Study of the Applicability of Eddy Current NDT for Fatigue Damage Evaluation in Aluminum Alloy 2024-T3

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Abstract

Mechanical components are generally expected to be damaged by fatigue processes along their lifetime. Since the maximum allowable stress value is reached, some irrecoverable and cumulative damage appears in materials. That process is related with the nucleation of superficial or volumetric discontinuities (micro-cracks or micro-cavities) and begins when any localized stress is greater than the material yield stress. For components where fatigue damages are determinative, the existence of a reliable way to measure and evaluate them is highly desirable. Quantitative evaluation of fatigue damage in materials is a complex task and involves their macroscopic and microscopic properties as well as other physical ones. In this work, high cycle fatigue tests were performed at laboratory in aluminum alloy 2024-T3 specimens and the changes verified in their electrical resistivity were accurately measured. Curves, correlating the number of loading cycles with the electrical resistance changes of a section of specimens were plotted and significant changes were observed. It is well known that magnetic permeability and resistivity changes in materials, associated with the test frequency and the geometric aspects of the tested object are the main parameters considered for the application eddy current as a nondestructive testing method. So, based on the presented results, the development of an eddy current test arrangement for cumulative fatigue damage evaluation in aluminum alloy 2024-T3 is suggested.

Keywords: fatigue, damage, electrical resistance measurement

1. Introduction

Studies about fatigue in structural or mechanical parts have wide objectives. It is estimated that fatigue is responsible for 80% a 90% of the in service failures of structural and mechanical components, causing economical, environmental and social prejudice. It is possible to define the fatigue as a localized degradation process, progressive and permanent, that occurs in materials subject to stress and strain variation and that produce cracks nucleation or an entire fracture, after sufficient number of cycles [1]. The continuum damage theory can be used to study fatigue damage evolution in metals and predict its fatigue lifetime [2, 3, 4]. Determination of measuring parameters that can be more sensitive to damage accumulation and easier to be tested is a key to successful application. The damage creation event in metals represents the creation of surface or volumetric discontinuities, micro cracks and cavities respectively [4]. A material is considered free of damage (a virgin material), in the absence of micro cracks and cavities at microscopic scale (10^{-3} – 10^{-2} mm) in its body. The condition of damage is the rupture of the material.
According to Eq. 1 damage can be defined as:

\[
D = \frac{A_D}{A} = 1 - \frac{\tilde{A}}{A}
\]  

(1)

Where:

\( D \) is the damage;  
\( A \) is the cross-sectional area of a given damaged specimen;  
\( A_D \) is the total defective area on that cross-section;  
\( \tilde{A} \) is the effective loaded area \((\tilde{A} = A - A_D)\)

The experimental methods used for quantitative damage evaluation in materials may be classified as direct and indirect. In the direct methods, the evaluation of the damaged area is performed measuring the micro-defects density by means of microscopy, porosity or x-ray diffraction for example. In the indirect methods, the damage evaluation is done measuring changes in some physical and/or mechanical properties of the material, affected by the induced damage, for example electrical resistance changes measurements. In this case, the potential drop measuring technique (PD) has been widely used [5]. In this approach, a constant electrical current is applied into a specimen of the material. With a help of two sharp electrodes, separated by a known length \( l \) and connected to a precision voltmeter, the potential drop over \( l \) can be measured, as represented by Figure 1.

![Figure 1. Potential drop measuring schematic representation.](image-url)
Those values are governed by the Ohm’s law, expressed by Eq. 2.

\[ R = \frac{V}{I_{c}} \]  

(2)

Where,

\( R \) is the electrical resistance (Ω);
\( V \) is the potential drop (volt);
\( I_{c} \) is the electrical current (Ampere).

Since the value of the electrical resistance is known, it is possible to obtain the resistivity \( \rho \), by means of Eq. 3.

\[ \rho = \frac{RA}{l} \]  

(3)

Where,

\( \rho \) is the resistivity of the material (Ωm);
\( R \) is the electrical resistance (Ω);
\( l \) is the distance or length of the piece of material (m);
\( A \) is the cross-sectional area of the specimen (m²).

Considering the high cycle fatigue, damage measurements may be obtained (in a simplified way) according to the Eq. 4 [6]:

\[ D = 1 - \frac{R}{R'} = \frac{\Delta R}{R'} \]  

(4)

Where,

\( D \) is the damage;
\( \Delta R \) is the increment in the electric resistance variation between the virgin material and the damaged material;
\( R \) is the electric resistance of the virgin material;
\( R' \) is the electric resistance of the damaged material.

Notice that when \( D = 1, R' \to \infty \), that corresponds to the rupture of the specimen.
The objective of this paper is to demonstrate, experimentally, that the electrical resistivity of aluminum alloy Al 2024 T3 changes, due to the fatigue damage. So, based on that verification, the authors suggest the development of another indirect fatigue damage measuring process, based on eddy current (EC) nondestructive testing method (NDT).

2. Experimental procedures

2.1 Materials and specimens

For this work, fatigue specimens of aluminum alloy 2024-T3 were machined. Their shape and dimensions (in mm) are presented in Figure 2.
2.2 Test equipment

High-cycle fatigue tests were performed using a high frequency a reverse loading fatigue machine presented in Figure 3. This equipment is capable to apply reversal loading, simultaneously, to five specimens. The test speed (cycles per minute) can be precisely adjusted and total number of cycles is electronically stored.

![Figure 3. Reverse loading fatigue machine.](image)

The values of electrical resistance changes of fatigued specimens are typically very low. In this work, all electrical resistance changing measurements were performed using a Tinsley – model QJ57 high accuracy direct current double bridge. To assure that the measuring place over the surface of the specimens was always the same an acrylic stand was employed. A general view of that set is shown in Figure 4.

![Figure 4. Specimen electrical resistance measuring set.](image)
2.3 Tests conduction

Initially, the electrical resistance of a “virgin” specimen was measured and registered. So, the specimen was attached to the reverse loading machine, an adequate value of stress amplitude was adjusted and several (thousands) loading cycles were applied. After that, the specimen was removed from the loading machine and its electrical resistance was measured and registered again. The process was repeated many times, until the rupture of the specimen.

3. Results and discussion

Curves correlating the measured change of the electrical resistance ($\Delta R$) of each Al 2024-T3 specimen with the number of loading cycles ($N$), under different stress amplitudes, were plotted. A typical curve is presented in Fig. 5.

![Figure 5. Typical electrical resistance change versus number of cycles curve.](image)

For such curve, it can be said that until approximately 180000 cycles the electrical resistance remains reasonably stable. From that point, those values begin to increase and by 230000 cycles the rupture condition is achieved. In this interval, the electrical resistance changes by five times, moving from less than $1\cdot10^{-6}$ $\Omega$ and reaching ~ $5.6\cdot10^{-6}$ $\Omega$. As the geometry and dimensions of the specimens are known, by means of Eq. 3 it is possible to obtain corresponding resistivity values. Using Eq. 4, damage versus number of cycles curves can also be plotted.

Since changes in the electrical resistivity of Al 2024-T3 alloy specimens can be inferred from the measurement of the corresponding electrical resistance, measured by means of PD...
techniques, and taking into account that eddy current NDT depends on that same physical quantity (as well as the magnetic permeability), it is possible to consider the development of an eddy current-based fatigue damage evaluation system.

4. Conclusions

This study showed, by means of experimental processes, that the electrical resistivity of Al 2024-T3 alloy specimens increases, due to the presence of defects caused by fatigue such as: inclusions, dislocations, vacancies and micro-cavities.

This phenomenon can be considered to develop an effective fatigue damage evaluation system, based on eddy current nondestructive measuring technique.

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6. REFERENCES