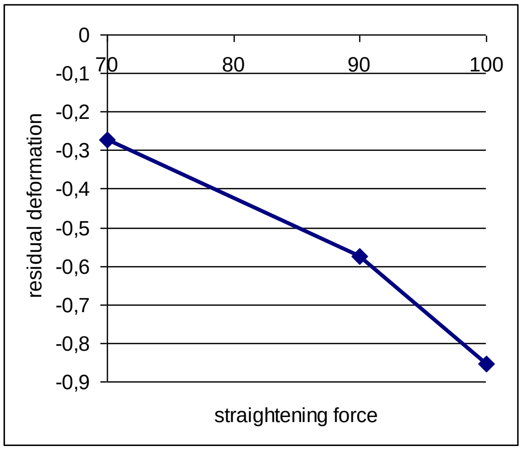

Figure 9 The effect of different straightening force on residual deformation.

Combined straightening in ±15° and ±30° directions

Some commercial straightening equipment performs straightening in a direction different from the desired straightening direction. Instead a combination two (or more) straightening strokes of ± x° from the desired correction direction is used. Thereby several straightening operations are performed in a sequence resulting in a straight component. *Figure 10* shows the residual stresses around the circumference after one straightening operation at different angles with 90 kN. As expected the results are the same but transposed to different angles. In *figure 11* the residual stresses are shown after two straightening operations and it can be seen that two operations in the 0° direction does not change the residual stresses at all. In the 15° the residual stresses are somewhat negatively affected and in the 30° incrementally more negative. However, as can also be seen in *figure 12* the residual deformation in the z-direction is increased with about 10%.

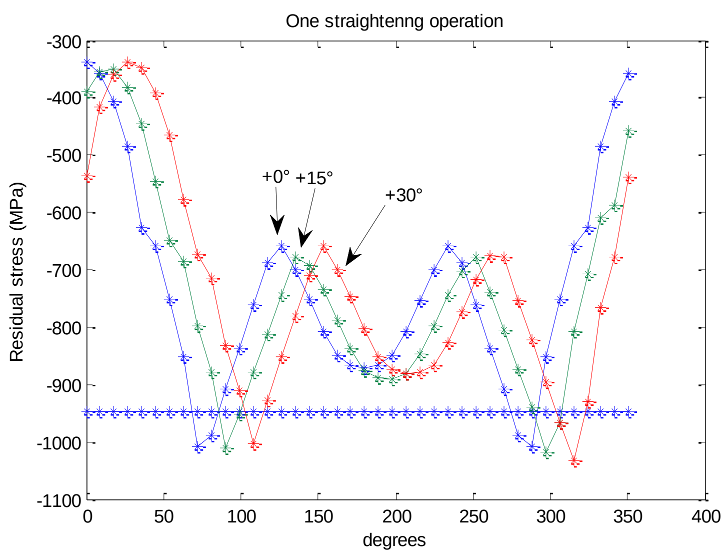

Figure 10 The effect of different direction of straightening force on residual stresses after 1st stroke.

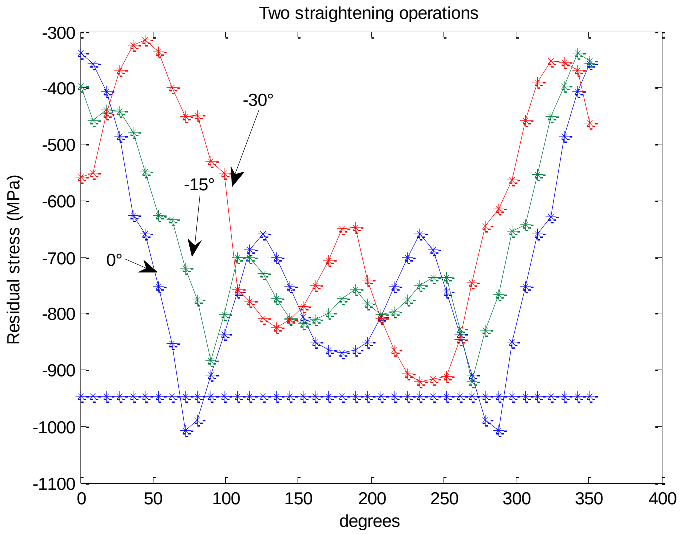

Figure 11 The effect of different direction of straightening force on residual stresses after 2nd stroke.

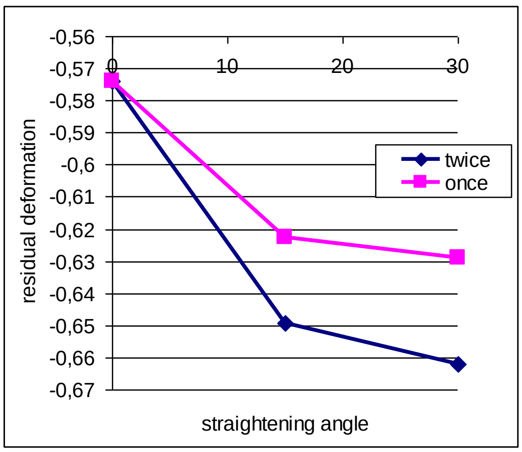

Figure 11 The effect of different direction of straightening force on residual deformation after 1st and 2nd stroke.

By increasing the number straightening operations the residual deformation can be increased for a given load.
It can be concluded that by making several straightening operations at an angle deviation from the desired straightening direction more residual deformation can be achieved without increasing the applied load. Similarly this implies less negative effect on the residual stresses for the same residual deformation.
By using combined straightening it is possible that deformation is introduced in new directions. These deformations are however very small and can be controlled by tuning the force in the second straightening step.

Conclusions and future research

The most interesting conclusions that can be made from the experiments performed in this study are:

- Straightening affects the residual stress state along the entire perimeter (on the axial centre) of a component. The fatigue strength was affected by straightening as well.
- The fatigue strength was evaluated with maximum stress at the point of 120°. Straightening with 80 kN resulted in about 7 % lower fatigue strength, while straightening to 97 kN lead to some 20 % reduction in fatigue strength.
- Residual stresses were affected differently around the perimeter of the shaft. At the point of straightening force application (0°), the compressive residual stresses turned to tensile. At the opposite side (180°) the residual stresses turned more compressive than before straightening. At 120°, the stresses were negatively affected and the residual stresses turned less compressive.
- Compressive residual stresses were negatively influenced by straightening at the point of 120°. The higher of the two straightening forces had even more negative effect on residual stresses.
- By making several straightening operations at an angle deviation from the desired straightening direction more residual deformation is achieved without increasing the applied load. Similarly this implies less negative effect on the residual stresses for the same residual deformation.
- By using combined straightening it is however possible that deformation are introduced in new directions. These deformations are however very small and can be controlled by tuning the force in the second straightening step.
- Large case depths (as for induction hardening) give the largest change in residual stress at 0°, i.e. where the straightening force is applied. For more shallow case depths (as for carburised components) the largest changes occur in the 120° and 240° directions. This is caused by a larger plastic deformation of the core for more shallow case depths
- Reversed straightening should be avoided since it changes the residual stress state even more negatively and introduces a new point with poor properties

The following areas have been identified as interesting for future research

- A limited study of the influence of strain hardening approach used in simulation was included in this work (not displayed in this short report). This is an important matter when multiple straightening in different directions is applied. This area should a subject for further research.
- It is known that the tempering and when it is performed, before or after straightening, affects the potential of how large magnitudes of distortion that can be corrected using straightening. This needs to be more investigated in detail using both experiments and simulations.

5.1 Delivery to FFI-goals

The project addressed the target of reduced CO_2-emissions through reduced weight or improved performance by reducing the negative effect of straightening of powertrain components. The result is that a greater understanding has been gained of how straightening must be performed in order to minimize its negative effects.

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Dissemination and publications

6.1 Knowledge and results dissemination

The project has a strong coupling to other projects within FFI such as Realistic Verification, KUGG1 and 2 and In-line Non Destructive testing all performed within the KT-cluster. There is a strong believe that cooperation between the KT-cluster and the so called "Utbildningsklustret"-cluster would be one important factor for promoting a quicker implementation of all the projects mentioned above.

6.2 Publications

The project results have been a part of Johan Fahlkrans licentiate thesis work. An article with the title "Straightening of induction hardened shafts – influence on fatigue strength and residual stress" by Johan Fahlkrans, Arne Melander och Johannes Gårdstam has been sent to the scientific publication HTM.

A contribution for the 6th Conference of Thermal process modeling and heat treatment simulation 2013 is planned.

Results from project have been presented at the "KT-kluster-dagarna" in Katrineholm 2010 and at the VBCentrums yearly meetings at 2009 and 2010.

References

[1] Mats Randelius, Johan Åslund, Seyed Hosseini (2008). Straightening of case hardened bars before or after tempering – a literature survey and experimental study. VBCentrum report VBC-R-2008-001.

[2] Johan Åslund, Seyed Hosseini, Sven Haglund (2009). Influence of straightening on fatigue properties – a study of bending fatigue and residual stresses of case hardened SS2511 steel. VBCentrum report VBC-R-2009-004.

[3] H.Kristoffersen; Kylning vid induktionshärdning– mätning av kylförlopp, VBC-R2007-005

Participating parties and contact person

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