MAGNETO-INDUCTIVE DIAGNOSIS OF STEEL PARTS WITH UNKNOWN FATIGUE LOAD HISTORY

Gerd DOBMANN 1, Zbigniew Hilary ŻUREK 2
1 Universität des Saarlandes, Saarbrücken, Germany
2 Silesian University of Technology, Katowice, Poland
Contact e-mail: gerd.dobmann@t-online.de, zbigniew.zurek@polsl.pl

Abstract. The paper presents a modification of a magneto-inductive diagnostic technique. This modification allows the diagnosis of the microstructure and to characterize mechanical degradation of loaded constructional elements, where the history of the fatigue loads is unknown. The measuring device and technology are presented; in many cases they are cheaper than professional flaw detecting devices. High diagnostic resolution is obtained in comparison to LCR bridge circuit devices and precision LCR Meters. The repeatability of measurements is documented for electrical and magnetic parameters of steel. Simulation is shown identifying the degradation of parts of a railcar wheel-set, in which changes of electric and magnetic parameters are non-linear.

1. Physical parameters – the observer of the technical condition

Periodical testing of constructional elements of machines helps to maintain their fitness for service. In many cases images of the initial and final microstructure obtained from a microscope do not fully reveal changes in electrical and magnetic parameters. Changes of parameters depend on microstructural changes occurring at different microstructure levels of degradation. The parametric investigation should be assisted by identification of carbon-iron system for carbon steels [15,3,8] or by the Schaeffler diagram for Ni/Cr-alloyed steels [15, 3, 8]. The structure selected by the design determines the operational evolution of electrical and magnetic parameters [15] in the given stress and temperature range [12] or under particular environmental conditions. The diversity in the chemical compositions and treatment of the alloys requires a flexibility of the diagnostic approach.

Apart from hardness [2], steel may be characterized by electrical and magnetic parameters [2], which may be significant in non-destructive diagnostics aimed at detection of fatigue degradation. In general, changes may be described by parameters such as electrical conductivity, magnetic permeability as well as electrical permittivity characterizing non-metallic intrusions. The mutual correlations of the change of the parameters to different degradation states form a more complete image. A simplified relationship of operation and evolution of physical parameters is shown in Fig.1.
The basic diagnostic model (used for educational purposes) consists of a coil wound around the material (or adjacent to material), characterized by $R_1$ and $L_1$ parameters. The coil is supplied by a sinusoidal current. The coil voltage depends on inductive coupling with the material (Fig.2) due to electromagnetic wave transition, internal and external reflections. The changes in coil and material parameters are represented by the $L_2-R_2-R_3-C$ circuit. This circuit can reveal the operationally-induced changes in magnetic permeability and electrical conductivity with the assumption that $\gamma \gg \omega \varepsilon$ (i.e., electric permittivity is negligible). The electrical and magnetic parameters together with frequency $f$ as diagnostic parameters, are indirect observers of the technical material condition.

The main factors influencing the material are:
- thermal and mechanical processing,
- material tension $\sigma, \sigma_I, \sigma_{II}$, for sample $\sigma, \sigma_{II}$,
- phase transitions of the structure,
- operational history,
- ambient conditions (operating temperature, temperature of material during measurements, erosion, corrosion).

The structure degradation on the microstructure level and structural changes may be observed in the following quantities:
- material conductivity $\gamma$,
- magnetic permeability $\mu$,
- electrical permittivity $\varepsilon$.

Depending on electrical and magnetic parameters of the material, tests are conducted in magnetic field of different intensity (low, high) and with appropriately selected frequency ranges taking into account desired depth of penetration [5, 6, 7, 13]. The simplest design based on the analytical model [6] employs one magnetizing and measurement coil (Fig.3). Operational changes of material are imaged in the coil parameters [10]. Other existing solutions are based on electrical Kirchhoff’s circuit laws [11, 7].
An additional problem is given by the sum of the internal stress of the first and second order and method of limiting its influence on local averaging magnetic permeability. The impact of additional tempering on parameter changes in the samples was also analysed.

2. Diagnostic Parameter

The voltage drop across the empty coil \( E_0 \) and voltage drop across coil containing the sample \( E \) are related as follows:

\[
\begin{align*}
\overline{E}_0 &= \overline{TZ}_0 \\
\overline{E} &= \overline{TZ}_c \\
\overline{E} &= \overline{Z} \\
\overline{E}_0 &= \overline{Z}_0 \\
\frac{Z}{Z_0} &= \frac{\omega L}{\omega L_0} - j \frac{R - R_0}{\omega L_0}
\end{align*}
\]

![Digital LCR Meter]

**Fig. 3. Basic measurement scheme [1]**

The quantities represented in the ratios \( \frac{\omega L_{p}}{\omega L_0} \) and \( \frac{R_{p} - R_0}{\omega L_0} \) (normalized impedance components [6]) are, apart from impedance \( Z_m \), main indirect parameters which make it possible to assess the rate of degradation. They are calculated from the parameters of series connection of \( L_s \) and \( R_s \) elements of the tested circuit. The coil may enclose or it may be adjacent to the sample [6, 11, 13].

When results obtained from material samples are compared, it is important to maintain the sample geometry (sample radius \( r_0 \)) and measurement coil geometry on account of the significant impact of \( \eta \) coefficient \((\eta = (D_p/D_s)^2)\). This is shown in theoretical formulas calculated with the help of Mathematica software from the following equations:

\[
\eta = (\frac{D_p}{D_s})^2, \tag{5}
\]

\[
k = Sqrt[-i \times \omega \times \gamma \times \mu_s \times \mu_o], \tag{6}
\]

\[
\mu sk = \frac{2}{k \times ro} \times \frac{J_1(k \times ro)}{J_0(k \times ro)}. \tag{7}
\]

\[
\frac{\omega L}{\omega L_0}[\gamma \cdot \mu_{se} \cdot \omega \cdot \eta] = 1 - \eta + \eta \mu_{se} Re[\mu_{ef}], \tag{8}
\]

\[
\frac{R - R_0}{\omega L_0}[\gamma \cdot \mu_{se} \cdot \omega \cdot \eta] = -\eta \mu_{se} Im[\mu_{ef}] \tag{9}
\]
Two types of materials will be discussed on account of changes in electrical and magnetic parameters due to high operational temperature as well as dynamic non-symmetrical mechanical loads during very long period of operation.

3. Operational change in magnetic parameters of steels operating in high temperatures

Martensitic steels such as 20H12M1F (X20CrMoV12 1, acc. DIN) which was the predecessor of P91 steels and earlier types of steel such as 13HMF PN-75/H-84024 (14MoV6 3, 1.7715) and 15HM PN-75/H-84024 (13CrMo4 5, EN) are intended for operation under creep conditions for critical elements of the pressurized parts of power boilers with supercritical operational parameters (Fig. 4) [10, 11].

In case of the specified steels, the resource data base was accessible and it was possible to determine initial magnetic and electrical parameters (Fig. 5) from the beginning of life.

Fig. 4. Elements of system, from which test samples were acquired

<table>
<thead>
<tr>
<th>ferrite + pearlite</th>
<th>bainite, i.e. ferrite with precipitated carbides</th>
</tr>
</thead>
</table>

\[
f_x = \frac{2}{(\pi \times D_p^2 \times \gamma \times \mu_s \times \mu_r)} \tag{10}\]
Fig. 5. Examples of microstructure before and after operation; determined changes in the coercivity $H_c$ and the effective permeability $\mu_{\text{eff}}$ of the component

The presented steels operate at high temperatures and high mechanical loads. The image from the optical microscope shows significant changes in the structure. For the remaining steels in this group such changes are less visible [15, 16, 17].

The operational changes in the coercivity and the effective permeability (Fig. 5) are multiple of standard deviation for the group of the analysed samples and are statistically noteworthy. The measured operational changes of the material parameters are significant since they may be compared to the steel resource base at the beginning of life.

4. Operational evolution of electrical and magnetic parameters of steels operating at high dynamic loads and high ambient temperatures

The impact of complex and high dynamic loads on material degradation may be, as an example, be presented by wheel plates of locomotive driving wheels. The discussed plates were manufactured of cast steel LI1500 PN-H-83152 (PN-ISO3755:1994 270-480). In this case, the resource base was unavailable. In order to compare operational changes in magnetic and electrical parameters, those regions of wheel plate were selected where dynamic loads significantly vary. The positions, in which samples with maximum cast steel stress rupture were selected, are shown in Fig. 6.

Fig. 6. Character of dynamic load and location from which samples were taken (marked by asterisk)

The complexity of stresses is due to axle load and drive transmission. During lab tests, the load cycle may be simplified due to an asymmetrical load cycle. Operational temperature depends on prevailing atmospheric conditions and may be raised on account of dynamic interaction between wheel and rail or/and heat transmitted from brake shoes. The levels of the operational temperature cannot influence structural changes.
5. Measurement of operational changes in magnetic parameters

The structural image of material subjected to operational loads shows mainly changes in grain shapes (Fig. 7).

![Exemplary image of cast steel structure in region with minimum and maximum mechanical load](image1)

Fig. 7. Exemplary image of cast steel structure in region with minimum and maximum mechanical load and averaging changes in histograms of structural images

The basic ferrite-pearlite structure remained unchanged. The quantitative ratios of structures and their sizes did change. The quantitative analysis of the images of several sample cross-sections shows changes in ferrite content as high as several per cent. The measurement of magnetic parameters was conducted with Quantum Design PPMS equipment. The calculated parameters of magnetic permeability components are shown in Fig. 8.

![Examples of measurements of magnetic permeability components vs. frequency for excitation current equal to 10 mA](image2)

Fig. 8. Examples of measurements of magnetic permeability components vs. frequency for excitation current equal to 10 mA

In the frequency range up to 2 kHz the maximum changes in effective permeability do not exceed one per cent. Significant issue is presented by sample sizes (< 1mg) and their preparation for (Quantum Design). The subsequent measurement was conducted with precision HIOKI RLC bridge. For these tests bar samples with 4mm² cross-section area were prepared. Results of impedance and phase angle measurements are compared in Fig. 9a. In order to compare the course of normalized impedance components, changes in diagnostically significant range [6] of low $f/f_g$ ratios were demonstrated (Fig. 9b).
The conducted measurements have shown that it is possible to compare the regions of extreme degradation in the element’s body. The object of subsequent measurement was to show that such measurement can also be conducted using a basic version of cheap RLC meter. Such meters are equipped with four to five measurement frequency bands: 100Hz, 120Hz, 1000Hz, 10000Hz, 100000Hz. All this research is centred on demonstrating that diagnostic procedures used in detecting fatigue changes in the material may utilize cheap RLC bridge meters. The cost of the RLC meter used is lower by two or three orders in relation to previously used professional measurement devices. Short- and long-time stability was assessed for two types of meters, while applying recommended device switch-on time preceding the actual measurements by 0.5h. The measurement results and ranges of standard deviation for the tested series of samples are shown in Fig. 10. For measurement frequencies of 1kHz and 10kHz the results are statistically significant. The 1000 Hz frequency lies within the frequency ratio $f / f_x \leq 7$ indicated for ferromagnetic alloys by Förster [6].

The diagram (Fig. 10a) is charted against the measurement frequency and may be represented in 3D space - see Fig. 10b. The probability of the event that both measurement results for a given magnetic and electrical parameter (for operational time $t_0 \to t$) are the same, is estimated to be very small. If three variables are adopted in the description of the
operational degradation process, then this probability decreases, even if cheap RLC bridge meters are applied in the measurements. However, the description of degradation changes should include, as a minimum, three measurement parameters.

\[ F_{\text{damage}} \approx F(\sigma, \tau, t) \equiv F(\mu, \gamma, \omega) \quad (11) \]

Functions of changes in physical parameters are usually non-linear. To construct a complete description of the degradation changes, the following helpful notation may be used:

<table>
<thead>
<tr>
<th>state</th>
<th>material</th>
<th>structure</th>
<th>( \frac{L}{\omega L_0} \rightarrow \frac{L'}{\omega L_0} )</th>
<th>( \frac{(R - R_0)}{\omega L_0} \rightarrow \frac{(R' - R_0)}{\omega L_0} )</th>
<th>( \frac{L - L'}{\omega L_0} )</th>
<th>( \frac{(R - R') - R_0}{\omega L_0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>LII500</td>
<td>ferrite + pearlite</td>
<td>10.323</td>
<td>0.64741</td>
<td>19.011</td>
<td>1.9650</td>
</tr>
<tr>
<td>final</td>
<td>LII500</td>
<td>ferrite + pearlite</td>
<td>9.6756</td>
<td>0.64741</td>
<td>19.011</td>
<td>1.9650</td>
</tr>
</tbody>
</table>

When applied probes and measurement RLC bridges are normalized, unequivocal indirect or final record of degradation process for given material is achieved at the lowest cost. From the real and imaginary components, we may determine numerically the values of effective magnetic permeability and electrical conductivity in the first part of the course \( f \leq f_c \).

6. Conclusion

Degradation processes in the micro structure of the material, in macro- and micro-regions, may be detected with the help of simple measurement kits. It is possible to detect subtle changes in the grain structure [9]. The initial selection of samples for the precise tests with electron microscopes lowers the research costs. The methodology basing on the theory of eddy current flaw detection, the simplest analytical models [6,7] and cheap measurement RLC bridges is reliable, repeatable in both short and long terms and is also characterized by a high measurement dynamic [15]. We have proved that it is possible to test elements without prior knowledge of operational evolution of their initial parameters. We have obtained a reliable diagnostic tool supplementing eddy current diagnostics and facilitating both diagnostics and understanding of the problem. The dissemination of the described methods requires simple organization steps, then standardization of test probes, sample sizes and meter types. It is easy to construct a test probe basing on Texas Instruments products [18,19] such as coil set and measurement module and utilizing the attenuation effect of the detected changes in the resonance frequency zone.

References


[8] Ugitech. Magnetism and Stainless steel


[12] Żurek Zbigniew Hilary, Wito Mirosław: Diagnostics of degradative changes in paramagnetic alloys with the use of low frequency impedance spectroscopy. 7th International Symposium on NDT in Aerospace, 16-18 November 2015, Bremen, Germany


[14] Żurek Zbigniew H.: Projekt badawczy NN5102383 38, Metoda diagnostyki stanu stalowych (paramagnetycznych i ferromagnetycznych) elementów maszyn elektrycznych na przykładzie bandaży i kap wirników generatorów


