Evaluating material degradation by the inspection of minor loop magnetic behavior using the moving Preisach formalism

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The application of two magnetic nondestructive evaluation techniques is investigated to monitor material degradation caused by metal fatigue. First, a set of experimentally obtained major and minor quasistatic magnetization loops is analyzed within the framework of the moving Preisach formalism: the mean-field parameter \( k \) is found to increase with the number of stress cycles \( n \) and, moreover, the ratio \( dk/dn \) is higher during the last 10% of the fatigue lifetime. Second, during the fatigue test a constant magnetic field is applied to the sample and the magnetization variation during each stress cycle due to the magnetomechanical effect is monitored: the peak-to-peak magnetization first increases, then stabilizes, and finally starts to decrease at 95% of the fatigue lifetime. © 2006 American Institute of Physics. [DOI: 10.1063/1.2170960]

I. INTRODUCTION

Metal fatigue is responsible for a majority of fractures of structures and machines: cyclic mechanical loading leads to an accumulation of irreversible changes in the microstructure of the material, which can culminate into fracture. Concerning ferromagnetic materials, the microstructural dependence of the magnetic behavior makes magnetic techniques appropriate for the nondestructive evaluation of the fatigue damage progression. In this article, two magnetic evaluation techniques to monitor the fatigue process are investigated. The first technique consists of an extensive characterization of the hysteretic magnetic behavior based on the moving Preisach hysteresis model. \(^1\)–\(^3\) At predetermined interruptions of the cyclic loading a set of quasistatic major and minor magnetization loops is measured. These experimental data are used to identify the mean-field parameter \( k \) and the Preisach distribution function (PDF). Both \( k \) and the PDF are shown to be microstructure dependent. \(^1\)–\(^6\) Hence, the fatigue damage progression can be evaluated by monitoring their modifications. The second magnetic evaluation technique is carried out during the cyclic mechanical loading itself: a constant magnetic field is continuously applied to the sample, and the magnetization variation during each stress cycle due to the magnetomechanical effect is monitored. Both techniques provide information about the start of the final fatigue stage.

II. MOVING PREISACH FORMALISM

The Preisach model describes the magnetization process by an infinite set of elementary dipoles with nonsymmetric rectangular hysteresis loops defined by two parameters, the elementary loop coercive field \( h_c \) and the interaction field \( h_m \). The PDF \( P(h_c, h_m) \), which represents the dipole density, does not change during the magnetization process and characterizes the microstructure and the material under investigation. The PDF can be extracted out of the experimentally obtained magnetization loops using a two-dimensional mapping technique based on the Everett theory. \(^1\)

One of the disadvantages of the classical Preisach model is the fact that it cannot describe the experimentally observed noncongruency of the minor loops. An improvement in this direction is the moving Preisach model. \(^2\) In this model the switching of the Preisach dipoles is controlled by the effective magnetic field \( H_e \) differing from the applied field \( H_a \) by a mean-field contribution, which is function of the magnetization: \( H_e = H_a + kM \), with \( k \) a constant.

III. EXPERIMENTAL PROCEDURE

A fatigue test is executed on a ferromagnetic sample by applying a cyclic uniaxial mechanical load with constant stress amplitude \( \sigma_a \) and mean stress \( \sigma_m \). The sample is surrounded by the magnetic sensor based on a single sheet tester, consisting of an outer excitation coil and an inner winding, the latter giving rise to the induced voltage \( V_i \). Integration of \( V_i \) results in the mean magnetization in the cross section of the sample, \( M \). The excitation current is proportional to the applied magnetic field \( H_a \).

During the cyclic mechanical loading a constant magnetic field is applied to the sample, and the magnetization variation \( \Delta M \) during each stress cycle due to the magnetomechanical effect is measured continuously. At predetermined points of time the mechanical loading and the constant magnetic field excitation is interrupted for the measurement of a set quasistatic first order symmetric magnetization loops \( (H_a, M) \) (for a range of peak applied field values) and a set

| TABLE I. Chemical composition of the materials (wt %). |
|-------------|-----|-----|-----|-----|-----|-----|
|             | Fe  | C   | Si  | Mn  | P   | S   |
| CR1         | 99.6| 0.04| 0.02| 0.25| 0.003| 0.01|
| HR2         | 98.6| 0.2 | 0.28| 0.8 | 0.06 | 0.01|

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magnetization loops the following procedure is used:

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For zero load
tigue test, for both mechanical load conditions.

a range of magnetization levels
them between the same extremal applied field values, but for

made of cold rolled low alloy steel sheet with a thickness of
1 mm (EN-10130), while the HR2 specimens are manufactured
out of hot rolled steel sheet of 2 mm thickness (EN-10025).
Yield tensile stress $\sigma_y$ is 203 and 238 MPa, respectiv-
ely, for CR1 and HR2. The chemical composition can be
found in Table I.

The evaluation results of the hysteretic behavior within
the framework of the moving Preisach formalism are shown
in Figs. 1–4 for one particular fatigue test executed on a CR1
sample, with the following specifications: $\sigma_y=118$ MPa,
$\sigma_m=70$ MPa and number of cycles to failure $n_f=159253$.
The trends are similar for tests with other specifications and
for material HR2.

Here, the quasistatic magnetic measurements of both
major and minor loops at the fatigue test interruptions are
performed under two different static mechanical load condi-
tions: first at zero mechanical load and second under a me-
chanical stress equal to half of the yield tensile stress $\sigma_y$.
Both sets of experimental data result in a value for $k$ and in
a PDF.

As shown in Fig. 1, $k$ (for $\sigma=\sigma_y/2$) increases with fa-
tigue lifetime $n$ and, moreover, the ratio $dk/dn$ is higher
during the last 10% of the fatigue life, indicating the initia-
tion of a final stage in the fatigue lifetime. Noteworthy is
the fact that the experimentally obtained minor magnetiza-
tion loops under zero mechanical load are congruent for all
fatigue test interruptions, resulting in $k=0$. Also shown in Fig.
1 are the variations of the coercive field $H_c$ throughout the

IV. RESULTS AND DISCUSSION

Several low cycle fatigue tests with constant stress am-
plitude $\sigma_y$ are executed on hourglass shaped samples made
of two different steels: the specimens denoted by CR1 are

<table>
<thead>
<tr>
<th>$H_c$ (A/m)</th>
<th>$k_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma=0$</td>
<td>264.2</td>
</tr>
<tr>
<td>$\sigma=\sigma_y/2$</td>
<td>258.5</td>
</tr>
</tbody>
</table>

FIG. 1. Proportional variation of coercive field $H_c$ and mean-field parameter $k$, compared to their initial values (see Table II) and as a function of the fatigue lifetime, for both the zero load and the $\sigma_y/2$ mechanical condition.

For zero load ($\sigma=0$), $k=0$ during the fatigue lifetime.

Steps (3)–(6) are then iterated in order to find the optimal
value for $k$. This value for $k$ is used to determine $(H_c,M_{irr})_1$, which serves as input for the determination of the moving
PDF.

FIG. 2. Local coercive field distribution $Q(h_c)$ for the case $\sigma=0$, for several load interruptions denoted by the fatigue lifetime (in %, relative to the number of cycles to failure $n_f$).

FIG. 3. Local coercive field distribution $Q(h_c)$ for the case $\sigma=\sigma_y/2$, for several load interruptions denoted by the fatigue lifetime (in %, relative to the number of cycles to failure $n_f$).
fatigue lifetime, indicating similar trends for $H_c$ and $k$. This is in agreement with the relation according to Basso et al., $k \propto H_c / M_{sat}$.

Once $k$ is determined, the moving PDF $P(h_c, h_m)$ can be reconstructed for each load interruption. In Figs. 2 and 3 results are given in terms of the local coercive field distribution $Q(h_c) = \int_{h_m} P(h_c, h_m) dh_m$. Figure 4 depicts the peak values of $Q(h_c)$, denoted by $Q_{\text{max}}$. Again, three stages can be distinguished: $Q_{\text{max}}$ first decreases, then stabilizes, and starts to decrease at 90% of the fatigue lifetime. As can be noticed in Fig. 4, for both mechanical conditions the $Q_{\text{max}}$ values more or less coincide. However, when comparing Figs. 2 and 3, one can see that this is not the case for the position of the peaks.

The evaluation results using the second technique (continuous measurement of $\Delta M$ at constant applied field) are shown in Figs. 5 and 6 for a fatigue test executed on a HR2 sample, with the following specifications: $\sigma_{a}=160$ MPa, $\sigma_{m}=65$ MPa, and number of cycles to failure $n_f=35,502$. Trends are similar for tests with other specifications and for material CR1.

The magnetization variation measured during each stress cycle is in essence a relative quantity. Here, the magnetization variation $\Delta M$ is defined relative to $M_{\text{max}}$:

$$\Delta M(t) = M(t) - M_{\text{max}}.$$  

Figure 5 shows the magnetization variation $\Delta M$ under constant applied magnetic field during a stress cycle as a function of the cyclic mechanical stress $\sigma$. When following a particular $(\sigma, \Delta M)$ loop one can see that, starting at maximum magnetization $M_{\text{max}}$ situated at $\sim 75$ MPa and with $\sigma$ decreasing, $M$ decreases to $M_{\text{min}}$. When $\sigma$ again increases, $M$ increases to a local maximum at $\sim 150$ MPa and then decreases slightly. With $\sigma$ again decreasing, $M$ increases to $M_{\text{max}}$. Similar results for the relation between mechanical stress and the magnetization during cyclic mechanical loading can be found in Ruuskanen and Kettunen.

The peak-to-peak value of the magnetization, $\Delta M_{(p2p)} = M_{\text{min}} - M_{\text{max}}$, is shown in Fig. 6. Three stages can be distinguished: $\Delta M_{(p2p)}$ first increases, then stabilizes, and finally starts to decrease at 95% of the fatigue lifetime.

To conclude, three magnetic parameters where investigated, which all exhibit three stages in their relation to the fatigue lifetime: the mean-field parameter $k$, the peak value of the local coercive field distribution $Q_{\text{max}}$ and the peak-to-peak magnetization under constant applied magnetic field during a stress cycle $\Delta M_{(p2p)}$. The transition of these parameters to the final fatigue stage, occurring at approximately 90%–95% of the fatigue lifetime, can be used to estimate the remaining fatigue life of steel components.

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