Real-time corrosion monitoring of aluminium alloys under chloride-contaminated atmospheric conditions

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Abstract
In this study, the use of electrical resistance (ER) sensors to monitor the corrosion of Al94Cu6 alloy is assessed and compared with 2024-T3 coupons. Under uniform corrosion, a good correlation was found between the ER sensors and mass loss on coupons. Three different chloride depositions are studied: (i) pre-contamination with dry/wet cycles, (ii) Volvo standard accelerated corrosion test and (iii) neutral salt spray test. The obtained results show good reproducibility of the ER sensors under all tested conditions. This suggests that ER sensors more levelled the effect of localised corrosion through a large surface evaluation compared with cross-sections. The corrosion thickness obtained with the ER sensors does not correspond to the mean depth obtained by cross-sections. This can be explained by the distribution and size of the localised corrosion events according to a finite element model proposed. The ER method allows obtaining useful real-time corrosion data for the understanding of the corrosion mechanisms and the development of accelerated tests. The chloride concentration, the frequency of salt application and wet/dry cycles have a strong influence on the corrosion rate of aluminium alloys.

Keywords
2024-T3, accelerated tests, aluminium alloys, corrosion, electrical resistance sensors, finite element method, integranular, neutral salt spray

1 | INTRODUCTION

Aluminium, the most abundant metal on Earth, is widely used for many applications due to its low density, high strength stiffness-to-weight ratio, good formability, recycling potential and good corrosion resistance.[1-6] Alloying elements, such as copper, magnesium, manganese, silicon and zinc are often added to obtain various properties, such as high strength, fatigue resistance, high electrical, thermal conductivity and recyclability. These properties are crucial for the aerospace industry and of growing interest in the automotive industry.[7-12]

For decades, and mainly supported by the automotive industry, accelerated cyclic corrosion tests have been developed and used with the aim to predict or compare the corrosion resistance of different systems.[13-15] This approach has led to the development of cyclic corrosion tests that better simulate service conditions. For the automotive industry, the main aggressive pollutant is chloride, which is used as de-icing salts on the road during the winter period. Most of the accelerated corrosion tests used in the automotive industry have been developed since two to three decades in connection to the increased use of galvanised steel in the body in white. In the case of the aerospace
industry, the common standard today is the salt spray test, for example, ISO 9227:2017. However, neither the current standards used in the automotive industry nor the salt spray test can fully mimic service conditions of structural aluminium materials used in the aerospace or the automotive industry. Hence, there is a need to design more representative accelerated corrosion tests for aluminium alloys. To achieve this, real-time corrosion monitoring on such materials can be crucial.

In the literature, different corrosion monitoring methods have been developed for atmospheric conditions: quartz crystal microbalance (QCM),\textsuperscript{16–18} optic fibre-based sensors (OFCS),\textsuperscript{19,20} acoustic emission (AE),\textsuperscript{21–23} linear polarisation resistance (LPR),\textsuperscript{24,25} atmospheric corrosion monitor (ACM),\textsuperscript{26–28} electrochemical impedance spectroscopy (EIS),\textsuperscript{25,29,30} electrical resistance (ER),\textsuperscript{31–41} and radio-frequency (RF).\textsuperscript{42–44} QCM, OFCS and RF methods rely on the use of thin metallic films, usually deposited by physical vapour deposition and are thus, not compatible with industrial materials and aggressive environments. AE can be adapted to large industrial structures. However, the amount of corrosion events obtained is hard to convert into corrosion rates. Electrochemical-based methods, such as LPR and EIS, allow theoretically determining in real-time the corrosion rate. However, it requires the presence of a thin electrolyte and relies on several hypotheses, such as Tafel coefficients and the active surface. The principle of ACM sensors relies on galvanic coupling measurements between two metals. Under wet conditions and uniform corrosion, a good correlation can be obtained between the galvanic current and the mass loss. However, such galvanic coupling might affect corrosion mechanisms. Moreover, when the electrolyte is too resistive, for example, during the surface drying, the galvanic cell interrupts, while corrosion may subsist.

ER method has been used for decades in aggressive environments, such as on operating vehicles,\textsuperscript{31} ships,\textsuperscript{32} outdoor weathering sites,\textsuperscript{33} accelerated tests,\textsuperscript{34} indoor and conservation conditions.\textsuperscript{33,37,38} This method can be used both under immersed and atmospheric conditions, which make it particularly adapted for accelerated corrosion tests. It relies on the monitoring of the ER of a thin film affected by uniform corrosion, that is, usually for carbon steel, zinc or copper. Under localised corrosion, this relation is no longer linear and the obtained results only give qualitative information on the corrosion rate.\textsuperscript{36} Such a method with aluminium sensors is thus theoretically limited because of localised corrosion, such as pitting, intergranular or exfoliation, which are the main failure modes for structural aluminium alloys in the 2000 or 7000 series. However, under specific conditions, uniform corrosion can also occur due to the complete dissolution of aluminium in alkali or acidic pH conditions.

Al–Cu series alloys are the most widely used heat treatable alloys as aircraft materials, machine parts, and structural materials mainly due to their high strength-to-weight ratio and good mechanical properties. Copper is usually added to provide a substantial increase in strength and to promote precipitation hardening. Aluminium–copper alloys belong to the 2000 series. The distribution of copper in aluminium alloys varies from copper atoms dispersed in solid solution through the formation of clusters of copper atoms and then into a range of intermetallic particles.\textsuperscript{45} The Al2Cu intermetallic particles have negative effects on the corrosion performances of these alloys. The copper-containing phases on the surface tend to be cathodically protected by the galvanic corrosion of the aluminium matrix. Thus, these materials seem particularly adapted to the ER method under the aggressive environment with an important initiation of localised corrosion, rather uniformly distributed on the overall surface.

In this study, the corrosion behaviour of ER sensors made of a binary Al9Cu6 alloy has been studied under various conditions, such as accelerated tests, chloride deposited at the surface and immersed under alkali conditions. The obtained results are compared with AA2024-T3 coupons exposed under similar conditions.

## 2 | EXPERIMENTAL

### 2.1 | Materials

Aluminium 2024-T3 coupons of 50 × 50 × 0.8 mm were used under several exposure conditions. The nominal composition and typical microstructure are given in Table 1 and Figure 1, respectively. The microstructure was revealed using a Keller solution following the NFA 05 12/85 standard and obtained with a CV2 Olympus IX70 microscope. The micrograph presents a grain structure with heterogeneous morphologies, partially equiaxed. The black spots correspond to the traces of vacant intermetallic particles induced by the chemical etching. Before each

| Al  | Cr  | Cu  | Fe  | Mg  | Mn  | Si  | Ti  | Zn  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 90.7–94.7 | Max: 0.1 | 3.8–4.9 | Max: 0.5 | 1.2–1.8 | 0.3–0.9 | Max: 0.5 | Max: 0.15 | Max: 0.25 |

Note: Other elements: max 0.05% each, max 0.15% total.

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TABLE 1 Nominal composition of 2024-T3 aluminium alloys in % weight
exposure, the coupons were degreased with ethanol and acetone for 20 min under ultrasonic stirring. The backside of the samples was protected using a 3M 471 adhesive tape. Al$_{94}$Cu$_6$ ER sensors were realised from laminated 125 ± 12 µm thick foil from Good Fellow (AD220212/2). The AlCu composition and microstructure are detailed in Table 2 and Figure 1, respectively. The micrograph shows many intermetallic particles, approximately 30% of the surface of Al$_3$Cu. No heat treatment was performed on the Al$_{94}$Cu$_6$ alloy. This material was selected due to (i) its availability at the right thickness to make ER sensors and (ii) a good agreement with the behaviour of 2024-T3.[46]

## 2.2 Evaluation of localised corrosion

Samples were prior embedded in an IP epoxy resin, grinded (SIC 220) and polished down to 0.04-µm paste. The polished samples were then cleaned ultrasonically in ethanol. Samples were cut with a Servocut 301 cut-off machine after exposure in the most representative corrosion area. The samples were observed with a metallographic microscope (Leica DM 2500 M) to measure the deepest attacks and identify the types of corrosion (pitting, exfoliation, intergranular). The corrosion depth was measured on the two sides of the cut sample. Ten measurements (per side) of the depth of corrosion attack were performed when it was possible.

## 2.3 ER method

The sensors used to measure the corrosion rate are based on the principle of ER probes described elsewhere.[35] Under the action of corrosion, the metal is converted into relatively insulating corrosion products. The resistivity of the materials being a function of the temperature a differential approach is used, between a part of the probe exposed to the environment (sens) and a second part protected from corrosion but not of the temperature (ref). In the presence of uniform corrosion, the corrosion thickness can be calculated as a function of the initial resistance values and over time, as well as the initial thickness of the thin film. For localised corrosion, the results are more difficult to interpret and the ER method is only indicative of the corrosion rate.[36] The corrosion thickness calculation for homogenous corrosion is given by Equation (1), with $h$ as the initial sensor thickness; $R_{\text{ref, init}}$ as initial resistance of the reference track; $R_{\text{sens, init}}$ as initial resistance of the sensor track; $R_{\text{ref}}$ as the resistance of the reference track and $R_{\text{sens}}$ the resistance of the sensor track.

$$\Delta h = h \left( \frac{R_{\text{ref, init}}}{R_{\text{sens, init}}} - \frac{R_{\text{ref}}}{R_{\text{sens}}} \right).$$

## 2.4 Exposure conditions

### 2.4.1 Immersion conditions

Five sets of three aluminium 2024-T3 coupons, as well as three AlCu sensors, were immersed for 6 h in a 3 g·L$^{-1}$ NaOH solution at ambient temperature and pH 13. This condition was selected to ensure a complete aluminium depassivation and more uniform corrosion. The coupons were weighed before exposure and not backside taped. They were periodically withdrawn and immediately rinsed with deionized water, ethanol, dried and weighed to determine their mass loss. The eventual rebuild of the corrosion product during the weighting procedure was neglected. The coupon corrosion

## Table 2 Nominal composition of AlCu alloys in % weight

|   | Al | Cu | B | Cr | Fe | Mg | Mn | Si | Ti | Zn |
|---|----|----|---|----|----|----|----|----|----|----|
|   | 94 | 6  | 0.0002 | Max: 0.0005 | 0.0330 | 0.0011 | 0.3000 | 0.0155 | 0.0055 | Max: 0.0008 |
thickness was calculated by considering the surface exposed and the material density of 2.77 g·cm\(^{-3}\) (calculated from the material composition).

### 2.4.2 Atmospheric conditions

A set of twelve 2024-T3 coupons and five AlCu ER sensors were pre-contaminated (PCT) with 0.5 g·m\(^{-2}\) of chlorides (NaCl) and exposed to dry/wet cycles of 4 h at respectively 50\% and 90\% of relative humidity (RH). Under field conditions, the chloride deposition may range from 0.015 g·m\(^{-2}\)·year\(^{-1}\) in a rural environment to values above 550 g·m\(^{-2}\)·year\(^{-1}\) in the severe marine environment. Hence, the deposition used in this study, equivalent to 3.25 g·m\(^{-2}\)·year\(^{-1}\) should be considered as a rather mild marine condition.\(^{[47]}\) The temperature was kept constant at 35 ± 1°C in a climatic cabinet from Weiss. 90\% and 50\% RH are respectively above the deliquescence and efflorescence threshold of the NaCl of 75\% and 47\% RH, ensuring the formation of a thin and conductive electrolyte.\(^{[48-50]}\) The chlorides pre-contamination was done using a methanol-based solution and pure reagent NaCl as described elsewhere.\(^{[51]}\) During the first 8 weeks of exposure, one 2024-T3 coupon was collected weekly to perform cross-section analysis by optical microscopy. For two ER sensors, the exposure time was prolonged with second contamination of 1g · m\(^{-2}\) of chlorides following the same procedure. The metallic coupons and sensors were exposed horizontally to limit the chlorides leaching.

A Volvo standard accelerated test STD 423-0014 was used (VCT). This test is designed to assess the corrosion resistance of materials in environments where there is a significant influence of chloride ions, mainly sodium chloride from a marine source or from winter road de-icing salt. The rain solution consisted of a 1.0% ± 0.1% by mass of NaCl at pH 4.2 ± 0.1. The pH was adjusted by the addition of sulphuric acid H\(_2\)SO\(_4\) (Merck Millipore). The deposition rate was fixed at 15 mm·h\(^{-1}\), which corresponds to 120 ml·h\(^{-1}\)·80 cm\(^{-2}\). For 1-week exposure, the chloride deposition is approximately 136 g·m\(^{-2}\). The salt rain, in a 6-h period, constituted of three consecutive replicates of 15 min of spraying and 1 h 45 min at 95%–99% RH and 35°C. Consecutively to this step, humidity cycles at 50% RH/45°C and 95% RH/35°C were performed. The cycle was then repeated each week in a Control’Art cabinet. The metallic coupons and sensors were exposed at 15 ± 5° from the vertical axis.

Neutral salt spray test (NSST) was used following the ISO 9227:2017 standard. A 50 g·L\(^{-1}\) NaCl solution was used with a pH in the range of 6.5–7.2 at a continuous deposition rate of 1.5 ml·h\(^{-1}\)·80 cm\(^{-2}\). For 1-week exposure, the chloride deposition is approximately 955 g·m\(^{-2}\). The temperature was constant at 35 ± 1°C. The metallic coupons and sensors were exposed at 15 ± 5° from the vertical axis.

### 2.5 Finite elements modelling

Finite element modelling (FEM) was carried out using COMSOL Multiphysics 4.3. The studied cell consisted of a 1 × 1 × 0.125 mm aluminium piece. The thickness and width were similar to the AlCu ER sensors used. A 1-mm length was used to ensure the use of a low fine mesh and a reduced calculation time. The tetrahedral mesh was used with elements in the range of 0.0015 and 0.035 mm (extra fine). The voltage drop at the cell terminal was then extrapolated into corrosion thickness according to Equation (1). The point at the centre of the edge, where the current density was impressed, was considered for the calculations. The obtained corrosion thickness was independent of the resistivity used for the calculation.

### 3 RESULTS AND DISCUSSION

#### 3.1 Immersion conditions

The corrosion thickness with the time of 2024-T3 coupons and AlCu sensors immersed in the NaOH solution is presented in Figure 2. From the results, the corrosion thickness measured by the ER sensors on Al\(_{94}\)Cu\(_{6}\) is in good agreement with weight loss data obtained on 2024-T3 coupons. In addition, a good reproducibility was seen between the three sensors used. As further inferred from Figure 2, the corrosion rate was almost linear during the 6 h of immersion with
about 10 µm·h$^{-1}$. This behaviour can be explained by the well-known amphoteric behaviour of aluminium alloys and the dissolution of the passive film under alkali conditions.$^{[52–55]}$ The dissolution of Al and Cu are probably non-congruent (not studied in this research study). However, as copper particles represent a minor part of the total surface area, uniform corrosion is mostly observed. Consequently, under such conditions, and in agreement with the literature, a good correlation is found between the ER technique and weight loss. This could be of particular interest as alkali and/or acidic conditions are often used in the aerospace industry to remove Cu particles from materials such as 2024-T3. Hence, the kinetics of dissolution could be studied by ER sensors under such conditions.

### 3.2 Atmospheric conditions

Figure 3 shows the corrosion thickness measured by the AlCu ER sensors pre-contaminated with 0.5 g·m$^{-2}$ Cl after an 8-week exposure in a cyclic wet/dry condition. These data are compared with the mean corrosion depth of 2024-T3 coupons exposed in parallel and obtained by microscopy cross-sections. For the AlCu sensors, the corrosion increased rapidly during the first week of exposure and remained relatively high during the first 3 weeks. Thereafter, the corrosion rate strongly decreased, and the corrosion thickness reached 5.4 ± 0.3 µm after 8 weeks of exposure. Furthermore, good reproducibility has been observed between the five sensors. The small fluctuations observed on the signal corresponding to the evolution of the corrosion rate within the cyclic conditions. The ER detection threshold corresponds to 0.01 µm. The mean normalised derivative curve, corresponding to the corrosion rate, is presented in Figure 4 as a function of RH cycles. Due to signal noise, only a mean curve is presented. This curve was normalised to its maximum. The obtained results indicate that the highest corrosion rate appeared during the transition from wet to dry at about 70%–80% RH, that is, slightly above the efflorescence RH of NaCl. After 8 weeks, a mean corrosion depth of 24 ± 15 µm was obtained by cross-sections on the sensors. The corrosion mainly consists of intergranular attacks and exfoliation corrosion, as illustrated in Figure 5. The mean corrosion depth was higher than the corrosion thickness measured by the ER method, in agreement with the presence of localised corrosion. For 2024-T3 coupons, the evolution of the mean corrosion depth also reached a maximum after about 3 weeks and then remained constant for the rest of the exposure. The corrosion also consists of pitting corrosion with intergranular attacks (see Figure 5). Although the corrosion depth for Al$_{94}$Cu$_{6}$ and 2024-T3 are more or less in the same range after 8 weeks of exposure, it is obvious that the mode of failure differs for the two alloys with much more exfoliation for Al$_{94}$Cu$_{6}$. This is most likely related to the microstructure of the two alloys. Indeed, a high density of small intermetallic particles is present on the AlCu.

For two AlCu sensors, the exposure was prolonged up to about 19 weeks, as presented in Figure 6. After 10 weeks, the second contamination of 1 g·m$^{-2}$ of chloride was performed. Instantaneously, the corrosion restarts and quickly decreases with time. These results highlight the impact of punctual NaCl contaminations. A higher corrosion rate is observed after the second contamination. This behaviour might be explained by the higher active surface, as well as the increased NaCl contamination.$^{[56]}$ Under similar conditions, no insoluble aluminium chloride salts are expected to be formed, while NaAlCO$_3$(OH)$_2$ (dawsonite) could be...
expected at the cathode.\textsuperscript{[56,57]} The NaCl-induced corrosion can be explained both by the Cl adsorption on the passive film leading to local (anodic site) depassivation, as well as the Na concentration supporting the local pH increase and the cathodic depassivation. According to this, one can suppose that the decrease of the corrosion rate might be explained by the Na and Cl consumption, transport limitation and/or the corrosion product growth.

Figure 7 shows the corrosion thickness measured by AlCu ER sensors during 1 week of exposure in the cyclic corrosion test STD 423-0014. For the AlCu sensors, the corrosion measured by the ER technique remained high and reached 21.5 ± 1.0 µm after 1 week. As further inferred from Figure 7, a good reproducibility was observed for the three exposed sensors. The mean corrosion depth measured by optical microscopy on the sensor after 1 week was about 47 ± 21 µm. This corrosion mainly consisted of intergranular corrosion and exfoliation corrosion, as illustrated in Figure 8. The mode of failure is similar to the one already reported in Figure 5 for pre-contaminated sensors. The rather heterogeneous distribution of the localised corrosion contrasts with the good reproducibility of the corrosion thickness calculated by the ER technique. Similar results were obtained for the 2024-T3 coupons. The corrosion mainly consisted of intergranular corrosion, with a mean corrosion depth of 56 ± 24 µm after 1 week of exposure. With time, the mean corrosion depth tends to increase rather linearly, in agreement with the trend obtained by the sensors.

Figure 6 shows the AlCu electrical resistance (ER) corrosion thickness under cyclic wet/dry at 35°C, after an initial 0.5 g·m\(^{-2}\) pre-contamination of chlorides and the second contamination of 1 g·m\(^{-2}\) of Cl\(^-\) after 10 weeks [Color figure can be viewed at wileyonlinelibrary.com]

Mean normalised derivatives of the corrosion thicknesses with the cyclic conditions are presented in Figure 9. The maximal corrosion rate is systematically observed during the transition between wet to dry at approximately 70%–80% RH, in agreement with the previous results. This phenomenon has already been observed on steel and zinc.\textsuperscript{[35,36]} After 5 days, an increased corrosion rate seems to have also appeared during the dry to wet condition, also at 70%–80% RH. The increase in the corrosion rate with time is probably due to the increase of the active surface. Under the dry phase, the corrosion rate is low but non-null, indicating that corrosion remained active under such conditions.

Figure 7 shows the AlCu electrical resistance (ER) corrosion thickness and 2024-T3 coupons mean corrosion depth obtained by cross-sections under standard accelerated test STD 423-0014 [Color figure can be viewed at wileyonlinelibrary.com]
For the AlCu sensors, the corrosion mainly consists of intergranular corrosion and exfoliation corrosion, as illustrated in Figure 11. For one of the three sensors exposed, the battery failed after 4 days. After 1 week, 12 µm of corrosion thickness was calculated and a mean corrosion depth of about 85 ± 25 µm was obtained by cross-sections. The high deviation by cross-section analyses illustrates the heterogeneous corrosion distribution, with some localized events affecting almost the whole sensor thickness. However, the sensor tracks were not completely cut. This high standard deviation seen for the cross-sections contrasts with the good reproducibility of the sensors. On 2024-T3 coupons, after 1 week, a similar mode of corrosion and mean corrosion depth were obtained with 83 ± 28 µm. The mean corrosion depth increased rather linearly with the exposure time, in agreement with the real-time data obtained with the sensors.

For AlCu, the corresponding normalised derivatives of the corrosion thicknesses are presented in Figure 12. The corrosion rate appears relatively high during the first 3 days with a maximum after 12 h and tends to stabilise toward a constant rate during the rest of the exposure. No fluctuation in the corrosion rate with time could be observed, in agreement with the fact that this test was performed at constant temperature and RH.

In this study, under uniform corrosion at pH 13, a good correlation was obtained between the mean corrosion thickness from mass loss on 2024-T3 coupons and AlCu ER sensors. In the case of chlorides containing accelerated tests, the corrosion was not uniform on both AlCu sensors and 2024-T3 coupons. Hence, the ER sensor thickness calculated did not correspond to the mean corrosion depth obtained by cross-sections. However, a rather similar mode of failure (e.g., intergranular corrosion) and mean corrosion depth were obtained between the two materials, with mainly intergranular corrosion with some extent of pitting or/exfoliation corrosion in agreement with the literature.[58,59] The reproducibility of the ER corrosion thickness obtained with the sensor was, in all cases, very good in contrast with the large deviation of the mean corrosion depth. This result suggests that ER sensors probably more levelled the effect of localised corrosion through a large surface evaluation (130 mm²) compared with cross-sections. To assess this hypothesis,
finite element modelling of ideal localised corrosion events was realised. Two cylindrical and spherical model pits were considered, as presented in Figure 13. Although pitting corrosion is not the main mode of failure, in this case, it was selected due to its simplicity for calculations. The model pits were considered as empty in agreement with the high resistivity of aluminium corrosion products\cite{60,61} compared with that of aluminium. The corrosion thickness obtained with the ER method as a function of the pit size and density is presented in Figure 13. In this simplistic model, the width and density of pits were limited to avoid any merging. The obtained results show that the higher the pit size and density, the higher the ER corrosion thickness is measured. In addition, a strong influence of the geometry can be observed with a 3–5 factor in terms of corrosion thickness obtained with an identical pit width. This behaviour can be explained by the complex distribution of the electrical current in the remaining metal between the pits. As an example, the measured corrosion thickness of 5.4 µm in the PCT test with a mean corrosion depth of 24 µm, would correspond to a density of independent pits of about 300 mm$^{-2}$ by considering the cylindrical geometry. For the semispherical geometry, a higher density is found with a necessary merging of pits. Phenomenologically, these high densities of pits agree with the observations of the complex mode of corrosion (intergranular/pitting and exfoliation corrosion) on the AlCu sensors. For the VCT and NSST, the obtained corrosion thickness of 21.5 and 13.0 µm, respectively, confirm the presence of deeper and larger localised corrosion events observed by cross-sections. Despite its simplicity, this model gives orders of magnitude of theoretical influence of the density, geometry and size of model pits on the ER corrosion thickness. It also indicates a measured ER corrosion of about 10–20 µm which corresponds to potential severe damage on such 125-µm-thick sensor.

The corrosion rate obtained from the derivative of the measured ER thickness appears interesting to obtain real-time trend of the material–environment interaction.

![Cross-section micrographs after 1-week exposure in neutral salt spray test (left) AlCu electrical resistance sensor and (right) 2024-T3 coupons](Color figure can be viewed at wileyonlinelibrary.com)

![Finite element modelling of the electrical resistance (ER) corrosion thickness obtained as a function of the pit size (width and/or depth) and geometry. Width and depth from 10 to 120 µm by step of 10 µm](Color figure can be viewed at wileyonlinelibrary.com)
Such information is crucial for the development of representative accelerated corrosion tests for light alloys, as well as for a better understanding of the kinetics of corrosion mechanisms.

The chloride-contaminated conditions and corrosion data after 1-week exposure are summarised in Table 3. The corrosion thickness of AlCu sensors and the respective mean corrosion rate are presented in Figure 14. For NSST, the weekly chloride deposition is much higher than for the VCT and PCT tests with respectively 955, 136, and 0.5 g·m$^{-2}$.

The obtained results in PCT show that the corrosion decreased with time after the chloride contamination. With this low chloride contamination, the continuous RH cycling under constant temperature is not aggressive enough to ensure corrosion. As soon as new chloride contamination occurs, the corrosion strongly increased. For the NSST, high continuous chloride contamination was applied. The corrosion rate was much higher but also tends to decrease with time. The cross-section analysis indicates that under such conditions, the corrosion tends to progress in depth. For VCT, the combination of high chloride content and wet/dry cycles seems to ensure a rather constant corrosion rate and a more uniform distribution of the corrosion.

The highest ER corrosion thickness did not correspond to the deepest corrosion depth by cross-section, in agreement with the FEM model. This behaviour might be explained by a lower density of deeper pits in NSST in contrast to VCT.

During the 6-h dry phase of the VCT test, the RH was below the efflorescence threshold of the NaCl of 75% RH. However, the corrosion rate remained non-null. This phenomenon is particularly interesting as it would be extremely difficult to be observed with the existing methods compatible with aggressive conditions and industrial materials, such as LPR and EIS. It might be explained by the formation of soluble aluminium-chloride salts or compounds with lower deliquescence level.

| Test | Cl deposition (1 week) (g·m$^{-2}$) | RH/T                  | AlCu ER (1 week) (μm) | AlCu cross-section (1 week) (μm) | 2024-T3 (1 week) (μm) |
|------|----------------------------------|-----------------------|-----------------------|---------------------------------|-----------------------|
| PCT  | 0.5                              | 50%/90%, 4 h, 35°C    | 2.8 ± 0.2             | ND                              | 20 ± 6                |
| VCT  | 136                              | 50%/95%, 6 h, 45/35°C, 6 h | 21.5 ± 1.0           | 47 ± 21                         | 40 ± 24               |
| NSST | 955                              | 100%, 35°C            | 13.0 ± 0.6            | 85 ± 25                         | 83 ± 28               |

Abbreviations: ER, electrical resistance; NSST, neutral salt spray test; PCT, pre-contamination test; RH, relative humidity; VCT, Volvo standard accelerated corrosion test.

CONCLUSIONS

In this study, the use of the ER sensors to monitor the corrosion of aluminium-copper alloys has been assessed. The obtained results showed:

- Good reproducibility was obtained with the ER sensors under all the tested conditions.
- In agreement with the occurrence of localised corrosion, the corrosion thickness obtained with the ER sensors did not correspond to the mean localised corrosion depth obtained by cross-sections. This behaviour could be tentatively explained by the distribution and size of the pits.
- The proposed method allows obtaining real-time corrosion and corrosion rate data interesting for the understanding of the corrosion mechanisms and the development of accelerated tests. Higher corrosion rates were observed when the RH reached 70%–80% during the wet/dry cycles. The chloride concentration and contamination frequency strongly affect the kinetics of corrosion.

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CONFLICT OF INTERESTS
The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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