A Fatigue Life Assessment of Aircraft Alloys Using Fractal Analysis in Combination with Eddy Current Testing

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Abstract
For the forecasting of the fatigue life of metallic constructions it is important to understand the mechanism that leads to the failure. Neither, the continuum mechanics nor the micromechanics provide sufficient answers. However, a basic understanding of structural changes on different scaling levels is given by the physical Mesomechanics derived for a medium with local structure. For ferromagnetic steel, these mesomechanic structures were analyzed using surface topography as well as Barkhausen noise signals. The acquired results, described in earlier announcements, allow to assess the actual damage state of the material and to estimate the residual time before fracture appears macroscopically. Currently, attempts were made to transfer the fractal concept to non-magnetic materials, especially the feasibility of applying this method on Al7075 and Ti6Al4V aerospace materials and, in particular, the successful application of Eddy Current (EC) approach, with the potential to transition this inspection to an aircraft for an in-situ solution for Structural Health Monitoring (SHM). With the development of optimal test procedures, it became possible to establish the occurrence of mesomechanic deformations at the material surface by the use of topography images of confocal microscopy (CM). The efforts were concentrated on the development of Pulsed Eddy Current (PEC) approach, combined with sophisticated fractal analysis algorithms based on short pulse excitation and evaluation of the EC relaxation behavior. This article explains the idea, shows the measurement setup, and discusses the outcome of this work, which is the result of the cooperation with Wyle Laboratories Inc. on a U.S. Air Force research project, BAA-08-12-PKM.

Keywords: Fatigue Damage, Fractal Dimension, Pulsed Eddy Current, Residual Service Life, Mesostructure

1. Introduction
Structural Health Monitoring (SHM) is a necessary development to improve aircraft maintenance management activities by reducing aircraft down-time and maintenance induced damage, as well as enhancing the nondestructive inspection (NDI) fidelity with optimized sensor placement and the incorporation of diagnostic and prognostic concepts. The overall goal of this initiative is the development and eventual integration of an innovative in-situ nondestructive sensing approach for monitoring pre-crack material deformation in multi-layered aerospace structures due to fatigue loads.

The deformation of material prior to crack initiation caused by fatigue damage shows a complex, non-regular structure that developed initially on a microscopic level and later includes a mesoscopic and macroscopic area (10⁻⁶ to 10⁻³ m). Mesomechanics predicates that the deformation process occurs at three stages [1, 2]. Discussion of the microstructural background of these three stages follows. At the first stage of deformation, dipoles coagulation and interlacements are created. The second stage allows observation of the dislocations forming grids or a structure based on the primary and secondary dipoles; a jungle of dislocations and jogs. At the third stage, the bands appear as the boundaries, which disorient the areas of the material. The physical nature of deformation mechanism is distinguished at different stages, as illustrated in Figure 1. Single glides prevail at the first stage, multiple glides exist at the second stage, and the cross-gliding is in the third stage of the deformation process. Starting with the dislocation pile-ups (microstructure level), the
structural formations have exchange interactions between one another at the great distance. Depending on the energy of stacking faults and the periodic amplitude of deformation, the grid structures or major size structures, such as stable slip bands, can form (meso-I structure level). During the cycling, cross-band-like elements, such as manifold meso-bands, can occur in the material (meso-II structure level) and the processes of structure formation repeats at a higher level. Consequently, this process leads to the plastic deformation and contiguous areas rotation and, as a result, to new stress concentrators production. Hence, such hierarchical deformation structures are expected to have a fractal nature. A fractal is generally a rough or fragmented geometric shape that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole. The fractal dimension $D_F$ is a statistical quantity that gives an indication of how completely a fractal appears to fill space, as one decrease to finer and finer scales. Consequently, scaling behavior of micro- and meso structures can characterize fatigue with the fractal dimension as a measurement of damage, and the corresponding fractal dimension $D_F$ of the deformation structures should be a suitable parameter to characterize the change of the structure at different fatigue stages.

The functional dependence $D_F$ as a function of cycles number $N$ and the number of the cycles until the sample break $N_B$, following the results of the so far investigated materials, should not depend on the frequency of load cycles and the stress or strain amplitude. It is expected that the curve in Figure 1 has a more universal character and should not depend on the material type and load.

The approach of universal $D_F (N/N_B)$ curve has been used by IZFP Dresden not only for the detection of the damaged state of the material, but also for the prediction of the residual service life of the industrial components [3]. According to this approach, it was tried to get information about the fractal dimension of the surface structure levels from electro-magnetic noise signals of materials, exactly by the use of Barkhausen effect, and the Barkhausen noise signals respectively. It was determined that a test concept that works on the basis of the scale behavior of the deformation structures and Barkhausen noise signals can be qualified for damage assessments during the cycling loading of ferromagnetic metals before crack initiation. It was calculated as a parameter of fractal dimension $D_F$ received from the Barkhausen noise changes and a step like $D_F$ curve rising with the number of loading cycles was found.

![Figure 1. Schematic representation of scale levels of shear stability loss in deformed solids with included $D_F$ dependency from cycle number $N$ und number of the cycles until sample break $N_B$. The $D_F$ was computed from in-situ taken SEM images of X6CrNiTi181 steel surface during the fatigue tests by the autocorrelation function algorithm](image-url)
This work focused on the development of demonstrating the feasibility of new sensing capabilities that can be used for non-ferromagnetic materials, such as the multi-layered aerospace structures. More specifically, the work was aimed to establish the feasibility of applying fractal analysis methods on Al7075 and Ti6Al4V aerospace materials, and to develop an Eddy Current approach with the potential to be transitioned into an in-situ SHM solution. An optimal surface topography assessment method taken directly from the bulk-material was identified in confocal microscopy (CM). A reliable Pulsed Eddy Current (PEC) approach, combined with sophisticated fractal analysis algorithms based on short pulse evaluation, was also developed. Results of these investigations will be presented in this contribution.

2. Samples and experimental setup

Samples were fabricated of material of Al7075 and Ti6Al4V, which were adapted for bending fatigue tests. The used stress amplitudes for these tests are shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \sigma_{\text{mean}} \pm \Delta \sigma ) [MPa]</th>
<th>f [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al7075</td>
<td>295( \pm )241</td>
<td>10</td>
</tr>
<tr>
<td>Ti6Al4V</td>
<td>634( \pm )519</td>
<td>10</td>
</tr>
</tbody>
</table>

The specimens were notched in three positions at the sample edge, to generate areas with higher stress concentration, thus yielding a development of more pronounced deformation structure at the notch ground.

Tests were halted at 10, 200, 500 and 1,000 cycles, and later every \( N = 500 \) cycles for confocal microscopy (CM) inspection and PEC measurements of the two alloys. Shape and measuring positions for CM were close to the notch base; the PEC measurements were taken at the center of the specimens. Figure 2 shows a photograph of one of the samples and Figure 3 illustrates the measurement points of each method. The specimens were fatigued until the crack length was more than 3mm.

![Figure 2. Notched test specimens for bending tests](image1)

![Figure 3. Illustration of the geometry of a test specimen with positions marked with #1, #2, and #3 for measurement with confocal microscopy and with “EC” the measurement point for Eddy Current measurements](image2)
**Confocal microscopy**

To obtain high-resolution images of the surface topography at the measurement points and to determine the change during the fatigue life of the investigated specimens, high resolution imaging method, confocal microscopy (CM), was introduced. Confocal microscopy is an optical imaging technique used to increase optical resolution and contrast of a micrograph by using point illumination and a spatial pinhole to eliminate out-of-focus light in specimens that are thicker than the focal plane. Thus, the reconstruction of three-dimensional structures from the obtained images is enabled. Depending on used lenses, the magnification was changed so that the detected sizes vary from 3.2mm x 3.2mm up to 160mm x 160mm. The lateral resolution is between 3.3µm to 0.2µm. The imaging technique provides very fast and accurate topographic representations. The interference effects with this technique are very low.

**Eddy current technique**

Using conventional eddy current techniques, an oscillating magnetic field is applied, which induces an oscillating magnetic field in the electrical conducting sample that in turn induces eddy currents on the sample surface. Variations in the electrical conductivity and/or permeability of the sample due to defects or variations in the geometry or microstructure can be detected using this method. In our investigation we did not use conventional eddy current techniques; instead we used Pulsed Eddy Current (PEC) signals. In contrast to the conventional eddy current techniques, PEC does not analyze changes of the impedance of eddy current coil, but it analyzes the time signal of the voltage decay. A ferrite core sensor with two wound coils was used for the PEC. The coil located directly at the core is the measurement coil (40 turns), and the exterior coil (40 turns) is the excitation coil. Figure 4 shows a schematic cross-section of this sensor.

![Schematic cross-section of design of a PEC Sensor](image)

**3. Fractal Analysis**

As part of the project, a material deformation evaluation approach was developed as schematically shown in Figure 5. Two approaches were applied to measure the effects of mesoscopic deformations for the residual fatigue life assessment: (i) the well-established surface topography change assessment and (ii) the new approach to evaluating specific noise components of Eddy Current data. Adequate fractal analysis of the resulting data will then enable the means for the quantitative assessment of pre-crack fatigue related deformation.
**Analysis of CM images**

Various solutions to indirectly measure and derive the fractal dimension parameter exist [6]. Within the scope of this work, development efforts concentrated on both, surface topography and eddy current noise measurements, to obtain parameters that correlate to $D_F$. Analyzing the images obtained from the topography assessment, the fractal dimension $D_F$ is defined by using the Gaussian smoothing algorithms. The areas with quite different structures are well distinguished in the topography images. This analysis is performed separately for each part of the specimen. The initial image was transformed into a gray map with a 256 tone scale. The gray values, as a measure of height algorithms, can be used to determine the fractal dimensions of rough surfaces. Successive surface smoothing by applying a Gaussian kernel with a different peak width ($\sigma$), and numerically calculating the content of the surface, permits to obtain the fractal dimension by the relation [7]:

$$
\Delta F(\sigma) = F(\sigma) - F_0 \sim \sigma^{-\xi \alpha}
$$

and

$$
D_f = 2 + \alpha.
$$

Where, $F_0$ is the size of base area in the x/y plane, and $\xi$ is a calibration parameter, which depends on the eddy current parameters and is based on the fact, that eddy current signals do not represent height values. This parameter has to be determined by fatigue experiments at a later time.

**Analysis of PEC signals**

Using eddy current measurement techniques, it is possible to measure the electrical conductivity of the material at different depths below the surface depending on the excitation frequency [8-9]. During this work, we attempted to prove fractal analysis of the spatial eddy current noise yields a reliable $D_F$, thereby characterizing the different stages of fatigue damage. However, this eddy current noise is difficult to measure directly. The fractal features of the current noise can be studied by the current relaxation behavior, well described by the linear response theory [10]. Accordingly, the current relaxation, as a result of a jump-like
change of the exciting magnetic field at the time $t_0$, is described by the following two time correlation function:

$$\langle j(t) = \langle j(t_0) \rangle - \langle j(t_0) \rangle - \langle j(t) - (t \rightarrow \infty) \cdot (1 - R(t - t_0)) \rangle$$  \hspace{1cm} (3)$$

$$R(t - t_0) = \langle \Delta j(t) \cdot \Delta j(t_0) \rangle / \langle \Delta j^2 \rangle$$  \hspace{1cm} (4)$$

and

$$\Delta j(t) = j(t) - j(t \rightarrow \infty)$$  \hspace{1cm} (5)$$

Within these equations, $j(t \rightarrow \infty)$ is the equilibrium value of the relaxing current and should be zero in metals. The function $C(t) = 2(1 - R(t))$, where $R(t)$ is the relaxation behavior of the PEC, is the current difference autocorrelation function and should show an algebraic behavior in the case of fractal current nature, i.e.

$$R(t) \sim t^{2H}$$  \hspace{1cm} (6)$$

with

$$D_F = 2 - H,$$  \hspace{1cm} (7)$$

where $H$ is the Hurst-parameter.

The measured time decay of the excited eddy current is not related to the relaxation function, but rather related to their derivation. When the voltage is switched-off at $t_0 + dt$, the same formula can be used to neglect non-linear effects. For $<j(t_0) = 0$ and $(<j(t_0) \rightarrow <j(t \rightarrow \infty)) = -(<j(t_0 + dt) > <j(t \rightarrow \infty))$ it follows for $t > t_0$:

$$\langle j(t) \rangle \sim (R(t - t_0) - R(t - t_0 - dt)) \sim (dR(t - t_0)/dt)$$  \hspace{1cm} (8)$$

Consequently, to receive information on the relaxation function, the integrated PEC signal $IS$, according to the following equation

$$IS(t) = \sum_{k=0}^{n} S_k$$  \hspace{1cm} (9)$$

has to be analyzed. The long-term relaxation is then analyzed by a correlation function as defined below:

$$C(t - t_0) = V_{\text{max}} - V(t)$$  \hspace{1cm} (10)$$

where $V_{\text{max}} = V(t_0)$ and to the position of the $V(t)$ maximum of the measured voltage of PEC signal. Analysis of the slope of the correlation function in a dual-logarithmic coordinate system leads to the fractal dimension, similar to the procedure described in equations 6 and 7.
4. Results
As discussed earlier, Confocal Microscopy (CM) was used for topography analysis of the mesostructure. The selected CM images shown in Figure 6, present the changes in the surface topography during fatigue tests. These and more images taken in this way were analyzed using the Gaussian Smoothing algorithms to determine the fractal dimension of the surface topography, with results presented in Figure 7. An increasing fractal dimension parameter $D_F$ was found for all measurements in dependency to the number of cycles. It was concluded, that confocal microscopy images show a distinct development of mesoscopic deformation structures with bending fatigue, and that the $D_F$ values obtained from CM also show a continuous increase with bending fatigue.

![Figure 6. Development of the mesostructure for Ti and Al alloy specimen during the bending fatigue test obtained by confocal microscopy; N is the cycle number](image)

![Figure 7. $D_F$ over N computed at the images of the CM measured topography for Al alloy (left) and Ti alloy (right). Evaluation by Gaussian Smoothing; the error bars correspond to variations of the determined $D_F$ value for repeated measurements at neighboring positions](image)

The results of the fractal evaluation of the developed mesostructure using correlation function are presented in Figure 8. The increasing parameter of the fractal dimension, interrupted by some fluctuations, was found at all measurement points for a growing number of cycles.
However, major $D_F$ oscillations that were detected mainly at higher cycle numbers were indeed caused by micro-cracking and crack growth. For example, the $D_F$ values of the Al alloy increase up to $N = 500$ with small fluctuations. After this $N$ value, macro-cracks are detected, which caused major oscillations in the later $D_F$ curve. For the Ti alloy sample, the $D_F$ values increase only up to $N = 2,000$. At this cycle number, the macro-crack was detected. For higher $N$ values, $D_F$ decreases. Examples of micro-cracks at Al alloy samples, imaged after the fatigue tests, are presented in Figure 9. The size and frequency of micro-cracks decreases with an increasing distance from the macro-crack. The micro-cracks are oriented in the same direction as the macro-cracks. Such cracks were not observed at the Ti alloy.

5. Discussion

The presented work shows the established occurrence of mesomechanic deformations in Al7075 and Ti6Al4V alloys. The fractal behavior of these mesostructures was successfully and reliably derived from CM images and PEC by parameter fractal dimension $D_F$. A clear correlation between $D_F$ and fatigue loading cycles was established.

Concerning the fractal analysis of the CM images, Gaussian smoothing algorithms provided the most reliable results and was used exclusively hereafter. The CM images showed again a distinct development of mesoscopic deformation structures with bending fatigue; the resulting $D_F$ values obtained from CM, and also from PEC, correspondingly showed a continuous increase with bending fatigue, which strongly indicated an increase of the deformation structure development.

Eventually, formation of micro-cracks and then cracks occurred starting at different numbers of cycles. The presence of these cracks influences both, the CM image and the PEC data. Nevertheless, it is concluded that mesoscopic structures can be identified, and the $D_F$ value can monitor these deformations. Furthermore, micro-cracks and cracks are found to also affect $D_F$, but in distinctively different manner.
The fluctuation and differences between the $D_F$ behaviors of both measurement methods observed in the $D_F$ values during all tests, may have several causes. For one, the CM images do not contain all information about the deformation structure, which may be larger than the scan range of confocal microscopy images. Image processing, for instance, changing the z-scale to achieve better image contrast, may have an influence on the detection of mesostructure differences in the various stages of fatigue. In this case, the differences of the measured $D_F$ values will be even greater. Also, a relatively random choice of measurement point positions can influence the data. The topographic analysis handled the mesostructure locally; the EC sensor included a larger lateral area.

During the analysis procedure, an interesting change in the behavior was observed when cracks determine the characteristics of the eddy current signal. As shown in Figure 10, the calculated slope of the correlation function in a dual logarithmic coordinate system enables clearly distinguished data variations: distinct oscillations determine the behavior of the slope prior to crack occurrence; these oscillations gradually disappear with the onset and propagation of micro-cracks and cracks.

![Figure 10. Plots of the correlation function as a function of time for the Al sample 2 at N = 1010 (top left) and N = 3510 (top right). The fit curve was obtained by linear regression with a given length (L) for the fitting region. The fractal dimension as a function of the start-time ($t_u$) for different fitting regions (L) are shown at the bottom.](image)

This signal behavior and subsequent analysis confirm the anticipated influence of obstacles in their propagation path, particularly cracks, on eddy current distribution in a test specimen. Without the presence of a crack, the eddy currents propagate and distribute uninhibited and their oscillations reflect the applied AC voltage. Consequently, a crack would inhibit these oscillations, which results in the minima as seen in Figure 10. It can be concluded that the PEC measurements and fractal analysis do indeed yield data on crack occurrence on top of monitoring the development of mesostructures.

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