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Comparison of synchrotron radiation diffraction and micromagnetic stress analysis in straightened steel pipes

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\textbf{Abstract.} The use of magnetic Barkhausen noise (MBN) and harmonic analysis (HA) as non-destructive evaluation (NDE) techniques in the industrial environment increased in the last years. In our study, we evaluated the potential of those methods to measure residual stress on the surface of straightened steel pipes. To study the influence of the pipe manufacturing process and the following straightening process we used pipes of three different straightening levels. The straightening was done with different parameters, which resulted in a plastic deformation that leaves a visible helix on the surface of the pipes. High energy diffraction experiments were performed to obtain absolute values of residual stress on the surface and in the bulk of the pipe samples. With these residual stress values our MBN and HA data was calibrated. The surface of all pipes showed high compressive stresses while the highest tensile stresses were 0.5 to 1.4 mm under the surface. The stresses correlate to greater plastic deformation during the straightening process.

\textbf{Introduction}

During the magnetization process, domain walls are pinned by impurities and the domain can only increase its volume if the external field has enough strength. This results in a sudden jump in the magnetization. The induction in a coil can be used to measure these jumps \cite{1}. In a 3MA (Micromagnetic Multiparameter Microstructure and Stress Analysis) device MBN is used along with harmonic analysis, permeability and eddy current to measure stresses. The four methods give up to 41 parameters which can be used separately or in combinations. The different methods measure the stress in various depths. While harmonic analysis has a penetration depth of about 1 mm, MBN, permeability and eddy current only can reach depths of up to 0.2 mm due to the skin effect \cite{2}. The 3MA device has a potential as a NDE method in the automobile and machinery building industry but always needs a calibration to the specific material \cite{3}. This calibration can be done by using samples for which the residual stresses are known. Calibration methods include destructive methods like hole drilling or the non-destructive diffraction methods. X-ray and neutron diffraction can be used to get specific information and absolute stress values on the surface and the bulk of the samples. The high energy X-ray diffraction experiments were conducted at the HEMS beamline of the Helmholtz-Zentrum Geesthacht, located at PETRA III at DESY, Hamburg, Germany \cite{4,5} and with an X-ray tube located at BESSY at the Helmholtz-Zentrum Berlin.
Material

We used low-alloy steel pipes of grade STE460 (C 0.22%, Si 0.55%, Mn 1.6%, P 0.0030%, S 0.0035%; in wt%) with an outer diameter of 45 mm and a wall thickness of 4.2 mm (Fig. 1). After the pipes have cooled down in the initial production process, a further step is needed to straighten the slightly crooked pipes. The straightening is performed by a machine that rotates the pipe while it is moving forward and three roll pairs introduce forces on the surface. These forces generate plastic deformations, which result in a visible helix on the surface. A schematic view of the helix is shown in Fig. 2. Three different pipes were used to measure the influence of the straightening. One pipe was not straightened, a second one was produced with a standard parameter set of the straightening machine while the third one was straightened with higher forces, which results in a straighter pipe with higher residual stresses.

![Fig. 1: Strongly straightened pipe](image1)

![Fig. 2: Schematic of the helix on the pipes surface](image2)

Experiments

**Magnetic Methods.** A commercial 3MA device built by the Fraunhofer Institute for Nondestructive Testing IZFP was used to study the residual stress on the surface of the pipes with NDE. The goal is the use of a 3MA device in the steel pipe production and for calibrating the straightening machine to achieve a compromise between straight tubes and an acceptable residual stress level in the tubes. Tensile testing was carried out on sample strips cut from the pipes to obtain calibration functions for the used parameters. The third harmonic amplitude (Fig. 3) was chosen from HA, which gives a penetration depth of around 1 mm, while the coercive field (Fig. 4) was chosen from the MBN as a parameter with a penetration depth of around 0.02 mm. Both parameters give a monotonic calibration function in the tensile range and therefore can be used to measure stresses in the sample.

![Fig. 3: Calibration graph for the amplitude of the third harmonic](image3)

![Fig. 4: Calibration graph for the coercive field](image4)
We measured the outer surface of the straightened pipes in an area of the whole circumference and 200 mm in length. Only combinations of the possible 41 parameters give reliable and reproducible results. The residual stresses were calculated using the calibration functions (Fig. 3, Fig. 4). For the unstraightened pipe both the amplitude of the third harmonic (Fig. 5(a)) and the coercive field obtained through MBN (Fig. 5(d)) show a homogeneous tangential stress distribution in a narrow range of 20 MPa. The helix on the surface of the strongly straightened pipe can be measured with the harmonic analysis (Fig. 5(c)) and MBN (Fig. 5(d)). The tangential residual stresses of the strongly straightened pipe are higher and show larger differences of up to 150 MPa between the lowest and highest stresses.

Fig. 5: Tangential residual stress surface plots for the unstraightened pipe (a,b) and the strongly straightened pipe (c,d) using the third harmonic and coercive field parameter

**High-Energy X-ray Diffraction**

**Bulk measurements.** To investigate the real residual stress values in the wall thickness of the pipes, we used high-energy X-ray diffraction at the HZG beamline HEMS of PETRA III (DESY). Electrical discharge machining was used to cut 8 mm thick rings form the pipes. The rings were investigated at two points, which showed the greatest difference in the magnetic surface plots (Fig. 6). They are approximately half a circumference apart. The X-ray beam had a cross-section of 0.05 mm x 0.2 mm and the measurements were conducted in transmission (integrating over the whole ring width of 8 mm) at a photon energy of 87.1 keV (Fig. 7). A scan line from the outer to the inner surface of the ring was measured in 0.05 mm steps.

The setup allowed measuring tangential and radial stresses while axial stresses were relieved through the cutting. The integral of the stress components in the direction perpendicular to the mea-
sured layer, i.e. tangential stresses, has to be zero; this was used as a boundary condition for determining the stress-free lattice parameter $d_0$. Interestingly, the straightening process has only a small influence on the radial residual stress distribution. The radial residual stress is about zero through the wall thickness in the unstraightened and normally straightened ring, while the strongly straightened ring shows small compressive stresses in the outer part. (Fig. 8). The radial stresses at the surface are also near zero, what they should be.
The tangential residual stress is about zero through the wall thickness in the unstraightened ring (Fig. 8(a)). The straightening then introduces tensile tangential stress in the outer part and compressive tangential stress in the inner part, which is visible in the normally straightened pipe (Fig. 8(b)). The additional forces during the strong straightening process result in stronger tensile and compressive stresses (Fig. 8(c), Fig. 8(d)).

Moreover, there is a clear difference in the tangential stress distributions at the two different points. While for point 1 the highest stresses in a depth of 0.5 mm, point 2 shows the highest stresses in a depth of 1 mm. The depth between 0.5 and 1.5 mm, where the maximum tangential stresses occur, is also the depth for which the harmonic analysis is most sensitive. The overall difference in the tangential stresses roughly corresponds to the stress difference obtained from the magnetic inspection (Fig. 5), which is about 60 MPa. Furthermore, the absolute stress values obtained from diffraction correspond well to those obtained from the magnetic harmonic analysis. Thus, the validity of the magnetic method is confirmed and the harmonic analysis is well suited to determine tangential stresses resulting from the straightening process.

**Surface measurements.** The used transmission method is not suitable for resolving the near-surface layer (<100 µm). However, the residual stresses in that layer are important for our study because the penetration depth of MBN is exactly in this range. The energy-dispersive method using a white photon beam of an X-ray tube with an energy of up to 60 keV and the \(\sin^2 \phi\) method were used [6]. Fig. 9 and Fig. 10 compare the tangential residual stresses determined at points 1 and 2 with both X-ray methods. Compressive residual stresses in tangential direction around 400 MPa are present at both points. While for point 1, the results of both diffraction methods fit well together, for point 2 there seems to be a gap. However, it is difficult to draw further conclusions without overlapping of both measurement regimes. In conclusion, the tangential stresses at the surface seem to be limited by the yield stress of 460 MPa of the steel.

**Summary**

Residual stresses in straightened steel pipes were investigated with magnetic NDE methods. Tensile testing was used to for calibrating the magnetic methods to determine the most useful set of parameters. High-energy X-ray diffraction was used to evaluate the results of the magnetic technique.

The results of the high energy X-ray diffraction measurements show that the magnetic technique used yields reasonable stress results. With a calibration for the third harmonic tangential residual stresses between 100 and 160 MPa for a strongly straightened pipe were determined. These results
are in good agreement with the results obtained from high-energy X-ray diffraction. Therefore, the third harmonic together with a proper calibration is a useful NDE tool for the detection of residual stress during the production processes. Other near-surface parameters like the coercive field still need more investigation in the compressive stress range.

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Literature References

References


