Fatigue damage assessment by the continuous examination of the magnetomechanical and mechanical behavior

Lode Vandenbossche and Luc Dupré
Department of Electrical Energy, Systems and Automation, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

(Presented 12 November 2008; received 17 September 2008; accepted 16 November 2008; published online 5 March 2009)

To evaluate the material degradation of ferritic steels caused by low cycle stress-induced fatigue, the continuous examination of changes in the magnetomechanical behavior during the cyclic mechanical loading is proposed, and this is validated by comparing with the continuous examination of changes in the mechanical stress-strain behavior. In this context two magnetomechanical examination methods are investigated, differing only in the magnetic field that is continuously applied to the sample during the stress-controlled cyclic mechanical loading, i.e., a constant magnetic field (method $H_{\text{stat}}$) or a time-varying magnetic field (method $H_{\text{dyn}}$), with the magnetic frequency significantly larger than the mechanical frequency. In both methods the magnetization variation $M(\sigma, H)$ during each stress cycle due to the magnetomechanical effect and the strain $\varepsilon(\sigma)$ are continuously measured throughout the complete cyclic mechanical loading test. When analyzing the fatigue-induced changes in the magnetization trajectory $M(\sigma, H)$ determined by both methods ($H_{\text{stat}}$ and $H_{\text{dyn}}$), several stages in the fatigue lifetime can be distinguished (i.e., a steady state and a final stage for as-received samples and an initial stage, a steady state and a final stage for annealed samples), which fully mimic the corresponding stages in the inelastic strain-stress behavior. All investigated magnetomechanical and mechanical parameters change significantly during the final fatigue stage (i.e., the last 2%–5% of the fatigue lifetime). This information can be used to estimate the remaining life of steel components. © 2009 American Institute of Physics.

[DOI: 10.1063/1.3070642]

I. INTRODUCTION

During the service life of constructions or machines the cyclic mechanical loading of steel parts can lead to an accumulation of fatigue damage. This material degradation process is usually divided into three stages:1 (a) slip and agglomeration of dislocations; (b) nucleation and growth of microcracks, leading to the coalescence of cracks—this stage occupies most of the fatigue life and is a period of stable damage progression; and (c) formation and propagation of a dominant crack, eventually leading to final failure. To avoid that the fatigue damage process ends in a sudden fracture, it is vital to assess the material degradation preferably in a nondestructive fashion. Concerning ferromagnetic materials, the microstructural dependence of the magnetic behavior makes magnetic techniques appropriate for nondestructive evaluation. In this context typically the change in magnetic parameters is determined at several interruptions of the cyclic loading.2–4 However, due to the abrupt character of metal fatigue it can be difficult to make predictions about the onset of fatigue failure based on experimental data obtained at only limited number of load interruptions. Therefore we explore in this paper the possibility to examine the fatigue process during the cyclic mechanical loading itself, by exploiting the magnetomechanical effect. The magnetization depends on both magnetic field and mechanical stress; hence, during the cyclic mechanical loading the application of a constant magnetic field can be considered, and the magnetization variation resulting from both the applied mechanical stress and the enforced magnetic field can be continuously monitored throughout the cyclic mechanical loading test. Here, two magnetomechanical evaluation methods are proposed.

As a first method (termed as $H_{\text{stat}}$), a constant magnetic field is continuously applied to the sample during a stress-controlled cyclic loading test, and for each cycle the change in magnetization $M(\sigma)$ due to the magnetomechanical effect is measured. This $M(\sigma)$ behavior is showing hysteretic, asymmetric, and not monotonic features (see Fig. 1), which are typical for iron and ferritic steels.5,6 For method $H_{\text{stat}}$, the

FIG. 1. Method $H_{\text{stat}}$: the magnetization $M(\sigma(t), H=H_0)$ as function of one stress cycle $\sigma(t)=\sigma_0 \sin(2\pi f_{\text{mech}} t)$ is obtained experimentally under the application of a constant magnetic field $H=H_0$. The monitoring parameter $\Delta M$ is indicated graphically. Details: $H_0=800$ A/m, $\sigma_0=208$ MPa, $f_{\text{mech}}=0.714$ Hz, mat-A, cycle number $n=5000$. 

---

4Electronic mail: lode.vandenbossche@ugent.be.
peak-to-peak magnetization \( \Delta M = \{ \max[M(\sigma)], -\min[M(\sigma)] \} \) is then monitored throughout the fatigue test for each stress cycle \( n \).

As a second method (termed as \( H_{\text{dyn}} \)), a time-dependent magnetic field is continuously applied to the sample during a stress-controlled cyclic loading test, and for each cycle the magnetization variation \( M(\sigma, H) \) due to the magnetomechanical effect is measured. Here, the magnetic excitation frequency is significantly larger than the mechanical frequency, with \( f_{\text{mag}}/f_{\text{mech}} \) an integer. The typical \( M(\sigma, H) \) behavior is depicted in Fig. 2. For method \( H_{\text{dyn}} \), the peak-to-

FIG. 2. Method \( H_{\text{dyn}} \): the magnetization \( M(\sigma(t), H(t)) \) for one stress cycle \( \sigma(t) = \sigma_m \sin(2\pi f_{\text{mech}}t) \) is obtained experimentally under the application of a time-varying magnetic field \( H(t) = H_i \sin(2\pi f_{\text{mag}}t) \). In (a) \( M(t) \) is shown as a function of \( H(t) \) and in (b) as a function of \( \sigma(t) \), both for one mechanical cycle. The monitoring parameter \( \Delta M_r \) is indicated graphically. Details: \( H_i = 2000 \text{ A/m}, f_{\text{mag}} = 25 \text{ Hz}, \sigma_m = 200 \text{ MPa}, f_{\text{mech}} = 0.714 \text{ Hz}, \) mat-A, cycle number \( n = 5000 \).

FIG. 3. Peak-to-peak magnetization \( \Delta M \) and inelastic strain range \( \Delta \epsilon_i \) versus fatigue lifetime obtained on mat-A with method \( H_{\text{stat}} \) (\( H_0 = 800 \text{ A/m} \)).

peak remanent magnetization \( \Delta M_r = \{ \max[M(\sigma)], -\min[M(\sigma)] \} \) is then monitored throughout the fatigue test for each mechanical cycle \( n \).

Furthermore, to validate both magnetomechanical methods, also the strain-stress hysteresis loops \( \epsilon(\sigma) \) are measured simultaneously throughout the same fatigue test in order to assess the different fatigue life stages based on the inelastic strain \( \epsilon_i = \epsilon - \sigma/E \), with \( E \) as the elastic modulus. During the fatigue test the local inelastic deformation associated with the stress field around a crack tip can be observed on a macroscopic scale as an increase in the stress versus inelastic strain hysteresis loop width: \( \Delta \epsilon_i = \max(\epsilon_i) - \min(\epsilon_i) \).

II. EXPERIMENTAL DETAILS

Fully reversed fatigue tests are executed on the ferromagnetic samples by applying a cyclic uniaxial load with constant stress amplitude \( \sigma_m \) and zero mean stress. To prevent buckling during compression, the investigated samples are hour-glass shaped samples with circular cross section, machined out of cylindrical rods. Only the central sample region with smaller cross section (of diameter 4 mm and

FIG. 4. Peak-to-peak magnetization \( \Delta M \) and inelastic strain range \( \Delta \epsilon_i \) versus fatigue lifetime obtained on mat-B with method \( H_{\text{stat}} \) (\( H_0 = 800 \text{ A/m} \)).

FIG. 4. Peak-to-peak magnetization \( \Delta M \) and inelastic strain range \( \Delta \epsilon_i \) versus fatigue lifetime obtained on mat-B with method \( H_{\text{stat}} \) (\( H_0 = 800 \text{ A/m} \)).

### TABLE I. Material details (yield strength \( \sigma_y \) and fatigue test details (stress amplitude \( \sigma_m \) and number of stress cycles to failure \( n_i \)), combined with results of the magnetomechanical techniques, corresponding to Figs. 3–6. Based on both \( \Delta M_{\sigma} \) and \( \Delta \epsilon_i \), estimates are made about the fatigue lifetime \( n/n_i \) at the transition to the final fatigue stage.

<table>
<thead>
<tr>
<th></th>
<th>( \sigma_y ) (MPa)</th>
<th>( \sigma_m ) (MPa)</th>
<th>( n_i ) (–)</th>
<th>Transition of ( \Delta M_{\sigma} ) (%)</th>
<th>Transition of ( \Delta \epsilon_i ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mat-A</td>
<td>( H_{\text{stat}} ) 285</td>
<td>208</td>
<td>21244</td>
<td>95.5</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>( H_{\text{dyn}} ) 285</td>
<td>200</td>
<td>36947</td>
<td>97</td>
<td>98.5</td>
</tr>
<tr>
<td>mat-B</td>
<td>( H_{\text{stat}} ) 390</td>
<td>250</td>
<td>29352</td>
<td>98.4</td>
<td>98.6</td>
</tr>
<tr>
<td></td>
<td>( H_{\text{dyn}} ) 390</td>
<td>246</td>
<td>41215</td>
<td>98</td>
<td>98.8</td>
</tr>
</tbody>
</table>
length 60 mm) is further examined. Samples of two different ferritic structural steels are considered: mat-A is a S-Mn free cutting steel (0.14% C, 1.1% Mn, and 0.3% S), stress-relief annealed (at 650 °C for 3 h) after machining to hour-glass shape, whereas mat-B is a hot rolled low carbon steel (0.12% C), as received after machining to hour-glass shape. More details about the materials and the fatigue tests can be found in Table I.

The experimental magnetomechanical setup is the incorporation of a magnetic measurement setup inside a mechanical testing apparatus. During the cyclic mechanical uniaxial loading, a magnetic field $H$ is continuously enforced parallel to the stress direction and the following scalar properties are monitored continuously: magnetization $M(t)$, strain $\varepsilon(t)$, stress $\sigma(t)$, and field $H(t)$. Applied force and sample elongation are measured by a load cell and a linear encoder, respectively. Furthermore, the sample is surrounded by two windings: an outer excitation coil to apply a magnetic field to the sample and an inner winding giving rise to the induced voltage $V_i$. Analog integration of $V_i$ results in the mean magnetization in the cross section of the sample, $M$. Two high-permeability U-shaped yokes are used to close the flux path.

III. RESULTS AND DISCUSSION

For both materials mat-A and mat-B a number of fully reversed low cycle fatigue tests are performed. The plastic deformation during these fatigue tests is very small: the plastic strain is always smaller than $10^{-4}$. The two considered magnetomechanical examination techniques ($H_{\text{stat}}$ and $H_{\text{dyn}}$) are carried out for both materials, hence resulting in four characteristic fatigue assessment results, as depicted in Figs. 3–6. The corresponding fatigue test details are given in Table I. In Figs. 3–6, the parameters are depicted with data points rather than with trend curves which gives a good impression about the experimental scatter. For clarity, only one data point is shown for every 25 load cycles.

When comparing both magnetomechanical methods performed on one particular material, the same trends become apparent. For the annealed material mat-A three stages in the fatigue lifetime can be distinguished: both $\Delta M$ and $\Delta M_i$ first increase, then stabilize, and finally start to decrease significantly at about 96% of the fatigue lifetime. For the as-received material mat-B only two stages can be distinguished: both $\Delta M$ and $\Delta M_i$ are quasiconstant during the majority of the fatigue lifetime and finally start to decrease at about 98% of the fatigue lifetime. An initial transition stage at the beginning of the fatigue test is not present for mat-B, probably due to its higher initial dislocation density compared to the annealed mat-A. Moreover the fatigue-induced variation of the inelastic strain-stress hysteresis loop width $\Delta \varepsilon_i$ fully mimics the observed trends in the magnetomechanical parameters (i.e., three stages for mat-A and two for mat-B), showing clearly the correlation between the changes of the magnetomechanical and the mechanical properties.

Both magnetomechanical methods provide information about the start of the final fatigue stage, and this is the case for both materials. The transition to the final fatigue stage, occurring at approximately 97% of the fatigue lifetime, can be used to estimate the remaining life of steel components.

ACKNOWLEDGMENTS

This research was carried out in the frame of the Interuniversity Attraction Poles under Grant No. IAP-P6/21, funded by the Belgian government, and in the frame of the GOA Project No. BOF07/GOA/006.
