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# Residual stress state in an induction hardened steel bar determined by synchrotron- and neutron diffraction compared to results from lab-XRD

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ABSTRACT

Induction hardening is a relatively rapid heat treatment method to increase mechanical properties of steel components. However, results from FE-simulation of the induction hardening process show that a tensile stress peak will build up in the transition zone in order to balance the high compressive stresses close to the surface. This tensile stress peak is located in the transition zone between the hardened zone and the core material. The main objective with this investigation has been to non-destructively validate the residual stress state throughout an induction hardened component. Thereby, allowing to experimentally confirming the existence and magnitude of the tensile stress peak arising from rapid heat treatment. For this purpose a cylindrical steel bar of grade C45 was induction hardened and characterised regarding the microstructure, hardness, hardening depth and residual stresses. This investigation shows that a combined measurement with synchrotron/neutron diffraction is well suited to non-destructively measure the strains through the steel bar of a diameter of 20 mm and thereby making it possible to calculate the residual stress profile. The result verified the high compressive stresses at the surface which rapidly changes to tensile stresses in the transition zone resulting in a large tensile stress peak. Measured stresses by conventional lab-XRD showed however that at depths below 1.5 mm the stresses were lower compared to the synchrotron and neutron data. This is believed to be an effect of stress relaxation from the layer removal. The FE-simulation predicts the depth of the tensile stress peak well but exaggerates the magnitude compared to the measured results by synchrotron/neutron measurements. This is an important knowledge when designing the component and the heat treatment process since this tensile stress peak will have great impact on the mechanical properties of the final component.



## 1. Introduction/background

Residual stresses can be introduced by different processes and can roughly be divided into mechanical or thermally induced, or a combination of the two mechanisms [1]. Shot peening of a surface is an example of a process to mechanically induce residual stresses while the residual stresses arising from induction hardening instead are an example of thermally induced residual stress. The induction hardening process is performed with a relatively rapid heating of the steel surface followed by rapid quenching. This process creates a distinct difference in microstructure between the surface and the core of the material where the surface has undergone a martensitic transformation and thereby causing a strain in the atomic lattice due to the larger specific volume of martensite. This process results in compressive stresses in the hardened region and tensile stresses in the non-hardened sub-surface [2].

In general, residual stresses generated by for instance induction hardening are conventionally measured by means of x-ray diffraction (lab-XRD). This technique can be used non-destructively if the measurements are performed on the surface. However, often the residual stress state below the surface is of even greater interest. Hence, lab-XRD measurements in combination with destructive layer removal by means of electrochemical polishing is commonly employed [3]. There is however two major assumptions involved when measuring residual stresses with lab-XRD that

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needs to be considered: (1) assuming the normal stress component at surface to be zero and (2) relaxation from layer removal. The first effect is an assumption based on the frequently employed measurement strategy, the $\sin^2\psi$ method, which assumes that the normal stress component is zero since the measurement is performed at the surface [4]. However, this condition is only true for the very outer surface and when the material removal is performed this condition might not be valid anymore due to relaxation effects described by Noyan and Cohen [5]. The second effect that might have an influence is that the residual stresses will be relaxed by the removal operation, especially at greater depths. Hence, the measured stresses will be lower compared to the actual stress state. It is of great interest to evaluate how large error this will generate. Possible methods to measure the actual stress state non-destructively is with synchrotron diffraction (S-XRD) or neutron diffraction (ND).

A number of papers have been published where S-XRD has been used for measuring residual stress. Atienza et al. [6] measured the stresses in a pearlitic steel rod in order to study the effects of cold drawing. The results were compared to numerical data from FEM calculations showing the same behaviour for both the experimental and numerical data. Similar work has been done in by Martinez-Perez et al. [7] where the residual stress profiles were measured in both the ferrite and cementite phase of cold-drawn pearlitic steel rods. Another example of experiments performed with S-XRD is described in the work done by Steuwer et al. [8] where the crack growth of austenitic 316H steel was studied by mapping the strains at the crack front.

Korsunsky et al. [9] showed results of residual stress measurements performed on an induction hardened gear tooth. In this case the strains were measured using neutron diffraction. The results illustrate residual stress maps of the tooth cross section where the effect of the induction hardening is shown. Another example of residual stress measurements with neutron diffraction is presented by Albertini et al. [10] reporting on residual stresses measured on crown gears. This study focused on a modified thermal heating process called multi-frequency induction tempering which was employed on UNI55Cr3 steel grade samples. The measurements were done with both neutron diffraction and lab-XRD which showed a relative high compressive stress in the surface which gradually changes to a tensile stress. The stress amplitude deeper inside the sample was verified by neutron diffraction. However, due to the low resolution from neutron diffraction the surface measurements did not agree.

The thesis work performed by England et al. [11] investigated two different diesel engine components, a connecting rod and a section of a crank shaft. They were measured by synchrotron diffraction, neutron diffraction and lab-XRD in order to study how the different techniques measured the stress state. The crank shaft was made of forged AISI 1548 steel which was surface induction hardened. The connection rod was forged AISI 15B41 steel which was quenched and tempered to form a fine tempered martensite in the surface and a ferritic pearlitic structure in the core and finally shot blast for cleaning. The results show a difference between the different techniques. It was also shown that a correction for the layer removal with lab-XRD only has a minor influence on the final results. The synchrotron data showed relative good agreement to the lab-XRD while the neutron diffraction showed a somewhat larger difference.

Though, in the literature there are no papers where S-XRD and ND measurements were performed revealing the residual stress state throughout the complete hardening zone, showing the full effect of the induction hardening process. This lack of knowledge, of the actual residual stress state, is important to address since from a manufacturing point of view a rapid induction hardening process is of great interest. However, rapid heating and quenching conditions also increase the risk of residual stress or sharp gradients of residual stresses that might limit the fatigue strength of a produced component. In the present work special attention is paid to gain better knowledge of actual stress state through the complete hardening zone showing the full effect of the induction hardening process.

The main objective with this work is to give evidence regarding the location and magnitude of the tensile stress peak since these are fatigue limiting factors. This will further be used as input to simulations in order to better predict components' fatigue resistance. A secondary objective has been to compare the results measured non-destructively by advanced techniques such as synchrotron and neutron diffraction to more commonly used technique lab-XRD to study the techniques' strengths and drawbacks.

## 2. Material

A cylindrical, diameter 20 mm, sample of steel grade C45 with initial ferritic/pearlitic microstructure and chemical composition according to Table 1 was induction hardened. The induction hardening was performed with scanning along the sample with the settings 24 kHz frequency, 48 kW power, 4990 A in coil current, scanning speed of 200 mm/min and a rotation speed of 1200 rev/min. The quenching was done by a shower unit using Aquaquench 365 quenchant medium with 4.5% concentration and 15 l/min flow.

The microstructure of the C45 sample was characterised on a polished and nital (2%) etched cross section and the hardness was measured with micro hardness tester Qness using the Vickers method and with a 1 kg load.

## 3. Experimental procedure

### 3.1. Synchrotron diffraction

The S-XRS measurements were performed at the European Synchrotron Radiation Facility (ESRF) in Grenoble on beam line ID15A that is specially designed to perform residual stress profile measurements. This beam line is equipped with an optical hutch where the synchrotron beam can be controlled in terms of width of the beam. In these measurements the beam width was limited by absorptive slits to a $0.2 \times 0.2 \times 2 = 0.08\ mm^3$ gauge volume.

The measurements were performed by moving the sample relative the beam according to Fig. 1 where case 1 measures the axial and radial strains and case 2 the axial and hoop strains [7].

The actual diffraction that is occurring when the beam irradiates the sample has a volumetric extension inside the sample which is illustrated in Fig. 2. This illustration shows that the resolution is high in axial and radial strain direction while in hoop direction the resolution is low due to the beam extension.

### 3.2. Neutron diffraction

The neutron diffraction measurements where performed at ISIS in Oxford at the beam line Engine-X. In these measurements the

**Table 1**
Chemical composition of C45 sample.

| C [%] | Fe [%] | Mn [%] | Si [%] | Cr [%] | Ni [%] | P [%] | S [%] |
|---|---|---|---|---|---|---|---|
| 0.47 | Bal. | 0.71 | 0.24 | 0.19 | 0.11 | 0.013 | 0.024 |