Nondestructive Determination of Mechanical Properties of Open-Die Forgings and Potentials for Full Implementation in Production Process Chain

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Abstract
Saarschmiede Freiformschmiede (SSF) is continuously developing and implementing NDT-techniques into its process chain to ensure highest product quality. The co-operation with Fraunhofer Institute for non-destructive Testing (IZFP) permitted to correlate 3MA-signals to mechanical properties measured destructively by tensile testing. High accuracies between destructive and non-destructive determination of tensile properties have been observed during first examinations.

Implementation of the 3MA-technique into SSF’s production chain permits shorter lead times due to fast pre-evaluation of mechanical properties before final inspection by destructive techniques. This paper will show the advantages of using the 3MA-technique for the pre-determination of mechanical properties. Shorter lead times and reduction of direct costs are examples that enlighten its benefits. Results of calibration measurements on creep-resistant steels and steel grades, that are tough at low temperatures will be presented and the possibility for implementation into the production chain will be introduced.

Keywords: Electromagnetic Testing (ET), Magnetic Testing (MT), materials characterization, 3MA, mechanical properties, SIMPOSIUM

1. Introduction
Continuous improvement in non-destructive testing is indispensable to guarantee high quality of open die forgings. For the last 40 years, Fraunhofer Institute for Nondestructive Testing (IZFP) has been developing the 3MA-technique (Micromagnetic Multiparameter Microstructure and Stress Analysis), that combines four techniques of measuring electric and magnetic effects in a sample. Correlations between magnetic properties such as coercitivity and magnetic permeability on the one hand and hardness, tensile strength and residual stresses on the other hand are defined. The measurement of hardness by application of 3MA-technique has been standardized in several guidelines.

Saarschmiede Freiformschmiede (SSF) is continuously developing and implementing NDT-techniques into its process chain to ensure highest product quality. The co-operation with Fraunhofer IZFP permitted to correlate 3MA-signals to mechanical properties measured destructively by tensile testing. High accuracies between destructive and non-destructive determination of tensile properties have been observed.

Implementation of the 3MA-technique into SSF’s production chain shall permit shorter lead times due to fast pre-evaluation of mechanical properties before final inspection by destructive techniques.

A first trial to standardize hardness measurements by 3MA-technique is implemented within a german engineering guideline [1].

3MA-technique is used for the determination of mechanical properties in press hardened steels, from different OEMs and suppliers of automotive industry, e.g. Volkswagen [2],[3],[4],[5].
2. Experimental Methods
The tests for applicability of the 3MA-method for determination of mechanical properties on forged products were performed in two steps. The first step consisted in the production of small rods with a determined range of mechanical properties. In a second step the method was tested on production parts. Based on destructive data, the modelling of the 3MA-signals was performed at IZFP.

2.1 Destructive Testing of Forgings
The microstructure and mechanical properties of the forgings as well as the magnetic hysteresis a segment was cut at the rim of each rod and one tensile test in tangential direction compared to the rod’s axis, one slab for hysteresis testing and one microsection were elaborated.

The tensile test was performed at room temperature according to Din EN ISO 6892-1 at a sample having a diameter of 10 mm. The microsections were used to determine grain size according to ASTM E112, microstructure and degree of cleanliness K0 according to DIN 50602. Furthermore the depth of strain hardening due to machining was determined via microscopic investigations.

2.2 Non-destructive testing
Hysteresis measurements of slabs prepared out of each rod were performed using an adapted hysteresis frame developed at IZFP. The macroscopic initial magnetization and hysteresis loops are measured using an electromagnet shown in Figure 1.

![Figure 1. Hysteresis frame](image)

The cylindrical sample is placed between pole pieces of the yoke. A sinusoidal current excitation is generated in order to ensure a homogeneous magnetization in the sample. The flux density is measured using a search coil, and the magnetic strength is measured using a transverse type Hall sensor.

Residual stresses were measured using three different methods. To measure stresses in the depth up to 150 µm below surface XRD-measurements have been performed using a diffractometer (XStress3000/G2R, Stresstech). For stresses ranging from 150 to 1.2 mm the bore-hole method was used type RS200 (Vishay Measurements Group). The Siemens ring-core-method was used to evaluate the residual stresses in a depth of 2 to 4 mm.

3MA-technique comprises the analysis of magnetic Barkhausen noise, incremental permeability, upper harmonics in the magnetic tangential field strength, and eddy current impedance [6]. Approximately 40 measuring quantities span a feature space in which different material states can be separated by means of pattern recognition or multivariate regression analysis using a set of calibration data obtained on samples of well-defined, quantitatively known target properties (e.g. Vickers hardness, yield strength, residual stress). A large range of experimental data collected in the last 30 years, have shown a hard correlation between 3MA signals and mechanical tests [7],[8].
Production of forgings

Six test rods have been produced in order to get a first evaluation of the applicability of the 3MA-method. The test rods have a length of 1500 mm and a diameter of 600 mm. Two steel grades have been chosen that represent SSF’s production portfolio. The first steel grade is tough at low temperatures, 27 NiCrMoV 15-6, the second one is creep-resistant, 22 CrMoNiWV 8-8. The corresponding chemical piece analysis is shown in table 1.

<table>
<thead>
<tr>
<th>Material</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>W</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 CrNiMoWV 8-8</td>
<td>0.21</td>
<td>0.04</td>
<td>0.70</td>
<td>0.004</td>
<td>0.002</td>
<td>2.10</td>
<td>0.82</td>
<td>0.73</td>
<td>0.62</td>
<td>0.31</td>
</tr>
<tr>
<td>27 NiCrMoV 15-6</td>
<td>0.26</td>
<td>0.07</td>
<td>0.21</td>
<td>0.004</td>
<td>0.001</td>
<td>1.60</td>
<td>0.41</td>
<td>3.50</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>27 NiCrMoV 11-5</td>
<td>0.27</td>
<td>0.06</td>
<td>0.21</td>
<td>0.003</td>
<td>0.001</td>
<td>1.64</td>
<td>0.41</td>
<td>2.91</td>
<td></td>
<td>0.09</td>
</tr>
</tbody>
</table>

The three rods of each steel grade were quality heat treated to different tensile strengths resulting in a calibration range for tensile strength representing most specifications of SSF’s customers.

The measurements of Barkhausen noise and incremental permeability used within 3MA are sensible to residual stresses in the measured surface. Therefore it was indispensable to ensure that the machining parameters used to create the UT-shape of the parts don’t influence the results of the 3MA-measurements. Furthermore it is important to know the distribution of the residual stresses in order to properly adapt the simulation model. To evaluate the influence of residual stresses induced by machining each rod was machined using defined feed rates from 0.6 to 1.6 mm/turn at defined areas of the rod to reach a large spectrum of surface roughness, ranging from 1.6 to 12.5 µm.

3MA-measurements were performed at 12 o’clock-position on each segment of each rod to evaluate the influence of residual stresses due to different feed rates. The obtained signals were then correlated to the tensile properties measured at a segment taken from the rim of the rods.

Further 3MA-measurements were executed around the circumferential diameter of the rods to evaluate homogeneity of the measured signals. This is done by comparing the increase in scattering when adding these values to the calculation.

After receiving the results of the calibration tests on the test rods, further 3MA-measurements were performed at shafts in the production at SSF. Tests were performed in the same direction as the direction of the tensile sample in relation to the shaft’s axis. These measurements were performed at generator and turbine shafts of the steel grades 22 CrMoNiWV 8-8, 27 NiCrMoV 11-5 and 27 NiCrMoV 15-6. Chemical piece analysis of each steel grade is shown in table 1. Each shaft has at least two test positions, so that the calibration was calculated for more test positions than the number of shafts investigated. Table 2 lists the number of parts per steel grade, the testing positions and gives the standard deviations for the calibration calculations.

All measurements had been performed in the contour for ultrasonic testing, which guarantees a comparable surface state with surface roughnesses Ra ranging from 3.2 to 6.3 µm.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Number of shafts</th>
<th>Number of test positions</th>
<th>Standard Deviation (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 CrMoNiWV 8-8</td>
<td>4</td>
<td>13</td>
<td>0.89</td>
</tr>
<tr>
<td>27 NiCrMoV 11-5</td>
<td>7</td>
<td>11</td>
<td>3.42</td>
</tr>
<tr>
<td>27 NiCrMoV 15-6</td>
<td>10</td>
<td>32</td>
<td>2.90</td>
</tr>
</tbody>
</table>
3. Results

In the following sections the results of microstructural analysis as well as destructively determined mechanical properties are presented. Measurements of hysteresis and 3MA-signals at test rods and production shafts as well as resulting calculations for calibration of the 3MA-method are shown.

3.1 Destructive testing

The results of destructive mechanical testing of each rod are presented in table 3. The tensile strength ranges from 852 to 1010 MPa for 27 NiCrMoV 15-6, and from 744 to 885 MPa for 22 CrMoNiWV 8-8.

### Table 3. Mechanical Properties of Test Rods

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Sample No</th>
<th>Yield Strength $R_{p0.2}$ (MPa)</th>
<th>Tensile Strength $R_m$ (MPa)</th>
<th>Elongation A (%)</th>
<th>Reduction of Area Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 NiCrMoV 15-6</td>
<td>83550</td>
<td>751</td>
<td>862</td>
<td>20.0</td>
<td>73.0</td>
</tr>
<tr>
<td>27 NiCrMoV 15-6</td>
<td>83560</td>
<td>853</td>
<td>955</td>
<td>17.9</td>
<td>70.4</td>
</tr>
<tr>
<td>27 NiCrMoV 15-6</td>
<td>83570</td>
<td>914</td>
<td>1010</td>
<td>16.0</td>
<td>67.1</td>
</tr>
<tr>
<td>22 CrMoNiWV 8-8</td>
<td>83480</td>
<td>619</td>
<td>744</td>
<td>20.0</td>
<td>74.6</td>
</tr>
<tr>
<td>22 CrMoNiWV 8-8</td>
<td>61800</td>
<td>692</td>
<td>806</td>
<td>17.2</td>
<td>66.9</td>
</tr>
<tr>
<td>22 CrMoNiWV 8-8</td>
<td>83540</td>
<td>774</td>
<td>885</td>
<td>17.0</td>
<td>70.1</td>
</tr>
</tbody>
</table>

Microstructural investigation performed at each rod shows uniform bainitic quenched microstructure for both steel grades and grain sizes ranging from 5.5 to 8 according to ASTM E112. Corresponding micrographs are presented in figure 2. The degree of cleanliness is determined to be $K_0 = 3.0-12.0$ for steel grade 22 CrMoNiWV 8-8 and $K_0 = 4.75-9.0$ for steel grade 27 NiCrMoV 15-6. Figure 2 c) shows that the depth of strain hardening due to machining of the surface is 11 µm.

![Figure 2](image)

**Figure 2.** Microstructure for both steel grades: a) 22 CrNiMoWV 8-8, b) 27 NiCrMoV 15-6, c) depth of strain hardening due to machining

3.2 Magnetic testing

Figure 3 shows the correlation between magnetic and mechanical properties of the test rods. Linear correlations with accuracies from 99.9 to 100 % are linking coercitivity to yield and tensile strength and standard deviations are less than 1 MPa for steel grade 27 NiCrMoV 15-6 and up to 3.4 MPa for steel grade 22 CrMoNiWV 8-8.

The residual stress profile measured by XRD-analysis, bore-hole method and Siemens ring-core method is presented in figure 4. This profile can be separated into three distinct regions. Zone Z1: a layer of 30µm with strong tensile stress, zone Z2: a layer with compressive stress between 30 and 150µm depth and Z3: the bulk material moderately affected by residual stress.
3.3 Numerical modelling

The residual profile distribution imposes a multi-layer approach. The magnetic behaviour of the sample is described on three different layers (Figure 5).

Then, each layer of the sample has been characterized in order to build its own hysteresis model. Various hysteresis models which take into account the dynamic ferromagnetic response under sinusoidal excitation have been proposed. For better accuracy, the Jiles Atherton (JA) hysteresis model has been chosen for describing the magnetic behavior of the layers in static domain 0. This model describes the hysteretic behavior of a material through 5 parameters (Ms, a, α, k, c).

Specimens of the compressive and tensile layer cannot be obtained by cutting due to their small thickness. If the sample is submitted to tensile stress, the coercive field reduces comparing to the unstressed state. In order to access to the magnetic behavior of the top layer
with tensile stress, the coercive field is determined at high frequency $f_{HF} = 3$ MHz and at high level excitation using a special 3MA measuring set-up. The hysteresis loop of this layer is then built and the five JA parameters are determined using a genetic algorithm. In order to check the correctness of the deduced hysteresis loops, an incremental permeability measurement at high frequency $f_{HF} = 900$ kHz has been performed and compared to results of the numerical simulation.

Then, the hysteresis loop of the layer with compressive stress has been approximated considering steels with similar magnetic properties. The hysteresis model has been validated by comparing a numerical simulation to IP measurements of the sample at a lower frequency $f_{HF} = 50$ kHz.

The parameters of the JA hysteresis model of each layer are summarized in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Tensile layer</th>
<th>Compressive layer</th>
<th>Bulk layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$ (A/m)</td>
<td>$1.48 \times 10^6$</td>
<td>$1.6 \times 10^6$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>$a$ (A/m)</td>
<td>200</td>
<td>480</td>
<td>385.6</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$6.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$k$ (A/m)</td>
<td>1200</td>
<td>2000</td>
<td>1200</td>
</tr>
<tr>
<td>$c$</td>
<td>0.238</td>
<td>0.18</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The combined sample-sensor system has a multi-scale geometry (see figure 1). The sample itself is a multilayer system: the size of surface layer (skin passed layer) varies from 10 to 30 µm and the bulk material layer is around 1 mm. The width of the yoke of the 3MA sensor is 100 mm. This scales a ratio of $10^4$, which requires an adapted meshing that depends on the area of sample-sensor system. The magnetization frequency ($f_{LF}$) can vary between 50 and 1,000 Hz, whereas eddy current frequency ($f_{HF}$) is in the range between 10 and 100 kHz. The time scales ranges from $10^3$ to $10^4$. Therefore an adapted temporal discretization is required to identify the high-frequency phenomena. The magnetic material behaviour is described by a nonlinear hysteresis model. The conventional FEM computation results obtained by simulation of all the system step by step in time, using Flux®[3] software are encouraging but computation times are high, more than three hour for a quarter of a half of low frequency ($f_{LF}$) period and 20 points of high frequency ($f_{HF}$) period. To overcome these problems of resolution and memory space, a new computational strategy is developed. The new computation methodology is compared to the conventional one. The difference between the both is less 3%. The time computation is very low (1/6) [13].

The figure 6 shows the measured and the simulated IP signal. The initial set up are: $f_{LF} = 50$ Hz and $H_t=60$A/cm and $f_{HF} = 100$ kHz.
The figures denote that the measured 3MA incremental permeability signals are in agreement with the calculated one. The output parameters such as \( H_{25\mu} \), \( \Delta H_{25\mu} \), \( H_{50\mu} \), \( \Delta H_{50\mu} \) are correctly reproduced. The difference between the measured and calculated one are less than 9%.

### 3.2.1 3MA-measurements on forged rods for calibration

Figure 7 shows the correlation between the 3MA-signals, measured in tangential direction at segment number 1 of the test rods to the tensile properties measured destructively below this point. The standard deviation is 0.9 MPa for 27 NiCrMoV 15-6.

![Figure 7](image)

**Figure 7.** Correlation between 3MA-signals and tensile properties of test rods for test rods in 27 NiCrMoV 15-6

### 3.2.2 3MA-measurements on production parts

Further 3MA-measurements were performed at turbine and generator shafts. Figure 8 shows the correlation between the calculated 3MA-values and the mechanical properties measured at shafts in steel grades 22 CrMoNiWV 8-8, 27 NiCrMoV 15-6 and 27 NiCrMoV 11-5.

The measurements by tensile test give tensile strengths for 22 CrMoNiWV 8-8 from 776 to 806 MPa and the calculated 3MA-results range from 777.2 to 805.6 MPa. The calculated standard deviation is 0.89 MPa.

For steel grade 27 NiCrMoV 15-6 the measurements by tensile test give tensile strengths from 778 to 1010 MPa and the calculation results in tensile strengths ranging from 777.8 to 1004.4 MPa. The calculated standard deviation is 2.90 MPa.

For steel grade 27 NiCrMoV 11-5 the measurements by tensile test result in tensile strengths from 853 to 934 MPa and the calculation results in tensile strengths ranging from 851.0 to 934.7 MPa. The calculated standard deviation is 3.42 MPa.

![Figure 8](image)

**Figure 8** Calibration of tensile strength resulting from destructive tests versus calculated values based on 3MA-signals on production shafts in 22 CrMoNiWV 8-8, 27 NiCrMoV 15-6 and 27 NiCrMoV 11-5
4. Discussion

4.1 Material properties
The material properties achieved for the test rods are in good correlation to the specification margins given by SSF’s customers. Furthermore the metallographic investigations show uniform microstructure of the test rods without defects and anisotropy. Therefore they were considered convenient for reliable calibration tests.

Excellent correlation between coercitivity and tensile strength is shown in figure 3. The linear dependence of the values permits to deduce tensile properties from magnetic signals measured by 3MA. General basis for application of the 3MA-method is therefore granted.

4.2 Measurements on test rods
The stress profile determined at the test rods is shown in figure 4. Three regions can be distinguished. Zone Z1 is influenced by machining of the rods. Machining leads to strain hardening in a depth up to 15 µm as can be derived from figure 2 c). The high tensile stresses in this zone are resulting from the machining. In a depth of 50 µm the stresses invert into compressive stresses. This inversion is due to superposed compressive stresses due to phase transformations occurring during quality heat treatment. These compressive stresses fade into the depth of the material as the near-surface region is more affected by the heat treatment.

Figure 7 underlines the excellent correlation between destructively determined tensile properties and calculated ones based on 3MA-signals. These correlations between magnetic and mechanical properties were already discussed in chapter 4.1. Additionally the calibration results show that not only in principle but also in real measurements the link between mechanical properties and magnetic ones can be used to determine the tensile properties nondestructively.

4.3 Measurements on production parts
After receiving the first calibration results on test rods, further investigations were needed to prove the applicability on a broader range of shafts. It can be deduced from figures 7 and 8, that calculations of calibrations give reliable results, because the standard deviations are in the required range of max. ±5 MPa. A maximum standard deviation of ±5 MPa is needed to reach the same measurement error as the tensile test. Calibration calculations that are not presented within the context of this publication showed that it is indispensable to make separate calculations for each steel grade to reach this purpose.

5. Conclusions
The present work shows the possibility of implementing the 3MA-technique into the production chain of a forgemaster’s production. High accuracy of the calibration of the 3MA-method to the determination of mechanical properties at rim segments of shafts had been achieved. Calibrations had to be performed for each steel grade independently and high accuracies with standard deviations of about 5 MPa were achieved for steel grades 22 CrMoNiWV 8-8, 27 NiCrMoV 11-5 and 27 NiCrMoV 15-6.

The benefits of this innovation lie in the shortening of duration of SSF’s internal preliminary testing of mechanical properties. The determination only takes 15 min for one segment of a shaft. This implies further cost savings as there will be no more need for cutting test segments, transporting them to a laboratory, elaborating and testing them destructively. Results can be obtained in a time- and cost-saving way. Therefore the 3MA-technique reveals large potential for the implementation in the industrial production.
6. Acknowledgements
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