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Crack detection in aluminium plates for aerospace applications by electromagnetic impedance spectroscopy using flat coil sensors

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ABSTRACT

A flat coil sensor based on eddy current technology has been developed in K.U. Leuven for the purpose of structural health monitoring (SHM) of critical aircraft components. SHM is an upcoming technology and the implementation of those techniques receiving a high level of interest from the aviation industry. Aircraft manufacturers and airline companies nowadays are concerned with constant structural monitoring of their aircrafts. It is crucial not only for safety reasons but also for a faster maintenance and a healthy ready-to-operate fleet. Nowadays, eddy current sensors are already used as the main detection system for cracks on various critical points of an aircraft. These critical points can be found primarily on plate-like aluminium parts where small holes or rivets are present. In this study, a high-cycle fatigue test using the flat coil sensor was performed in order to monitor cracks in thin aluminium 2024-T3 plates. Results showed that this type of sensor was able to detect crack growth by impedance measurements and due to its flexible design it could be used as an embedded sensor for online monitoring.

1. Introduction

The aluminium skin of an aircraft is seriously loaded in fatigue especially during takeoffs, landing and turbulences. Furthermore, rapid temperature changes, the humidity of the environment and cabin pressurizations all influence the structural integrity of its aluminium body. Sometimes, repeated stresses result in fatigue cracks. The intensity and frequency of the applied stresses can cause a gradual growth of these cracks, especially near stress concentrations such as edges, fillet transitions or connection areas where rivets are present. In some cases, the fatigue damage can lead to a fatal disaster when appropriate damage detection techniques are not in place.

Structural health monitoring (SHM) of critical aircraft components is an interesting tool for rapidly assessing their structural integrity. SHM is using sensor networks and can automatically detect damage in engineering structures. In last years, the interest in and the literature on SHM is exponentially growing [1]. Some SHM techniques are already on the market, but applications for civil aviation are still in an experimental phase. Aircraft manufacturers and research institutes are currently exploring which of the SHM technologies may have potential to be implemented into real aircraft structures [2]. A promising SHM technology in the field of non-destructive testing (NDT) that can monitor critical parts of an aircraft is based on eddy currents. Eddy current sensors if used as a network can provide a solution for damage detection on medium to large critical areas on the aircraft. Eddy current methods make use of the alternating currents that are excited in the material under investigation and that create opposing magnetic fields to the magnetic field that causes them [3]. The defects in the specimen cause local interruptions of the induced eddy currents, which result in measurable impedance variations in a nearby search coil [4].

Alternative SHM techniques under development include piezoelectric sensors as well as optical sensors mainly used for the composite parts of an aircraft [5]. The eddy current technology has numerous advantages:

- It is a less complex damage detection technique than other detection systems providing simple data interpretation.
- It can give reliable measurements even if there is no direct contact between the material under investigation and the sensor.
- The weight of the sensors as well as the cost of equipment can be kept relatively low.
- It can be used in a large variety of frequencies determining penetration (detection) depth [6].

There are certainly some limitations to be considered.

- Scanning area of one eddy current sensor is relatively low.

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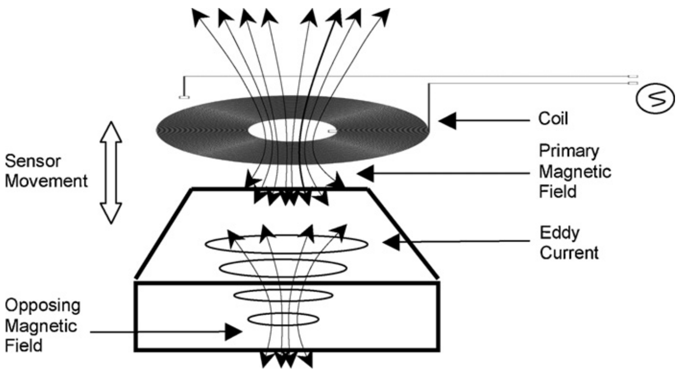

Fig. 1. Eddy currents in a conductive material.

- Eddy current only allows measurements on conductive materials.
- It has a general relatively shallow depth of penetration (skin effect), therefore, is mostly used in plate structures.
- Very small discontinuities that are parallel to the field flow are difficult to detect [7].

2. Materials and methods

In 1824, a French physicist François Arago discovered an electrical phenomenon, known as the eddy current phenomenon, which occurs when a conductive material is near an alternating magnetic field [8]. The basic principle is as follows: when a coil is fed with an alternating current, it builds an alternative magnetic field (primary, magnetic field). This field is encircled by an electric field according to Faradays law of induction,

$$\varepsilon = \frac{-d\Phi_m}{dt}$$

where ε is the electromotive force and Φ_m is the magnetic flux through a surface encircled by the coil. In a conductive material, this alternating electrical field induces eddy currents. The eddy currents are confined to shallow depths near the conductive target surface. Their effective depth (δ) is given by,

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

In the formula above, f is the frequency, μ is the magnetic permeability and σ is the conductivity of the material under investigation. These eddy currents build up their own magnetic field (opposing magnetic field), which will be superimposed on the primary magnetic field. As a result, the impedance of the coil is changing. This impedance variation carries information of the electromagnetic properties of the material and the geometry of the system under inspection.

Fig. 1 shows the formation of the eddy currents and how an opposing magnetic field is generated when the coil is approaching the conductive material.

In this study a unique eddy current flat sensor is investigated for NDT applications on aircraft components. Similar eddy current sensors have been designed by the European Aeronautic Defence and Space (EADS) Company and they are used in the areas of aircrafts where joints or access points are present [9]. Furthermore, another non-destructive technique for fatigue monitoring, i.e. crack growth detection includes meandering winding magnetometers mainly used on steel alloys [10,11]. In contrast to those sensors, the sensors reported here are specifically designed in order to fit on top of the rivets in a doubler repair, see Fig. 3. The sensors were made with the method of etching and printing copper on a Kapton foil.

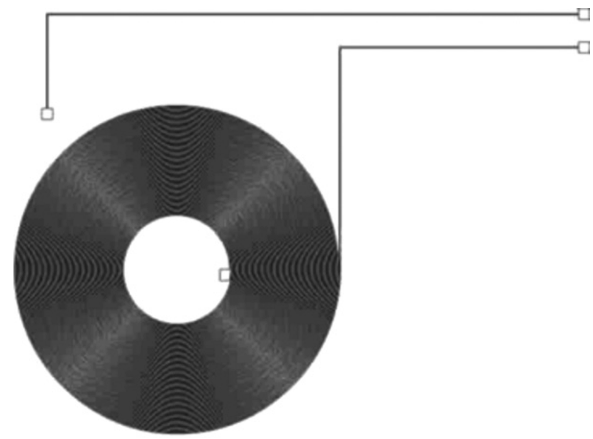

Fig. 2. Eddy current flat coil sensor drawing.

Fig. 2 shows the initial design of the flat coil sensor in AutoCAD. It is designed to fit exactly on top of a rivet that is used to connect two aluminium plates in an aircraft structure.

The sensor was tested on plates of the aluminium 2024-T3 alloy, which is the most popular high strength aluminium alloy for aerospace applications and extensively used by aircraft manufacturers. The coil has 50 windings and the width of each line as well as the pitch between them is 100 μm. The thickness of the Kapton foil is 25 μm, followed by an adhesive layer of 25 μm. The thickness of the copper that is printed on it is 35 μm. The material used for the coil is copper and the carrier material is made of a polyimide film (Kapton). Kapton has many advantages as it is flexible and almost transparent, which assists to position the sensor on the plates with high accuracy. Furthermore, it can remain stable in a wide range of temperatures, from −273 to 400 °C. This is essential since an aircraft undergoes a variation of temperatures during its lifetime. Fig. 3 below shows how the flat coil sensor can be attached directly on top of the rivets that connect two aluminium plates. Rivets are the principle method of connection of most of the aluminium sheets within fuselage structures. The manufacturer or the airline company can provide the necessary information regarding the most critical areas with potential cracks or existing cracks that are allowed to propagate within damage tolerance (e.g. after stop-drilling – a method to slow down the growth of an existing crack). In that way, the number of sensors, cables and total weight can be reduced. These sensors can be used as a tool to follow crack

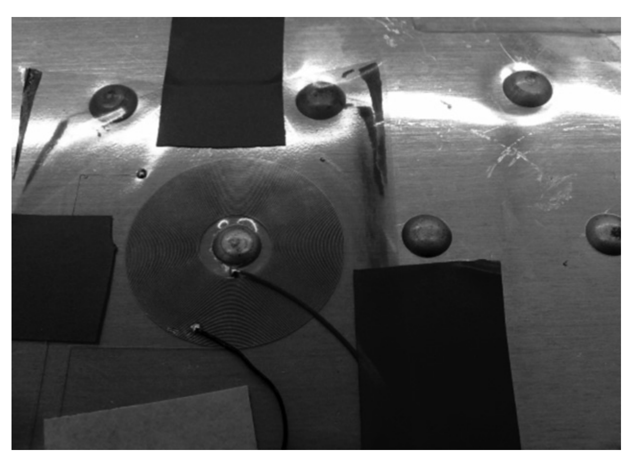

Fig. 3. Eddy current sensor attached (the tape used here is for demonstrative purposes) on an aluminium sheet with rivet connections. The sensor fits exactly on top of a rivet and monitors a possible crack appearance.

Fig. 4. Eddy current sensor glued on the 2024-T3 Al. plate, over the primer (left) and between layers (right).

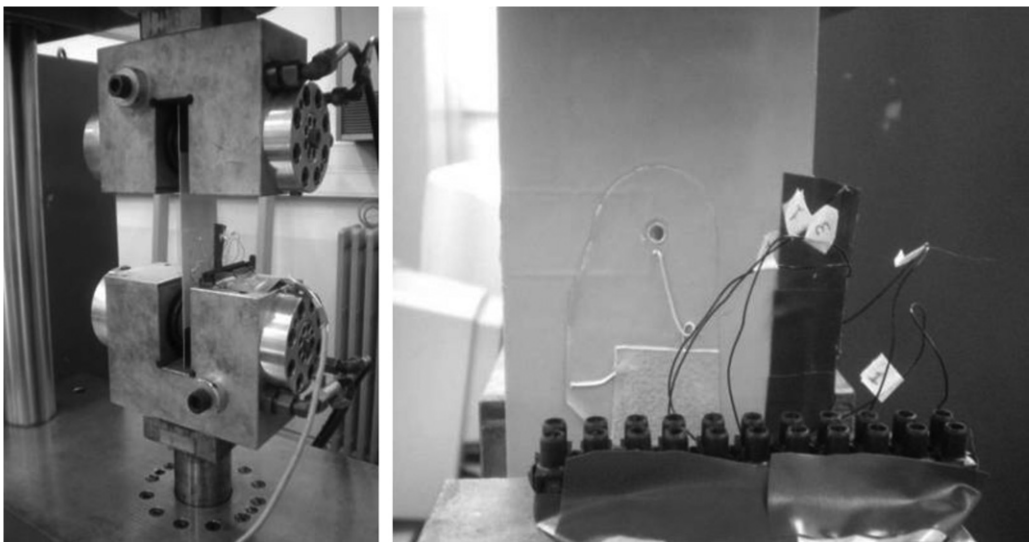

Fig. 5. Final setup on Schenck Hydroplus fatigue machine.

damage in areas where damage tolerance applies and where crack propagation is allowed to monitor before the replacement of the part is needed. In this study, the reliability of the eddy current sensor to detect a fatigue crack in the aluminium 2024-T3 plates was investigated. In classic Eddy current inspection techniques, the sensors are moved above and along the areas under investigation. The flat coil sensors tested in this study are embedded and attached on the areas under investigation. Therefore, in this SHM method, the sensor is fixed and someone can only look at the impedance at a fixed position and observe changes of crack size by the change of impedance.

3. Sensor integration and setup

Mounting the NDT sensor on the specimen under investigation can be a challenging operation. It is essential that the sensor is able to operate at any time regardless the harsh conditions. In this study, most of the aluminium parts provided and investigated

Fig. 6. Cypher C-60 (left) for phase and impedance and the LCR HM8018 (right) for inductance acquisition.

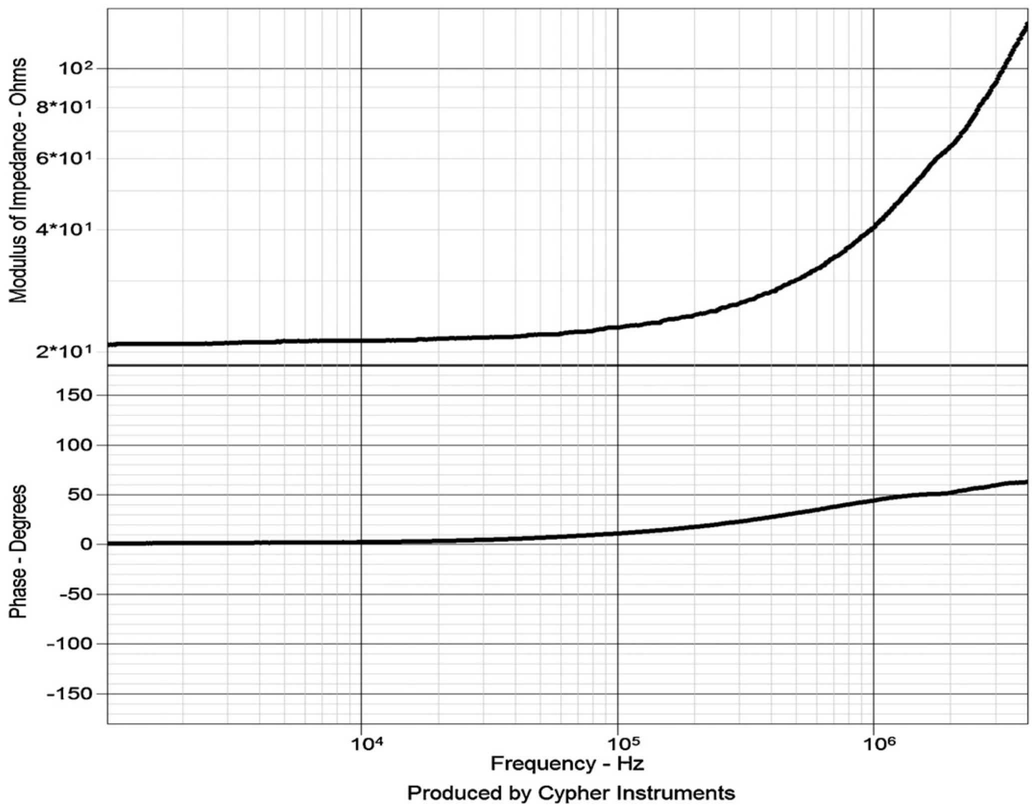

Fig. 7. The phase and modulus of impedance spectrum for the plate with hole recorded after 90,000 fatigue cycles and during hold at mean fatigue load (8 kN).

had to be tested in realistic in-flight loading conditions. Prior installation, all aluminium parts of an aircraft have to be coated with two layers of an epoxy primer and a top-coating frequently made of polyurethane. The first layer of the primer is directly applied on the surface to eliminate conductivity and maximize the protection towards corrosion. The top coating is applied for UV resistance, to colour and to resist fluids and chemicals. The flat coil sensor was embedded between the second layer of the primer and the finishing top-coating, see Fig. 4. The above procedure was followed to avoid the use of any additional adhesive for the sensor attachment. Only a small volume of epoxy glue was used on the sensor to attach it on the primer. Then, the sensor is painted with the top-coating together with the specimen under investigation. During the fatigue test, the sensor remained stable on the plate and was removed from the coating only when the plate was broken.

Fatigue cracks are the most common cracks that appear in the airframe of an aircraft. The aluminium plates, 300 mm (length), 80 mm (width) and 1 mm (thickness), were tested in a servo-hydraulic fatigue testing machine from Schenck AG (now Instron Schenck Testing Systems GmbH). This fatigue machine has a maximum load capacity of 160 kN. When simulating the cyclic loading, see Fig. 5, the sensor measurements would give information about the crack growth [12]. The sinusoidal load had a maximum value of 12 kN and a minimum of 4 kN. The frequency of the cyclic load was 15 Hz. The number of cycles generated in the test went up to 120,000 cycles. This amount of cycles is enough to create a considerable crack ~12 mm in the plate. To introduce a stress concentration from which the crack will initiate, a drill was used to create a hole of a 4 mm diameter in the middle of the plate simulating the hole from a rivet. The crack initiated at both sides of the hole and propagated horizontally opposite to the load direction.

Electromagnetic impedance spectroscopy is used to collect the data. From the Cypher Instruments C-60, see Fig. 6, the electromagnetic frequency chosen for further analysis is 15 kHz. The analysis for electromagnetic frequencies of 5 kHz and 10 kHz gave the same trends.

Fig. 6 shows the instruments used to measure and record the phase, impedance and inductance of the coil sensor during the fatigue experiment. The Cypher C-60 is an Impedance-Amplitude-Phase Analyser from Cypher Instruments Ltd. and it was used for the phase and impedance acquisition. The LCR Meter HM8018 from HAMEG Instruments GmbH was used for the inductance acquisition.

4. Results and discussion

In Fig. 7, the phase and modulus of impedance of the sensor over the electromagnetic spectrum as recorded by the C-60 Cypher instrument is presented. The measurement was taken when the fatigue crack of the plate was open, therefore after 90,000 cycles the plate was held at the mean fatigue load (8 kN).

The crack growth was responsible for the change of impedance in the flat coil sensor. Fig. 8 shows the size of the crack in millimetres, for both sides of the hole versus the number of cycles. This physical size of the crack in the plate was measured with a small ruler and a micrometre. The crack is not increasing equally at both sides of the hole.

After several numbers of fatigue cycles, the fatigue test was stopped in order to inspect the cracks. During the stop two static loading conditions were applied to the plate. In the first condition the static mean load of 8 kN was applied to keep the crack open and in the second condition a minimum load (~0.4 kN) was applied and the crack was not visible with the naked eye. At 0.4 kN the crack microscopically is not closed.

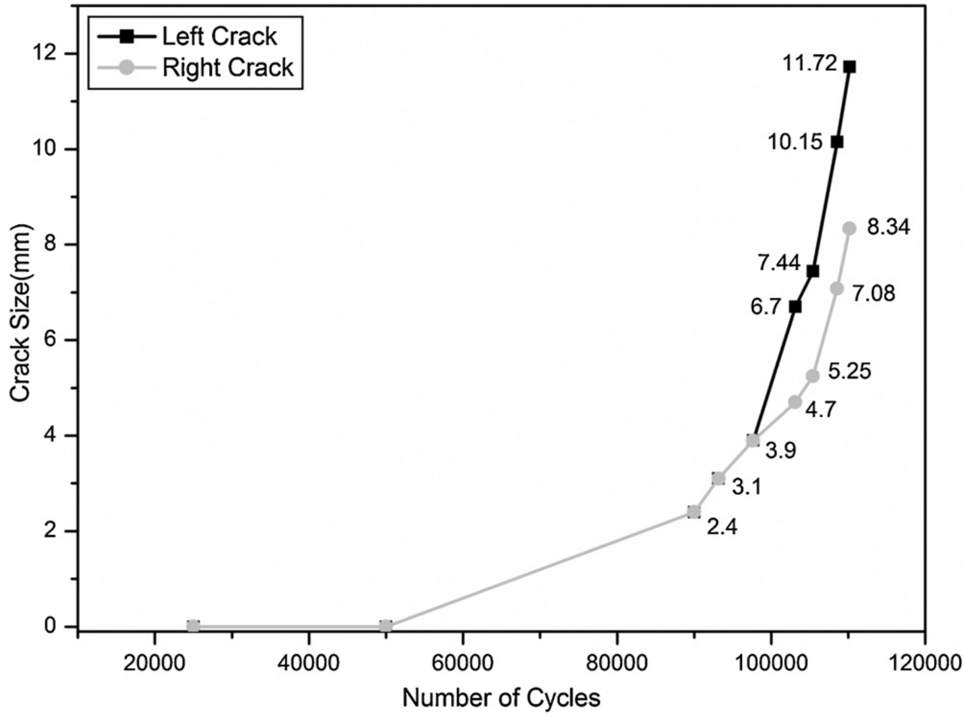

Fig. 8. Crack growth as a function of the number of cycles at load frequency: 15 Hz, mean fatigue load 8 kN, maximum fatigue load 12 kN and $R = 0.3$.

According to the handbook for sound engineers [13], the inductance of the spiral coil can be calculated with the Wheeler's equation shown below:

$$L = \frac{B^2N^2}{8B + 11C}$$

where B is the radius of the windings, N is the number of windings and C is the thickness of the winding of the copper. Using this equation, a value of 28.88 μH is obtained for the flat coil sensor. The experimental inductance measurements with the flat coil sensor after several cycles of fatigue gave values of 19.5–23.9 μH.

In Fig. 9, the data with circles show the impedance measured at 15 Hz when the crack is closed (∼0.4 kN) and the squares when the crack is open (8 kN) after several numbers of cycles. The crack started to grow at the hole after approximately 50,000 cycles. The impedance is increasing as the crack is growing below the surface of the flat coil sensor. When the number of cycles was around 100,000, the crack growth was fast. At the same time the instrument recorded very high impedances. Shortly after 110,000 cycles,

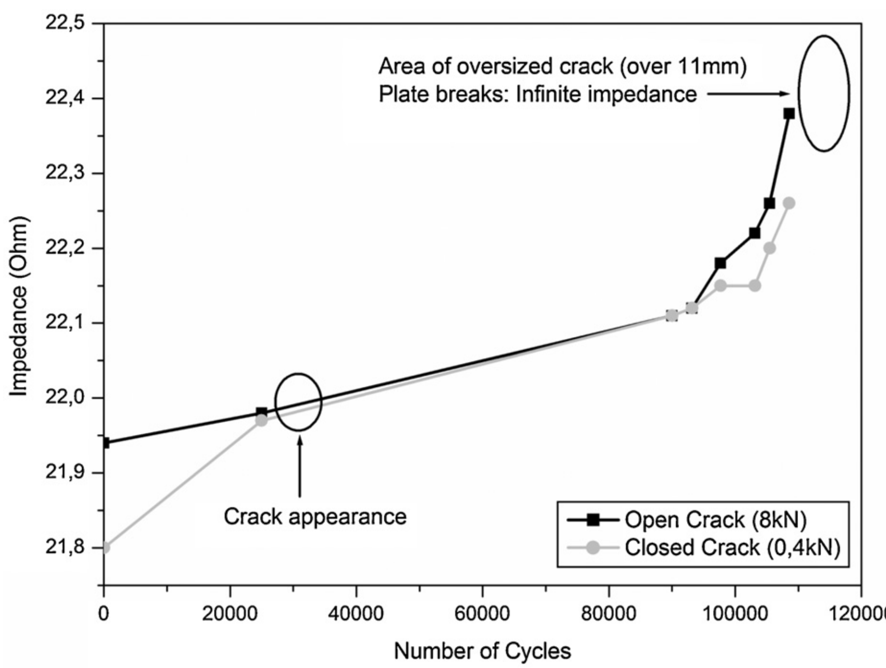

Fig. 9. Impedance measurements when crack is open (8 kN) and closed (∼0.4 kN) (at an electromagnetic frequency of 15 kHz).

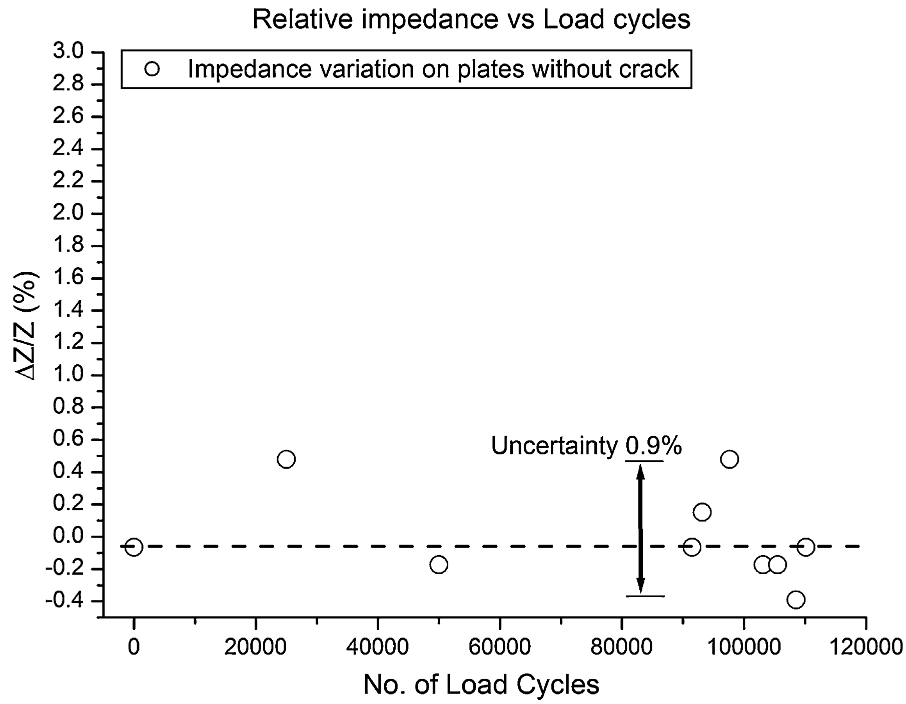

Fig. 10. Impedance variation as a function of load cycles on plates without crack.

the plate broke and the impedance of the eddy current sensor gave an infinite value. The impedance measurements for the open and closed crack have a very small variation, especially up to 94,000 cycles, which is desirable since the sensor should give similar measurements in both conditions (open and closed) when the crack is present.

Two plates were subjected to the same fatigue conditions in order to test the repeatability. It is important for the flat coil sensor to give similar measurements in open and closed crack conditions. The reason is that while the crack is open (with load) or closed (no load), the sensor should always indicate the existence of the crack present after a certain moment. The hole is created to assist the crack initiation on the plates. Before creating the hole, the plates were tested with the same fatigue load conditions to investigate the durability of the sensor during the full number of cycles. In Fig. 10, the white circles represent the relative difference of impedance of

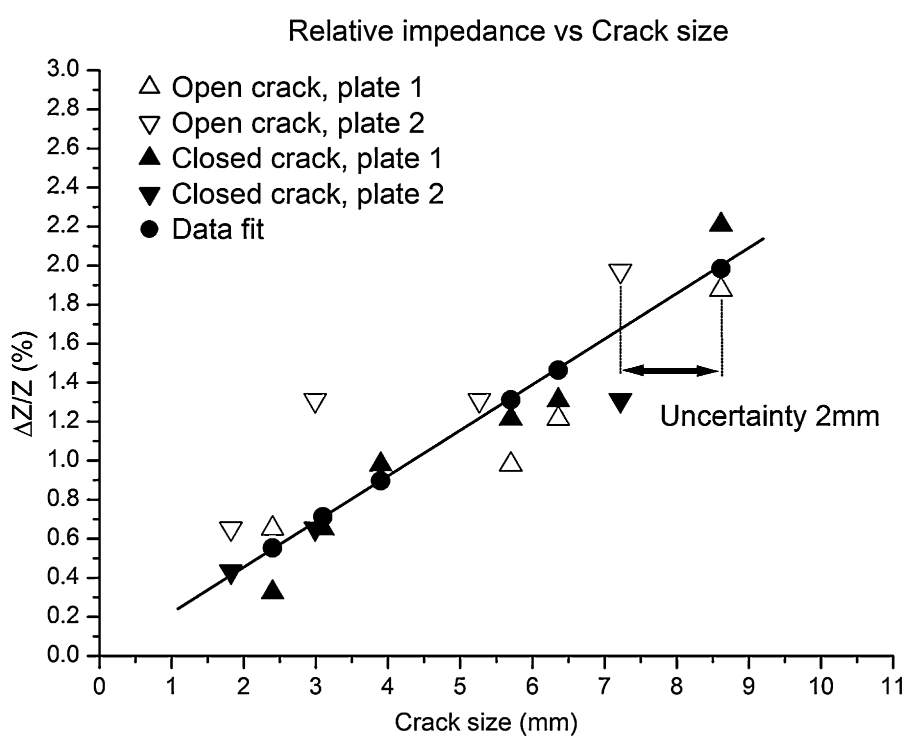

Fig. 11. Impedance variation as a function of the crack size on plates with crack.

the coil sensor on the plates without a hole or crack. The relative difference of impedance $\Delta Z/Z$ (%) is given by the following equation:

$$\frac{\Delta Z}{Z}(\%) = \frac{Z_n - Z_0}{Z_0} \times 100$$

where Z_n is the measured values at any point and Z_0 is the arithmetic mean value of all impedance measurements on the plate without hole before the crack initiation and is used as a reference for the tests. The results in Figs. 10 and 11 below are using this approach.

Fig. 10 presents the relative difference of impedance as a function of the number of load cycles at the plates with no hole, thus no crack. The impedance measurements were recorded at two identical plates without any hole in fatigue load conditions for reliability testing. Such as mentioned above, the average of the first measurements was taken before crack initiation. The results show that the values follow a steady line and deviate from the initial value with a small uncertainty of 0.9% during the total number of load cycles. As it can be seen, more measurements were taken after 80,000 cycles (because that is the point where a crack appears at the next test with the hole) and the deviation is smaller.

Fig. 11 below shows the relative difference of impedance measurements on the plates with the hole and the crack appearance. The relative difference of impedance is presented as a function of the crack growth at the plates that were drilled and the crack had appeared. This graph shows that the relative difference of impedance is increasing while the crack is increasing in millimetres. The black triangles show the relative difference of impedance measurements on each plate when the crack is open. The white triangles show the relative difference of impedance measurements on each plate when the crack is closed. As the crack is growing, the impedance measurements show a positive trend. Although small uncertainties are apparent, it can be seen that the impedance on the flat coil sensor is increasing in proportion to the crack growth. In that way the damage caused by small cracks can be monitored.

5. Conclusions

An increase of the relative difference of impedance is observed for the flat coil sensors in proportion to the crack growth in the aluminium 2024-T3 plates tested in fatigue. According to the results, a crack size of 10 mm corresponds to a 2% change of relative difference of impedance. The eddy current flat coil (ECFC) sensor is based on electromagnetic impedance spectroscopy using eddy currents. These flat coil sensors are embedded between the primer and the top-coating on aluminium sheets. The final motivation is to create an array of sensors that can even be embedded on the surface of the materials of the critical areas and can be used as an online crack detection system. The flexible design of the ECFC sensor allows it to be used as an embedded sensor for various aluminium plate-like parts or for surfaces with rivets (e.g. doubler repair) in order to monitor small cracks that are created due to fatigue conditions. There is still room of improvement concerning the design of the coil sensor as well as for the attachment of the sensor between the primer and the coating. Furthermore, reproducibility tests in various environmental conditions (temperature-humidity during flight) can give a total overview on the sensor's reliability. Possibilities for other means of connection and data acquisition that will reduce the weight and the use of cables are under consideration, e.g. wireless connection.

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Biographies

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Martine Wevers received the MEng Degree in Metallurgy and Materials Engineering in 1981 and the PhD degree in Science and Engineering in 1987, both from the Katholieke Universiteit Leuven. She is professor at the K.U. Leuven and coordinates the research group "Materials Performance and Non-Destructive Evaluation" at the Department of Metallurgy and Materials Engineering. She is specialized in the in situ or on-line damage monitoring techniques (acoustic emission, optical fibres and sensors for structural health monitoring), the evaluation of microstructural damage in materials using X-ray computed tomography, fatigue testing and fracture mechanics.