APPLICATION OF EDDY CURRENTS TO THE ESTIMATION OF CORROSION-FATIGUE DAMAGE

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## 1. INTRODUCTION

For a lot of mechanical steel components during service, corrosion-fatigue [1] is a very interesting and dangerous damage situation consisting in the combination of fatigue loading and chemical aggression due to environment. In particular, the effects of corrosion on fatigue properties are characterized by the formation of a wide-spread distribution of surface flaws ([2], [3]), whose nucleation is favored by the pits due to the aggressive environment and whose dimension increases with the number of cycles. These small cracks are then able to cross the micro-structural barriers ([1], [4]) with ease and at a much faster growth rate than in air.
In the railway industry (the application field considered in the present research), corrosion-fatigue is a normal situation since the ferrous materials, adopted for relevant components like axles and wheels, often work in humid environment and in presence of acids. Figure 1a shows, as an example, the condition of some axles retired after a 30 years service on freight trains.

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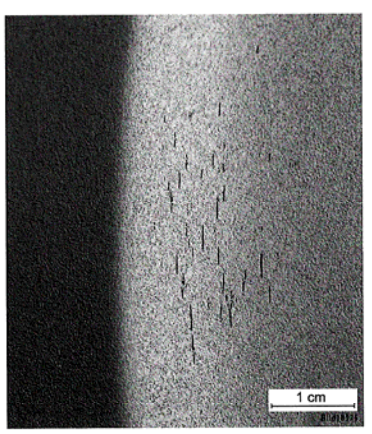


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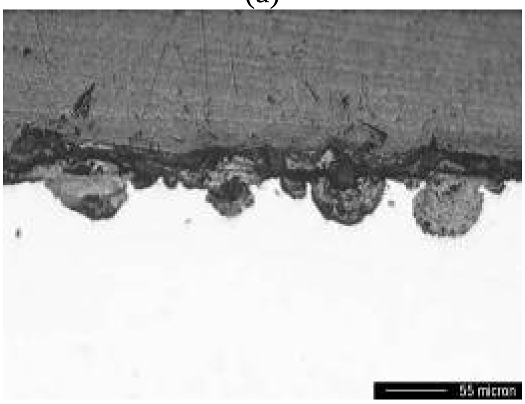


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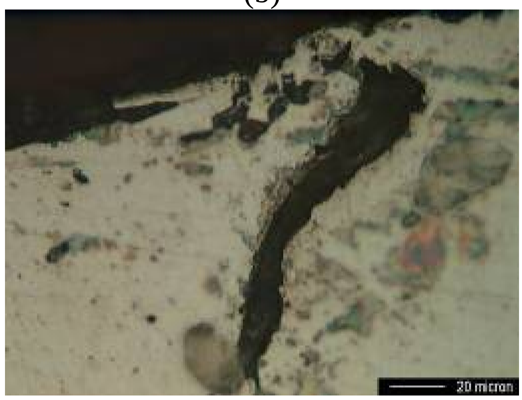


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Figure 1 – Typical corrosion-fatigue damage pattern on railway axles: a) axles retired after a 30 years service on freight trains; b) surface damage pattern [2]; c) and d) corrosion pits found on retired freight axles.

The typical damage pattern of corrosion-fatigue, acting on railway axles, presents its own features, based on the already cited wide-spread distribution of surface flaws (Fig. 1b), very different from other fatigue effects. Figures 1c and d show some corrosion pits observed from lapped sections derived from the retired freight axles [3]. As it can be seen, together with typical semi-circular pits, very sharp and deep defects can be found. Such defects can be suitable starters for cracks propagating during service.

Concerning in-service Non-Destructive Testing (NDT) of (possibly) corroded axles, the low penetration and the generally closed condition of such defects [3] make extremely difficult their detection and monitoring by means of traditional surface NDT methodologies. Moreover, corrosion modifies surfaces and adds rust, so making difficult the applications of usual detectors without a proper surface preparation.

Between the NDT methodologies proposed to inspect this kind of damage pattern, eddy currents (ET) is continuously improving its abilities due to the combination of an intrinsic high sensibility in detecting surface defects and the possibility to analytically and numerically reconstruct expected signals coming from proper sample blocks characterised by known artificial defects. This makes ET an effective tool for the quantitative determination of surface or sub-surface damages.

From this point of view, different researchers have published papers where effective quantitative correlations between experimental signals coming from artificial defects and their reconstruction is presented. Generally, two main approaches are adopted:

- the analytical one ([5]-[6]), where, even if adopting strict operative hypotheses, good results could be obtained choosing proper operative parameters;
- the numerical one ([7]-[8]), where some simplifying hypotheses can be assumed, but loosing the possibility to reach a synthetic understanding of the whole phenomenon.

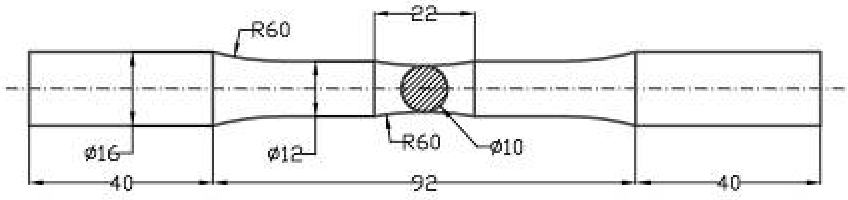
One of the main difficulties in the application of ET is to build proper sample blocks representative of the studied phenomenon. Generally [9], the best results in the correlation between experimental and reconstructed signals are obtained considering reference defects realised by traditional machining or EDM. Although such artificial defects are characterised by thin widths, they cannot suitably represent the complex local features of corrosion-fatigue damage which may present very irregular surfaces, partial contacts or gaps between faces and presence of corrosion products with different electro-magnetic properties.

The present research is devoted to the possibility to apply ET to the inspection of fatigue-corroded axles made in the A1N steel grade [10]. The first step is based onto the development of a methodology to obtain sample blocks, representative of corroded axles, by means of standard specimens subjected to known load conditions and controlled corrosive environment. Eventually, the obtained samples were used for a preliminary experimental ET inspection campaign by means of absolute and differential probes and a dedicated equipment expressly developed in order to give the best repeatability and the possibility to separate the signal due to corrosion-fatigue defects from the typical set-up noise of the methodology.

## 2. CORROSION-FATIGUE BEHAVIOUR OF A1N AXLE STEEL

A1N is a normalized 0.35% carbon steel, widely used in the manufacture of railway axles [10]: the matrix consists of a ferritic-pearlitic microstructure with a 20-40 μm ferrite grain size. Its basic mechanical properties are [11]: ultimate tensile strength UTS=597 MPa and monotonic yield strength $\sigma_{y,monotonic}$=395 MPa. Cyclic properties are as follows: 0.2% cyclic proof stress $\sigma_{y,cyc0.2}$=357 MPa, 0.05% cyclic proof stress $\sigma_{y,cyc0.05}$=289 MPa. The parameters of the cyclic Ramberg-Osgood relationship are equal to $E_{cyc}$=209303 MPa, n=0.150395 and H=907.34 MPa.

In order to investigate the fatigue properties of A1N steel in a corrosive environment at R=-1 (i.e. the characteristic stress ratio of railway axles during service), a series of tests were carried out [3] under rotating bending using hourglass shaped specimens with a minimum diameter of 10 mm (Figure 2a). Following machining, the specimens were hand polished up to #1000 grit emery paper and then electro-polished (94% acetic and 6% perchloric acid solution) in order to remove a 30 μm layer.

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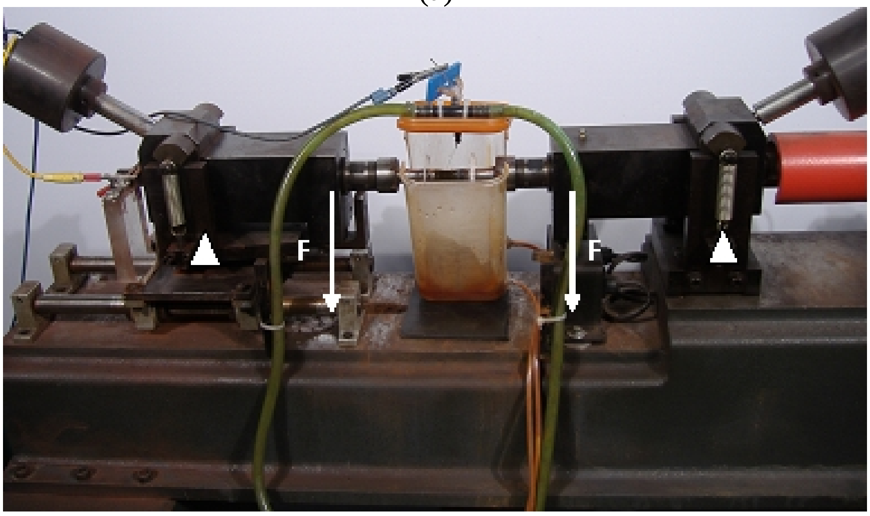


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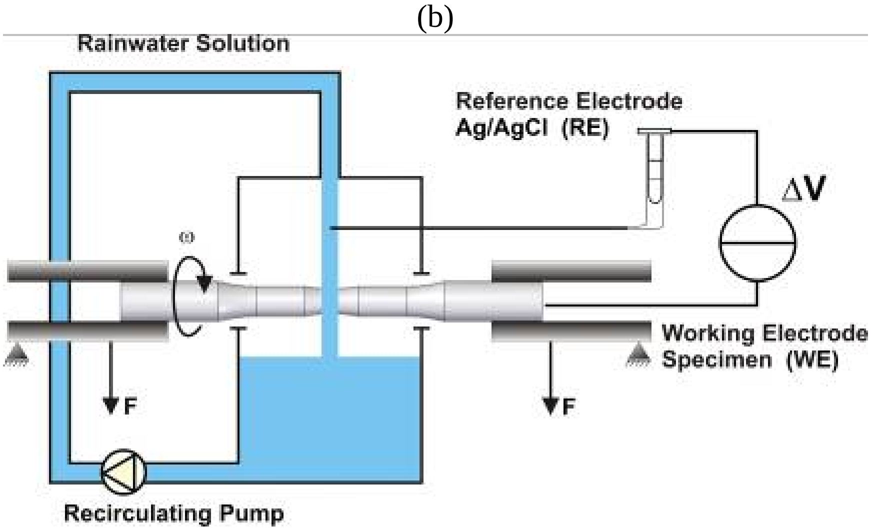


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Figure 2 – Experimental set-up for tests in corrosive environment: a) fatigue specimen; b) picture of a test; c) schematic drawing for corrosion potential measurements.

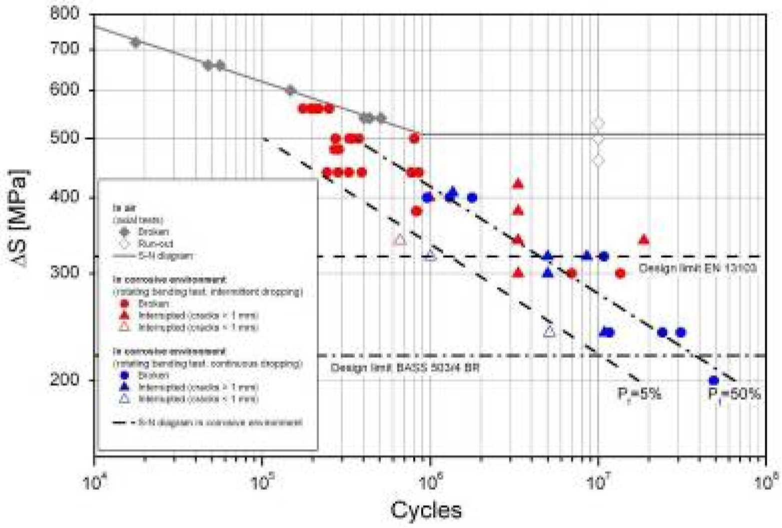
Fatigue tests were carried out by a four point rotating bending machine (capacity of 35 Nm) working at a frequency of 6-8 Hz (Figure 2b). This frequency value is representative of axles during a service speed equal to 60-80 Km/h.

Corrosion was applied to specimens by means of a dedicated dropping system (Figure 2c). The artificial rainwater solution [12], characterized by pH=6, was formulated as follows: ammonium sulphate 46.2 mg/dm$^3$, sodium sulphate 31.95 mg/dm$^3$, sodium nitrate 21.25 mg/dm$^3$ and sodium chloride 84.85 mg/dm$^3$.

Tests were carried out at stress levels below the fatigue limit in air (equal to 550 MPa for the considered steel grade): in particular $\Delta S$ was in the range of 200-400 MPa. The corrosion-fatigue behavior of the A1N steel was also characterized by corrosion potential measurements [13] according to the diagram shown in Figure 2c. It is worth noting that such corrosion potential resulted to be equivalent to the "free corrosion" of the material.

A summary of the experimental results, in terms of S-N diagram, is shown in Figure 3a. Details are reported in [14], while here the following interesting conclusions are recalled: i) for stress levels higher than the air fatigue limit, the curves in air and in the corrosive environment are very similar; ii) data clearly show that, at stress levels where cracks would not be able to nucleate and propagate in the air, the presence of a corrosive environment allows crack nucleation from corrosion pits and environmental assisted crack growth; iii) SEM observations always revealed the presence (Fig. 3b) of clusters of small cracks very similar to those found by Hoddinot on axles (Fig.1b). It is worth noting that, in order to enhance the identification of surface cracks, prior to SEM observation, the specimens (placed under a tensile testing machine) were slightly pulled to a load close to the yield load.

Due the just-described detrimental effects of corrosion-fatigue on A1N railway axles and the need to detect such damage pattern during maintenance inspections, the last conclusion suggested to use the same experimental equipment to realize effective sample blocks for the calibration of NDT equipments.

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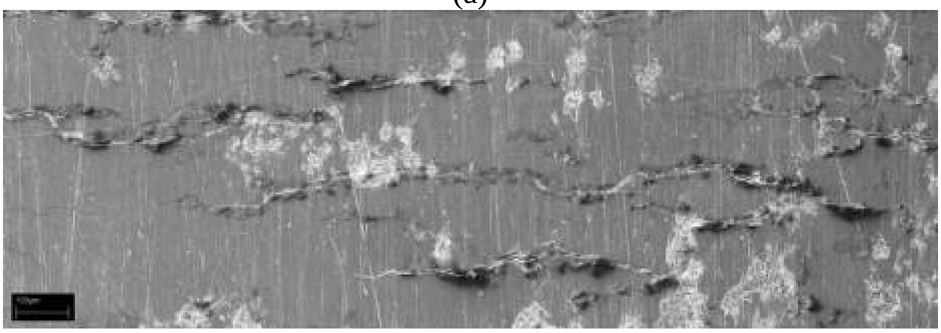


(b)

Figure 3 – Results of the experimental campaign carried out to determine the effects of corrosion-fatigue on A1N steel: a) S-N diagram in corrosive environment; b) specimen surface observed under SEM after 5 MLN cycles at ΔS=320 MPa.

## 3. EXPERIMENTAL REALIZATION OF EFFECTIVE SAMPLE BLOCKS

Tests for realizing sample blocks were carried out at a stress level equal to ΔS=400 MPa. Six specimens (Fig. 2a) were tested and interrupted at different number of cycles in order to develop different surface damage patterns due to corrosion-fatigue and to be representative of the evolution of such pattern during life. In particular, two specimens were interrupted after $3x10^5$ cycles, two after $6x10^5$ cycles and two after $9x10^5$ cycles (typical failure at the considered stress level was observed around $1x10^6$ cycles). This approach is supported by the previous statistical analysis of the length of surface cracks derived from tests interrupted at different portions of corrosion-fatigue life

[14]. Figure 4 shows, as an example, the Weibull probability chart of specimens subjected to ΔS =320 MPa and interrupted at different number of cycles. It can be noted that the data of all the sets are almost linear, thus confirming the validity of the Weibull distribution. Moreover, the increase in length is accompanied by a marked reduction of crack density: this fact clearly shows that crack coalescence is a key mechanism of crack advance. This statistical analysis could not be carried out on the NDT sample blocks because it is very difficult to observe, even at the SEM, the cluster of cracks without pulling them up to the yield stress (so ruining them). Figure 5 shows the development of oxides (rust) during a test. At the chosen number of cycles, oxides were removed using emery papers so to prepare the sample blocks for ET inspection.

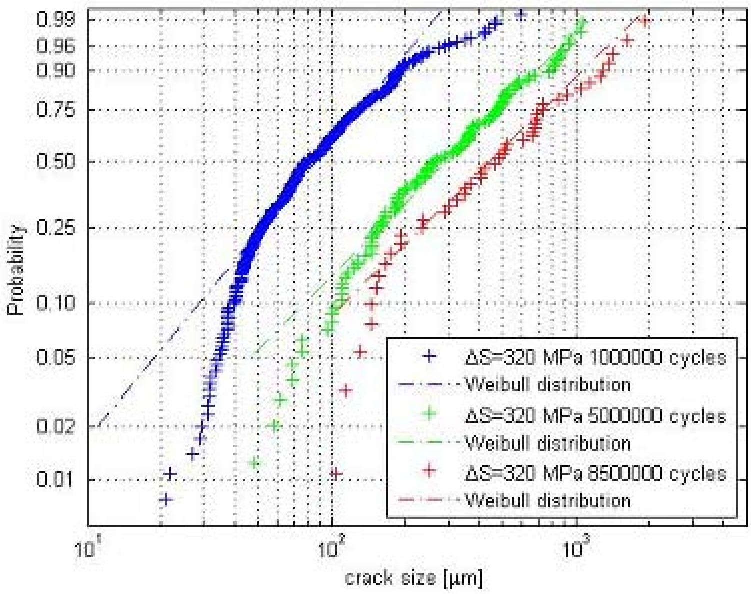
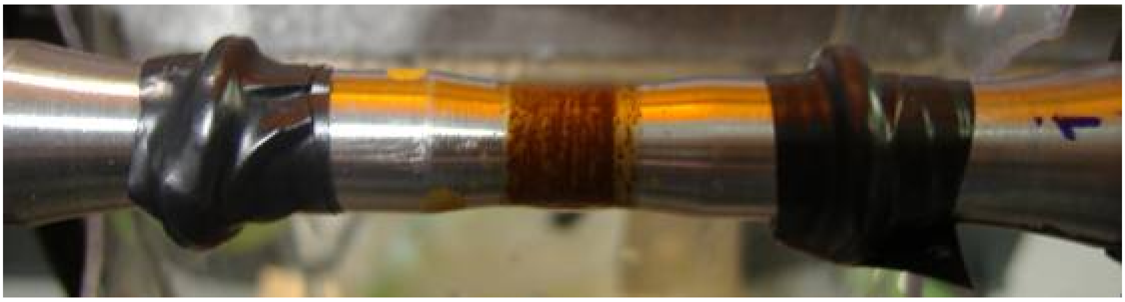



Figure 4 – Evolution of the population of surface cracks during fatigue life at stress level with ΔS=320 MPa.



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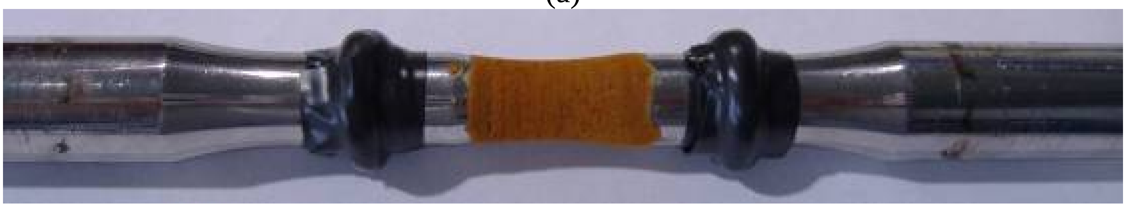

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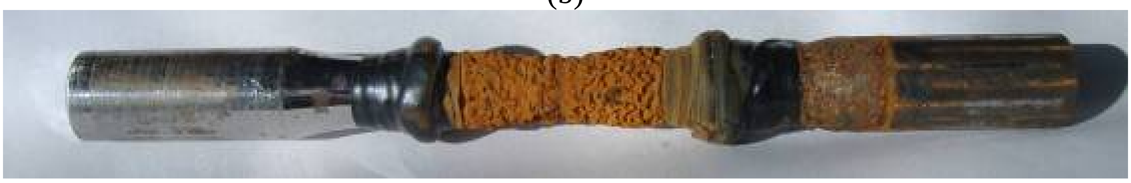

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Figure 5 – Development of oxides (rust) during a corrosion-fatigue test.

4. EXPERIMENTAL SET-UP FOR ET INSPECTION OF SAMPLE BLOCKS

ET inspections were carried out on sample blocks by means of a dedicated apparatus (Fig. 6a) expressly designed to control all the relevant parameters of ET inspections and to make repeatable measurements. In particular, a Nortec 1000S+ detector was adopted together with a differential probe able to work in the frequency range going from 500 kHz to 2 MHz. The frame of the equipment (Fig. 6b) is composed by a column and special V-wedges in order to guarantee the perpendicularity between the probe and the specimens, while a micrometric tablet is used to center the specimen below the probe (Fig. 6c). A centesimal comparator and a lever are used to exactly set the vertical position of the probe.

A special plastic wedge (Fig. 6d and 7) is applied to the probe. The need of such a wedge is due to the fact that the absolute position of the probe cannot be fixed during inspections since the profile of specimens changes with the developing corrosion-fatigue damage, while the chosen lift-off must remain the same. From this point of view, fixing the distance d (Fig. 7) by a screw, a fixed lift-off is guaranteed if the wedge itself is kept in contact with the specimen during the inspection. This condition was here satisfied adopting the weight of the probe as contact force. It can be added that the round section of the wedge realises also a better coupling with the hourglass shape of the specimen.

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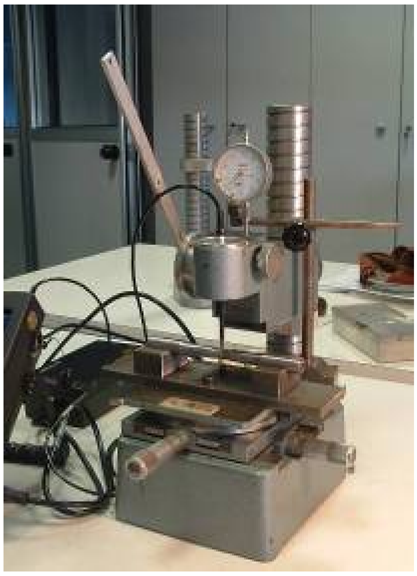

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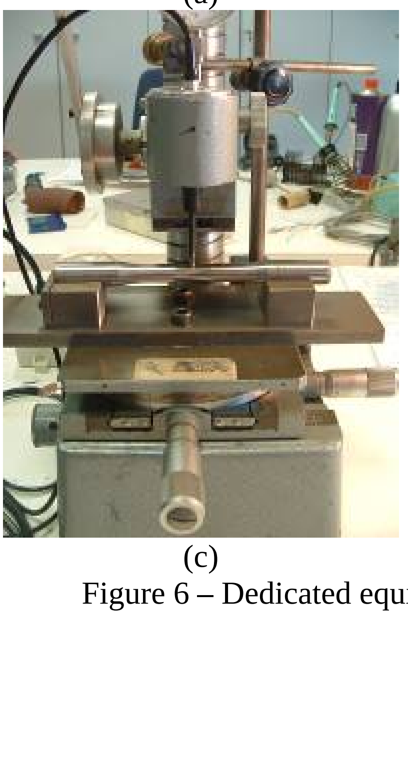

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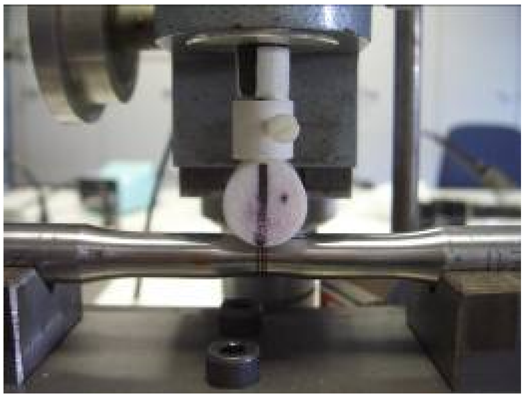


(d)

Figure 6 – Dedicated equipment for ET inspections of sample blocks.

The differential probe was positioned to have the most sensible configuration of coils parallel to the prospective cracks direction (i.e. transverse to specimen axis). The lift-off realised by the wedge was always set to 300 μm and the phase angle was set so to give the possible lift-off influence perpendicular to the expected signal response of defects (as suggested in [15]). In particular, the phase angle was always set to give lift-off influence along the horizontal direction on the screen, so expecting defect responses to be along the vertical direction. For the same reason, gain values were set to be higher for the vertical component of the signal (85 dB) in respect to the horizontal one (75 dB). Inspection were carried out considering a complete revolution (360°) of the specimen below the probe and acquiring the polar response.

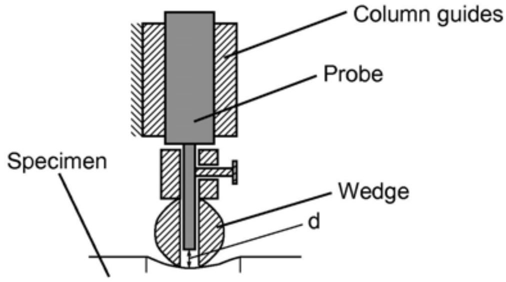
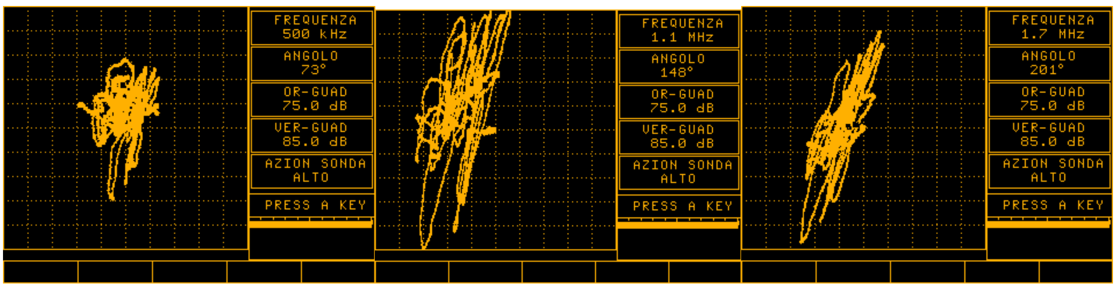



Figure 7 – Schematic of the plastic wedge adopted to maintain lift-off.

The frequency for the inspection was chosen by means of a sensibility check carried out on one of the corroded specimens interrupted at $6x10^5$ cycles. In particular, this specimen was inspected using the frequency values 500, 700, 900, 1100, 1300, 1500 and 1700 kHz (Fig. 8a shows the example of polar responses for 500, 1100 and 1700 kHz). It is interesting to note that the geometrical features of the polar response are maintained at different frequencies. The trend of the sensibility is reported in Figure 8b as a function of the adopted frequency. The higher sensitivity was observed in the range 900-1300 kHz, so all the inspections on corroded specimens were carried out at 900 kHz.

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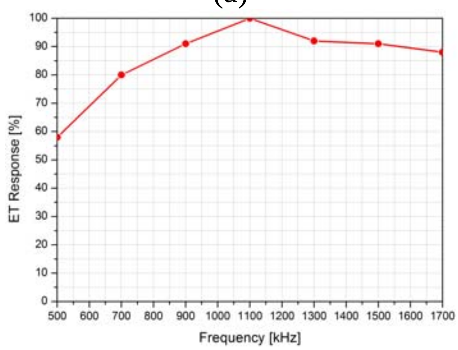
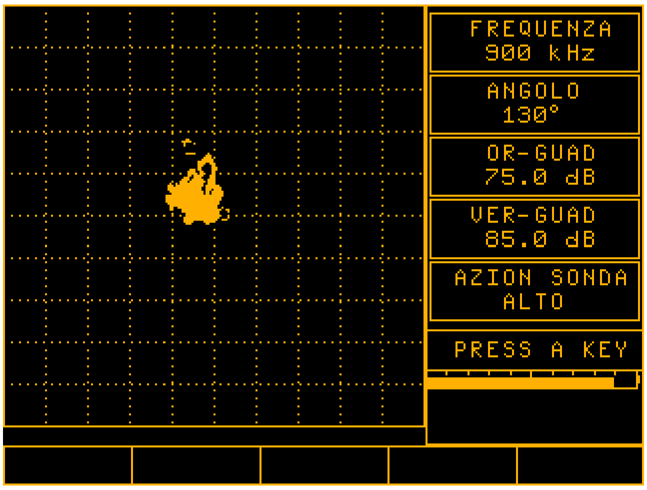



(b)

Figure 8 – Relationship between applied frequency and sensibility of the inspection: a) example polar responses for 500, 1100 and 1700 kHz; b) experimental trend.

## 5. ET INSPECTION OF SAMPLE BLOCKS

All the corroded specimens were inspected together with a not-tested one in order to derive a relationship between the amount of damage due to corrosion-fatigue and the response of ET inspections. Figure 9 shows, as an example, the ET response of the not-tested specimen together with one of the interrupted ones for each considered number of cycles. The responses, in general, showed movements of the polar diagram (always starting from the center of the screen) both in the horizontal direction (parallel to the lift-off effect) and the vertical direction.

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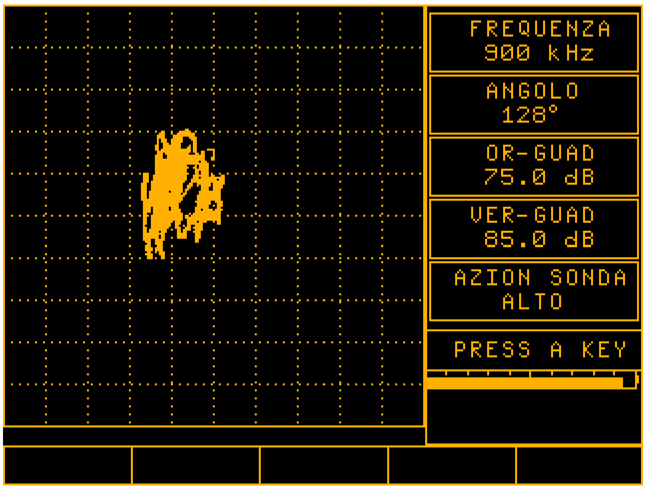


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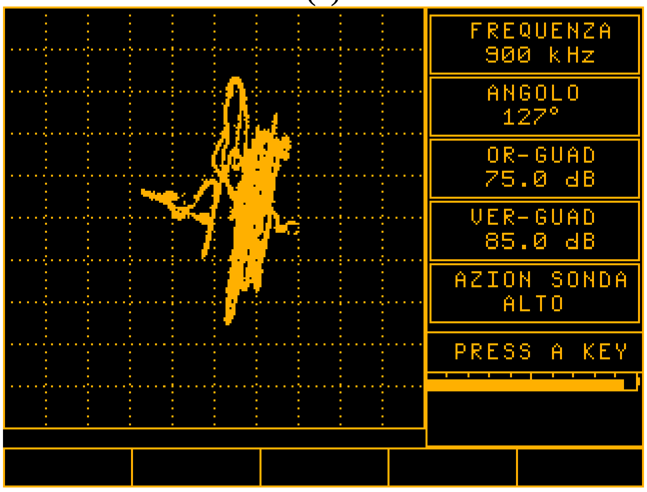


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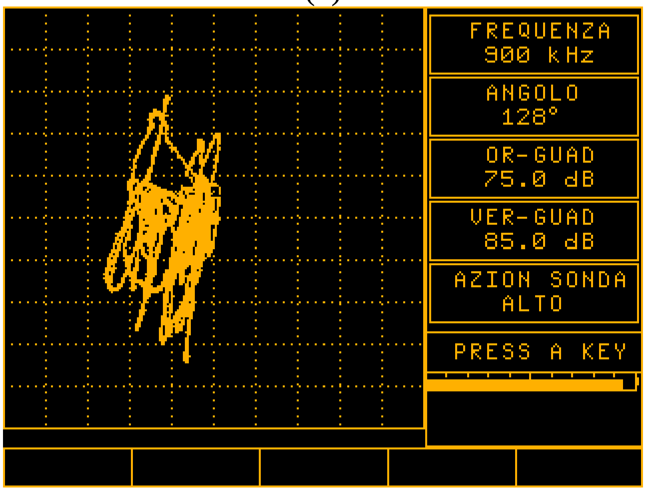


(d)

Figure 9 – ET inspection of fatigue-corroded specimens: a) not-tested; b) $3x10^5$ cycles; c) $6x10^5$ cycles; d) $9x10^5$ cycles.

Figure 10 shows the observed trend of responses. First of all, the ET response of the non-tested specimen is low, but not zero: this means that the initial surface condition presents at least some irregularities that can be appreciated by ET. In the first $3x10^5$ cycles, ET response is slightly higher than the one observed from the non-tested specimen so suggesting that the corrosion-fatigue damage (in terms of cracks) is slightly developed for a life corresponding to about one third of the expected total life. This observation is also supported by the very low scatter in ET responses at this number of cycles.

A different behaviour can be observed for inspections at $6x10^5$ and $9x10^5$ cycles. Here the differences in ET response at the same number of cycles are significant, so suggesting complex statistical crack patterns on specimens surface. It is also worth noting that the response at $9x10^5$ cycles seems to be a bit lower than the one at $6x10^5$ cycles. This fact can be ascribed to: i) the coalescence phenomenon of corrosion cracks with number of cycles: a lower number of bigger cracks, characterised by a possible variation of magnetic permeability and conductibility, could have yielded a slightly lower ET response; ii) ET response can be non proportional increasing with crack depth. In order to generalise this result, a higher number of specimens for each life portion should be prepared and inspected.

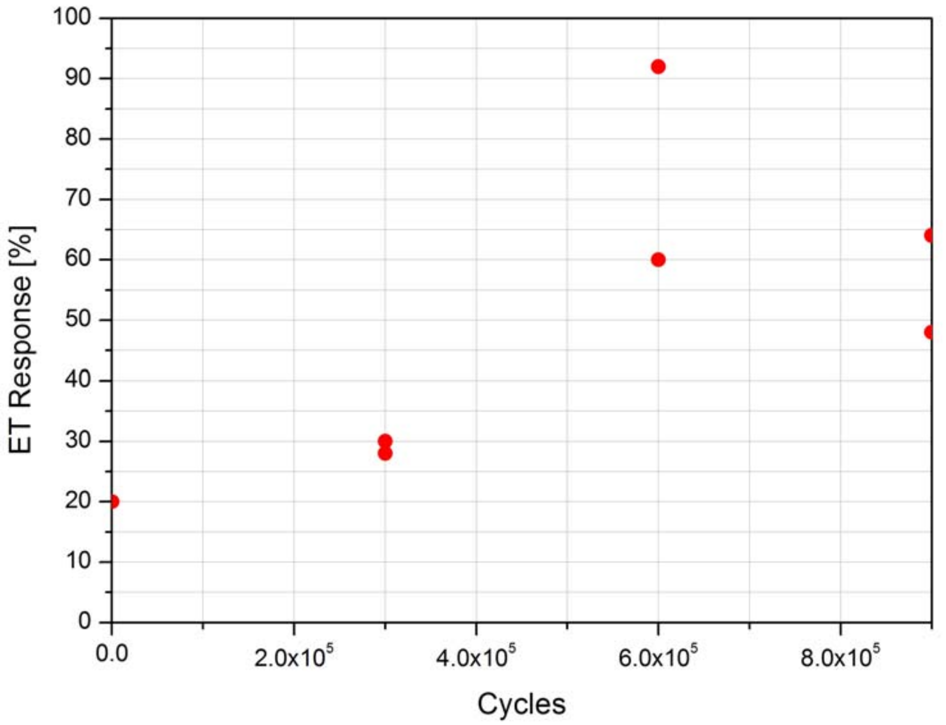

Figure 10 – Relationship between corrosion-fatigue damage evolution and ET response.

## 6. CONCLUDING REMARKS

The possibility to monitor the development of corrosion-fatigue damage pattern of railway axles made in A1N steel was here preliminarily explored. The relevant conclusions can be so summarised:

- an experimental methodology for reproducing the natural corrosion-fatigue damage pattern of axles on small-scale specimens was previously designed by the authors and here adopted to realise effective sample blocks to be used to calibrate ET inspections;
- a dedicated equipment was designed to make repeatable measurements and to have the possibility to control all the relevant parameters of ET inspections;
- a clear correlation between the corrosion-fatigue damage pattern and ET responses seems to be present;
- it is necessary to extend the number of inspected sample blocks in order to statistically generalised the obtained results.

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