Crack Detection in Aluminium 2024-T3 Plates and in an Airbus A320 Slat-Track using Electrical Crack Gauges

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Abstract: Structural health monitoring (SHM) is a valuable tool for the investigation and detection of cracks in various engineering structures. Due to the rapid growth of the aviation industry, SHM might have an important place in the field of aeronautics. Appropriate SHM sensors on critical structural components could help to reduce costs by avoiding unnecessary scheduled inspections and will increase the safety of the monitored structures. In this paper, tests on crack gauges made from conductive material are reported. The gauges were mounted on aluminium 2024-T3 plates and on an Airbus A320 slat-track. The aluminium plates along with the A320 slat-track are consecutively painted with layers of primer and coating according to the manufacturer standards. The basic concept of crack detection by the gauges is the interruption of the electrical conductivity by fatigue cracks. The gauges are embedded between the layers of primer and coating in order to be protected and insulated. Results obtained from resistance measurements showed that these crack gauges could detect cracks at a relatively early stage.

Keywords: structural health monitoring, crack gauges, slat-track, aluminium 2024-T3, fatigue testing

1. Introduction

In every aircraft, there are critical areas that are subjected to high fatigue loads. These critical areas can be found in various structural parts of an aircraft. They are characterized as high stress concentration points and need to be monitored in order to prevent a possible failure when small cracks are initiated from the stress concentrations. Maintenance departments of airlines are concerned about these problems. A famous example is the recent fatigue crack appearance in the wing area of Airbus A380 from Qantas [1]. Structural health monitoring (SHM) is considered as one of the most promising technologies that can be used for early detection of cracks and prevent an oncoming critical damage [2].

In this study, aluminium alloy 2024-T3 plates and a slat-track from Airbus A320 were used for crack detection. In general, slat-tracks in the form that they are manufactured today have not shown so far any significant problem that has been reported. Nevertheless, major slat-track and aircrafts manufacturers show a great interest in structural health monitoring of these components since new materials are considered and safety is always a major issue.

The last years, research has been conducted regarding SHM on slat-track related structures investigating fatigue and vibration loads that lead to structural damage [3, 4, 5]. A method for crack monitoring that could be applied on slat-tracks is using ultrasonic surface waves that are propagated through wedged-shaped sensors [6, 7, 8, 9]. Unfortunately, this method was not...
feasible due to the limited space on the mounted slat-track preventing attachment of the sensors when racks inside the slat track were present. Another method for crack detection on slat-tracks used flat piezoelectric transducers actuating different acoustic modes, including bulk waves and surface waves [10]. This method however provided rather complex data requiring advanced data analysis. On the other hand, crack gauges and the interruption of the electrical conductivity can be an efficient, simple and effective method for crack monitoring. Additionally, the equipment needed for data acquisition can be limited to a simple multimeter and the results obtained are instant and straightforward. The interest on permanent crack gauges as a SHM system is reflected by the ongoing research in European projects, such as the Aircraft Integrated Structural Health Assessment (AISHA) II and the Cooperative Hybrid Objects Sensor Networks (CHOSeN) from the seventh framework programme funded by the European Union [11, 12].

There are already commercially available crack propagation gauges for the detection of cracks. These crack propagating gauges are consisting of very thin flat metal stripes that are attached at critical areas. When a crack propagates through the gauge, each time the crack breaks a stripe of the gauge, a stepwise increase of resistance is observed. In figure 1, the drawing on the left shows an example of this type of gauges. The photos in the middle and on the right are taken from a Scanning Electron Microscope (SEM) at a scale of 200 µm and 20 µm respectively. The white stripes are part of the crack gauge and the dark area is the foil on which the gauge is deposited. At the right photo, the lateral view of one of the stripes of the crack gauge can be seen.

The main target of this study is to create a system consisting of crack gauges to be placed on critical areas of aircrafts and to be used with a simple multimeter technology to detect cracks. This system could be used on-line, when the aircraft is airborne or off-line, when the aircraft is on the ground. Offline monitoring has the advantage that no additional equipment is needed onboard the airplane, and the system can be monitored every time the plane is on the ground.

2. Materials and methods

2.1 Principle of investigation and explanation of open-closed crack conditions

The working principle of these crack gauges is the interruption of the electrical conductivity of the crack gauges. The crack gauges are thin conductive stripes embedded in the coating of the material under investigation. The electrical interruption is in appropriate intervals monitored using resistance measurements. When the aircraft is operating, static and dynamic loads affect the integrity of the aircraft structure on long term. Under high stress, there is a potential for crack
formation, and if a crack is present, it will open and close during the load cycles. At the crack position, tensile as well as compression forces therefore might be present. Without load, it is possible that the crack cannot be detected by visual inspection, and even ultrasonic methods will provide wrong read outs due to the change of stress direction, e.g. pressurized cabin or fuselage.

Figure 2: A large crack (30 mm each side) that interrupts the electrical conductivity of the embedded gauges

It is very important for the engineers to be able to monitor and detect cracks even if the cracks are not apparent. This can happen because the crack might be microscopically open but due to compressive stresses, it can close again and be very difficult to detect. Therefore, it is important to have a SHM system that can detect cracks irrespective whether the crack is open or closed. Because every part has its damage tolerance in crack size, this open and closed crack condition of the crack is vital to be taken into consideration in order to avoid sudden changes in crack growth.

2.2 Parts under investigation

In this study, the parts investigated are thin aluminium 2024-T3 alloy plates and an Airbus A320 slat-track. In the 2024-T3 plate, the crack growth was monitored by crack gauges and in the A320 slat-track the performance of the electrical gauge was investigated with an existing artificial crack. Figure 3 shows the parts investigated.

Figure 3: Parts tested: an Aluminium alloy 2024-T3 plate (in the front) and a A320 slat-track (in the back)

The sheets have dimensions 300 mm (length), 80 mm (width), 1 mm (thickness) and are made of the aluminium alloy 2024-T3, which is widely used in aerospace applications. It is a light material with high ultimate tensile strength (483 MPa), high tensile yield strength (345 MPa) and is used to support sheet applications on aircraft components such as wings and fuselage parts, where fatigue is an important driver [13].
The A320 slat-track has a length of 64 cm and is made of maraging steel (grade 250) as it needs to be very strong to withstand the very high loads during take-off, landing and flight. A slat is a component of the aircraft located at the front edge of the wing and it is mounted on curved tracks, see figure 4. The whole mechanism is called a slat-track and its function is to extend the slats that reconfigure the air stream and keep the airplane from stalling when it is flying at high angles of attack [14].

![Figure 4: Slat-track (Left side: position in airplane wing – Right side: dismounted)](image)

2.3 Implementation of crack gauges

Many metallic aircraft components are coated by primers and partially by finishing coatings. The same procedure was followed for the aluminium 2024-T3 plate and the Airbus A320 slat-track, see figure 5. The components are coated with a layer of epoxy primer and a layer of top-coating based on polyurethane. The surface of the component is first coated with a layer of epoxy primer, usually of yellow or green colour, in order to insulate from electrical conductivity and maximize protection against corrosion. After the epoxy primer, a top coating usually is applied on the component. It gives the decorative final colour for the product, and it provides chemical, stain and UV resistance. The painting procedure of the Airbus A320 slat-track was completed at the manufacturer of this component; ASCO Industries N.V., Zaventem, Belgium.

![Figure 5: Painting procedure (Left side: slat-tracks – Right side: finished Al 2024-T3 plate)](image)

For the tests of this study, the A320 slat-track was painted with primer and top coating and the aluminium 2024-T3 plates were coated only with the epoxy primer.
2.4 Aluminium alloy 2024-T3 plate set-up

For the aluminium 2024-T3 plates, the crack gauges are conductive stripes made from an electrically conductive component (PC 3000 from Heraeus GmbH). The component is a fast thermally-curing, solvent-free epoxy adhesive with silver as conductive component. The plate was firstly coated with a layer of 2 component epoxy primer (10P20-44 Akzo Nobel N.V.) in order to provide protection and electrical insulation. Then the conductive stripes were attached on the plate and afterwards the plate was painted again with the 10P20-44 primer for protection and electrical insulation of the conductive stripes.

For the creation of the electrical crack gauges, polyamide tapes (PPI 702) from PPI Adhesive products Corporation were used as guides. Between the tapes, the conductive adhesive was applied with the aid of a spatula. The thickness of the conductive stripes was determining the height of the crack gauges which is 85 µm and the width between the tapes was selected to be 1.5 mm. The plate with the crack gauges was left in the oven for one hour at 60 °C. Next, the polyamide tapes were removed and the connection pads that are made of copper foil were glued on the plate using conductive adhesives and the plates were placed again inside the oven for one hour at 60 °C for hardening. Finally, the plates were coated again with a layer of the epoxy primer and dried at room temperature.

For testing the crack monitoring feasibility, a high cycle fatigue test was performed on the aluminium alloy 2024-T3 plate (figure 6). Two different tests were performed with the same loading parameters and number of fatigue cycles. One test was performed without a hole in order to monitor the consistency of the measurements of the gauge during fatigue and another test with a hole to have a stress concentrator to initiate a crack.

![Figure 6: Al 2024-T3 plate set-up (Left side: Fatigue test – Right side: Embedded gauge)](image)

In this test, the aluminium alloy 2024-T3 plate was subjected to a fatigue load of minimum 8 kN and maximum 12 kN. The fatigue test was performed in the 810 servo-hydraulic fatigue testing machine of MTS Systems Corporation. The maximum dynamic load for this fatigue machine is 80 kN. The frequency of the cyclic load was 15 Hz and 135 000 cycles were applied. To initiate the crack, a hole with 3.5 mm diameter was drilled in the middle of the plate. The 135 000 fatigue cycles are enough to create a significant crack size of ~12 mm in the plate at each side of the hole. Six crack gauges were embedded on the plate, three on the left and three on the right side of
the plate, see figure 7. In a final SHM system, one gauge could be enough if it is carefully located in the area of the critical crack size. Figure 7 below, shows a close-up view of the middle part of the Al 2024-T3 plate with the embedded gauges and the hole for the crack initiation.

![Figure 7: Close-up view of the crack gauges embedded on the Al 2024-T3 plate](image)

The distance between the hole and the nearest gauges is 1 mm on each side and the distance between the gauges is 3 mm. The crack initiated at both sides and propagated perpendicular to the load direction.

### 2.5 Airbus A320 slat track set-up

To test the performance, especially with respect to the closed crack problem, the crack gauge was foreseen on the Airbus A320 slat-track and a 3 point bending test was performed. The crack gauge for the Airbus A320 slat-track is a conductive stripe from aluminium foil that is embedded between the layer of primer and the layer of top-coating. The dimensions of the aluminium stripe are 90 mm (length), 2.3 mm (width) and 18 µm (thickness).

![Figure 8: Slat-track set-up (Left side: 3 point bending test – Right side: embedded gauge)](image)

The 3 point bending test was performed on a 5567 Universal Testing Machine of INSTRON®, see figure 8. In this test, the slat-track was pressed from 0 – 2 kN and then released from 2 – 0 kN
for five times with a rate of 0.1 mm/min in order to obtain open and closed crack conditions. A fatigue crack with a length of 42 mm was already present in the middle of the slat-track. Its function is to open and close during the compression test with the purpose of breaking and re-attaching the crack gauge. In that way the electrical interruption on the gauge is monitored. During compression, the instrument monitors the moment that the crack opens and breaks the gauge and the electrical conductivity on the conductive stripe is interrupted. During load-release, the instrument monitors the moment that the crack closes and the conductive stripe regains conductivity. The test was repeated five times for reproducibility purposes. The crack gauge was embedded between the primer and the top-coating and in a position that does not interfere with the rolling track during movement.

3. Results and discussion

3.1 Crack propagation in a 2024-T3 plate

Initially, a durability test was performed on the plate without hole in order to verify that the resistance measurements on the gauges will remain the same if a crack is not present. Figure 9 shows the resistance measurements during the durability test. It can be seen that there was no significant alteration on the resistance values of each crack gauge.

Figure 9: Resistances on crack gauges on plate without hole
(120 000 – 140 000 load cycles is approximately the maximum number of cycles before the tested plate cracks. The lifetime of an airplane varies and is approximately 300 000 load cycles)
After the durability test, a hole of 3.5 mm diameter was drilled and a second fatigue test was performed. The plate was loaded in fatigue and the crack propagated horizontally and passed through all six gauges before the fatigue test was stopped at 135 000 cycles, see figure 10.

![Figure 10: Six embedded gauges and direction of crack propagation](image)

Figure 10: Six embedded gauges and direction of crack propagation

Figure 11 shows the time that the electrical conductivity of each gauge is interrupted during the fatigue test. As the crack is growing, it breaks consecutively the gauges and they show infinite values of resistance, thus no conductivity. As expected, the gauges 3 and 4 are the first that lose conductivity.

![Figure 11: Interruption of electrical resistance on the 6 gauges on the aluminium alloy 2024-T3 plate](image)

Figure 11: Interruption of electrical resistance on the 6 gauges on the aluminium alloy 2024-T3 plate
The crack appeared after 105,000 cycles and Figure 12 shows the crack growth at the left and the right side of the hole as a function of the fatigue cycles. It can be seen that the crack grew up to a length of 10 mm at each side after an additional 26,000 fatigue cycles. At this point, the crack has passed through all six embedded gauges. This means that the crack has broken all six gauges, and when the crack is open, all gauges have resistance values that are out of range. An out of range resistance measurement means that the measurements are way out of the initial values and the instrument shows an infinite value due to the interruption of conductivity.

At the end of the fatigue test, the crack had interrupted the electrical conductivity in all six gauges. To monitor the possibility of regaining conductivity when the crack was closed another small test was performed. The plate was subjected to a static load of 10 kN keeping the crack open. When the crack was open, all gauges (1-6) lost conductivity showing almost infinite values of resistance. Then, the static load was slowly decreasing to zero and the crack was closing again. Following this procedure, it can be observed if the gauges will regain conductivity and at which load. Table 1 shows the results.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Resistance Before Test (Ohm)</th>
<th>Resistance After End of Test (Ohm)</th>
<th>Conductivity regained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,626</td>
<td>5,993 then Out of range (-∞)</td>
<td>Yes at 6 kN</td>
</tr>
<tr>
<td>2</td>
<td>3,452</td>
<td>Out of range (-∞)</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>3,227</td>
<td>Out of range (-∞)</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>3,173</td>
<td>Out of range (-∞)</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>3,115</td>
<td>Out of range (-∞)</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>3,259</td>
<td>5,149 then Out of range (-∞)</td>
<td>Yes at 0 kN</td>
</tr>
</tbody>
</table>
The results showed that gauges 2, 3, 4 and 5 did not regain conductivity after the completion of the test. However, the crack gauges 1 and 6 that were positioned far away from the hole and near the end of the crack, initially regained conductivity for a period of time but the resistance was increasing until it showed values out of range. The results confirm that when these gauges are monitored, they can detect cracks propagating through the gauge causing interruption of electrical conductivity. Nevertheless, further tests need to be performed in order to optimize the crack gauge.

3.2 Airbus A320 slat-track

The Airbus A320 slat-track was subjected to a 3 point bending test with a load up to 2 kN and then it was released. An artificial crack was already present on the slat-track and the main purpose of the test was to investigate the reliability of the crack gauge when the crack was open and closed again. When the slat-track is compressed, the crack on the slat-track opens and breaks the gauge. In release mode, the crack closes and the gauge is reattached. Table 2 shows the vertical extension of the slat-track with respect to the compressive load applied.

Table 2: Compressive extension and load on A320 slat-track

<table>
<thead>
<tr>
<th>Load</th>
<th>Compressive extension (mm)</th>
<th>Compressive load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0,09</td>
<td>0,014</td>
</tr>
<tr>
<td>Maximum</td>
<td>3,54</td>
<td>2,049</td>
</tr>
</tbody>
</table>

The slat-track was compressed five times to test the reproducibility. The instruments monitor the exact point where the resistance becomes infinite, thus there is an interruption of the electrical conductivity. The loss of conductivity occurs at 0.6 kN during compression. At the same time, when the load on the slat-track is released, it can be observed that the crack gauge regains conductivity when the crack is closing. This occurs again almost at the same compressive load at 0.6 kN.

![Figure 13: Resistance measurements and load (dashed line: electrical resistance, dark line: load)
The result presented in figure 13 shows that the crack gauge used on the A320 slat-track can monitor cracks by the interruption of the electrical conductivity with a straightforward data interpretation. Figure 14 below shows that the resistance value of the crack gauge is increasing after each cycle. The bending test was performed with 5 cycles but the results show that it is possible after many fatigue cycles that the conductivity of the crack gauge can be interrupted. This could be due to deformation of the crack gauge after each cycle or even possible corrosion that can appear on the area that is cut. Future tests will be repeated in order to investigate more in depth this phenomenon.

![Figure 14: Resistance on crack gauge after each cycle](image)

4. A possible solution for the "closed crack problem"

For off-line monitoring and reliable crack detection the following issues have to be taken into account. Due to fatigue, cracks constantly open and close during flight. Off-line monitoring can take place during scheduled maintenance when the aircraft is on the ground and at that moment, cracks can be closed. In that case, the crack propagation gauges are re-combined even if the crack has passed through it. Therefore, the conductivity can be regained and, consequently, it cannot be seen if the crack has reached the critical size since the gauge gives no indication of electrical interruption. A solution to this important issue is presented below.

In order to find the first moment that the crack breaks the electrical crack gauge, a simple and effective solution for off-line monitoring can be put forward by using an electrical fuse. The fuse is located inside a small box and is connected to a Metal–Oxide–Semiconductor Field-Effect transistor (MOSFET) and the embedded electrical crack gauge. The first moment that the open crack reaches a size that breaks the gauge, the electrical conductivity at the electrical crack gauge is interrupted. When the electrical crack gauge loses conductivity, a high voltage is applied on the MOSFET. This voltage induces a conductive channel that goes to the electrical fuse and burns it.
During off-line monitoring, a simple push button test indicates if the crack propagation gauge is broken or not, see figure 15. In that way even closed cracks that could resume the electrical conductivity can be monitored.

Figure 15: Crack on A320 slat-track (left) and push-button test for crack indication (right)

When the button is pressed, e.g. the light indicates that the crack propagation gauge is not broken and the crack has not reached the critical point. The critical point is the point where the crack propagation gauge is placed as it indicates a crack size that is outside damage tolerance. If the button is pressed and there is no light on the box then the crack has passed through and has broken the gauge. That means that the crack has exceeded the critical size and the component needs to be replaced. To be able to utilize this method a small amount of electrical current is needed in order to flow constantly through the conductive crack gauge and the parallel circuit with the fuse. However, having an electrical current in a SHM system can be a disadvantage for some applications. In these cases, appropriate electrical insulation materials should be used.

5. Illustration of a possible SHM system

Figure 16 below shows a possible concept for implementation of crack gauges on e.g. slat-tracks using crack propagation gauges. The same concept can also be applied to aluminium alloy 2024-T3 structural parts. The idea is to have an integrated and lightweight network of crack propagation gauges embedded at critical areas of the aircraft that easily detect cracks, do not interfere with other electrical devices and are simple in philosophy and data interpretation.

Figure 16: Example of final implementation concept
6. Conclusions

Electrical crack gauges have been tested on aluminium 2024-T3 plates and on an Airbus A320 slat-track. The results showed that the interruption of the electrical conductivity due to the crack growth can be easily monitored. These electrical crack gauges can detect cracks when they reach a critical size and monitor them even when they are closed. In that way, they are an added value to safety and offer options to reduce/focus the scheduled maintenance of an aircraft. Additionally, with appropriate equipment they can be used either as an off-line or an on-line SHM system. Due to their design, they can be used to follow complex lines and cover medium to large areas of aircraft components. The embedded gauges are glued on the primer layer to ensure insulation and they can work as integrated systems on critical aircraft components. Because conductive crack gauges contain metallic parts, there is always a possibility for galvanic corrosion between crack gauge and the metallic parts under investigation. Therefore, the right material selection and proper embedment of the crack gauges should be taken into consideration.

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8. References


