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RAAI Project: Life-prediction and prognostics for railway axles under corrosion-fatigue damage

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Abstract

Corrosion damage induced by atmospheric agents has been shown to be able to trigger fatigue failures of railway axles. In this paper we firstly discuss consolidated results in modelling the growth of damage under corrosion-fatigue and its detection.

This is the background for describing the development of a new prognostic tool within the RAAI EU-funded project. In details, the new tool relies on a new automated scanner able to efficiently analyse optical measurements of the corroded axle surface and a crack growth simulation tool tuned through full-scale measurements of axle corrosion-fatigue damage.

Keywords: railway axles; corrosion-fatigue ; detection; prognostics

1. Introduction

Localised corrosive attack due to the electrochemical action of atmospheric agents, onto the surface of uncoated axles or corresponding to damaged zones of the coating for coated axles, are often found at the maintenance inspections. Moreover, it has been reported that fatigue cracks initiated at corrosion pits, have been the cause of recent railway axle failures both as reported by Hoddinott (2004); Transportation Safety Board of Canada (2001). The degradation due to corrosion shown by railway axles has increasingly become an area of concern. However, in spite of the many recent research activities on experiments (small-scale and full-scale tests) and degradation models, the problem that remains still open is the unavailability of a tool for quickly assessing the remaining service life of a corroded axle.

This is one of the aims of the RAAI (2015) EU-funded Project, whose concept for a new NDT method for measuring and assessing the corrosion-fatigue damage of an axle is here discussed after a brief overview of the previous results by the authors in this area.

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Nomenclature

d_{p-t-c}	- dimension of pit at the pit-to-crack transition
$\mathcal{B}$, β, n	- parameters of the crack growth model for corrosion fatigue
l	- crack length
l_t	- transition crack length for prevailing coalescence under corrosion-fatigue
l_f	- final crack length at failure
ΔK	- stress intensity factor range
ΔK_{th}	- threshold stress intensity factor range for fatigue crack propagation

2. Background: previous activities

2.1. Development of corrosion-fatigue damage under artificial rainwater

The development of corrosion-fatigue damage for EA1N (a normalized 0.45 % carbon steel with UTS=600 MPa) and EA4T (a Q & T low alloy steel with UTS =700 MPa) exposed to artificial rainwater has been investigated by a series of recent papers by Beretta et al. (2008, 2010); Moretti et al. (2014).

The behaviour of both steels was investigated by small scale specimens subjected to rotating bending under a continuous flow of artificial rainwater. In both the steels the initial phase of the corrosion-fatigue damage is constituted by the formation of pits with tiny secondary pits at the bottom and then the subsequent nucleation of cracks due to the high stress concentration (see Fig. 1).

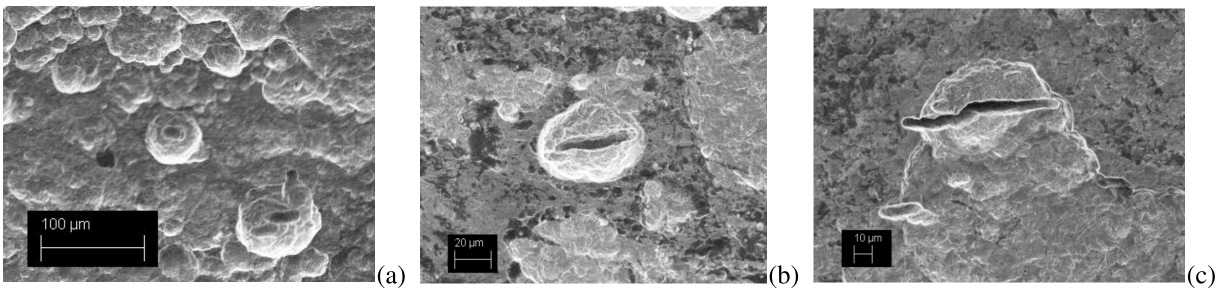


Fig. 1. Three phases of the pit-to-crack transition: a) a secondary pit at the bottom of the primary one; b) the formation of a microcrack; c) the micro-crack grows out of the primary pit (Moretti et al. (2014)).

2.2. Propagation of small cracks

The crack growth rate was obtained from measurements of crack length on the plastic replicas (Fig. 2.a) by the *secant method*. The data showed, at the different stress levels, a significant flattening of the growth curve from a length l_t due to crack coalescence. To describe this peculiar behaviour, we have adopted a crack growth model (an adaptation of the model by Murtaza and Akid (2000)) of the type:

$$\frac{dl}{dN} = \mathcal{B} \cdot \Delta\sigma^{\beta} \cdot l^{n} \quad \text{for} \quad l \leq l_t$$
$$\frac{dl}{dN} = \mathcal{B} \cdot \Delta\sigma^{\beta} \cdot l_t^{\,n} \quad \text{for} \quad l > l_t \tag{1}$$

where l_t is a characteristic length after which there is a prevailing crack coalescence with almost a constant growth rate in small scale specimens, $\mathcal{B}$ - β - n are material parameters obtained by fitting small crack growth data obtained on small scale specimens. This equation is only able to describe the crack growth sustained by the environmental effect. After the crack length has reached a significant size so that $\Delta K > \Delta K_{th}$, the crack then propagates according to the growth rate determined by usual propagation tests in air, as discussed by Moretti et al. (2014).

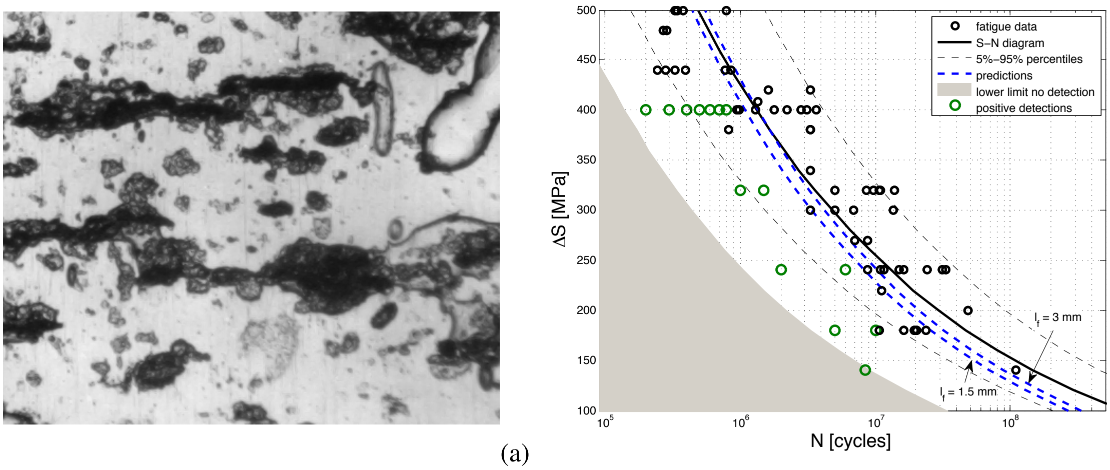


Fig. 2. Measurement of progressive damage:(a) observation of cracks propagating from pits with plastic replicas; (b) prediction of the S-N diagram from EA1N steel together with the region where the portable microscope could not detect cracks.

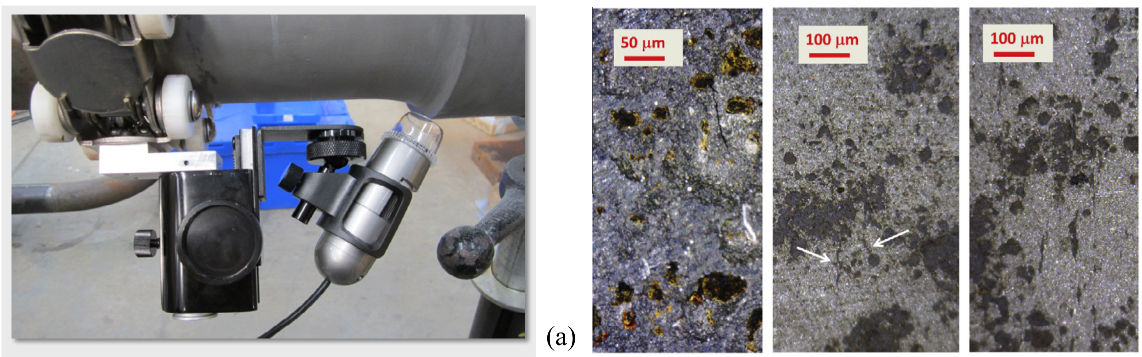


Fig. 3. Device for axle observation set-up in the WOLAXIM project:(a) holder and digital microscope; (b) detail of the surface observation on corroded axles (see Rudlin et al. (2012); Beretta et al. (2015)).

2.3. Damage detection

The measurements of growth rate and corrosion-fatigue dame led, during the WOLAXIM project, to the idea that optical observations of the surface of corroded axles could give informations about the progressive damage and the axle. In detail, the TWI team developed a special holder for a portable microscope to enable controlled movement of the microscope in both vertical and angular direction (see Rudlin et al. (2012)). The activity was also devoted to establishing an optimum mechanical and chemical procedure for rust removal before microscope observations. The microscope with holder was tested onto full-scale axles subjected to corrosion-fatigue: the conclusion was that the de-oxidizing procedure and the on-site observations allow the user to accurately detect and measure cracks with a length of the order of 200 μm.

The adoption of the cracks growth model of Eq. (1), developed on measurements from small scale specimens, allowed to estimate that detection of cracks with $l = 200\,\mu m$ could correspond to 5% of fatigue life spent, while life of specimens exposed to corrosion-fatigue could correspond to a final crack length $l_f = 1 - 3\,[mm]$. The optical device was applied to field measurements carried out within the WOLAXIM project. Beretta et al. (2015) also reported that a number of axles withdrawn from service at three different sites in the UK were examined using the device: the observations confirmed the sequence of phenomena evidenced by laboratory specimens.

3. Developments within the RAAI project

Even if the detection method setup in WOLAXIM represented a customized detection for those surface cracks that were impossible to detect with traditional NDT, some further improvements were needed.

In details, the idea for the RAAI project has been to develop a series of tools for arriving for a quick assessment about the remaining service life of a corroded axle with the 3 phases depicted in Fig. 4. In particular the decision to be supported by the new method is whether the axle is suitable for service after minor maintenance operations (such as repainting) or its remaining life is much shorter than the overhaul interval. In the latter option, a reliable life estimation is vital for safely managing the residual service of the axle before its replacement.

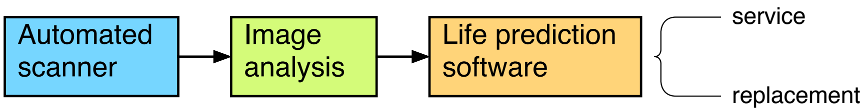


Fig. 4. Scheme of the corrosion-fatigue damage detection method developed within the RAAI project.

3.1. New automated scanner

The problems with the manual device were: i) the manual data collection of single shots with an inefficient scanning of large areas; b) the absence of axial movements. To overcome these limitations, the new scanner is designed to be mounted on axle from below, and is thin enough to work between wheel or other seats. The microscope can be adjusted to focus on the wheel seat area if needed. The microscope holder can rotate around the axle by means of a geared stepper motor, and can increment in the axial direction using a pneumatic movement, which alternately grips and closes a two part assembly while scanning the microscope records in video mode. The resulting images can be stitched to get a complete picture of the area.

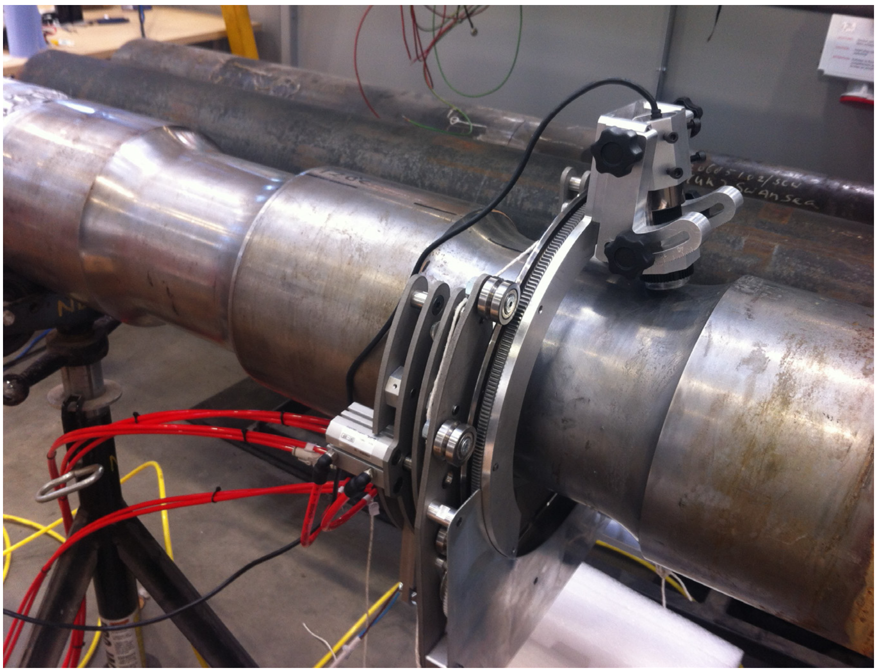


Fig. 5. Prototype of the newly developed automated scanner.

3.2. Automated image analysis

For structural health monitoring, a need has been felt for systems to become automated, Choudhary and Dey (2012). By developing an effective system to assist in structural reliability assessment, it is potentially possible to reduce the maintenance costs and still extend the useful life of a structure. Moreover, we can judge the condition of the structure health in a more objective way by acquiring and processing relevant data. This will be achieved by developing image-processing tools to better enable the visual corrosion assessment. The main scope is to develop a system that can collect and analyse the distribution surface flaws like pits and cracks efficiently. One of the challenges is the image acquisition to get clear images as it is difficult because of factors such as lighting, glare, brightness, blurring, surface material, surface roughness, scratches and grinding marks. The system requires a laptop, a microscope (shown in Fig. 3) and the automated scanner.

Image processing is a vast field dealing with manipulation and interpretation of the contents of digital images, and involves varied algorithms for many different purposes. Restoring the effects of corruptions during image acquisition; enhancing an image aid visualization and display; segmentation to identify regions and objects in an image on the basis of homogeneity criteria, such as colour, intensity or texture; and deriving properties and features of the regions that can be used to interpret the image. The first part of the analysis includes processing the images and finding the key areas-of-interest, after that image assessment will be performed to meet the industrial standards. The second part is devoted to image segmentation based on the key features like pits and cracks by using machine learning techniques and deep learning neural network. The main design framework of the project (as indicated in Fig. 6) contains four stages: data acquisition, image pre-processing, feature extraction and classification.

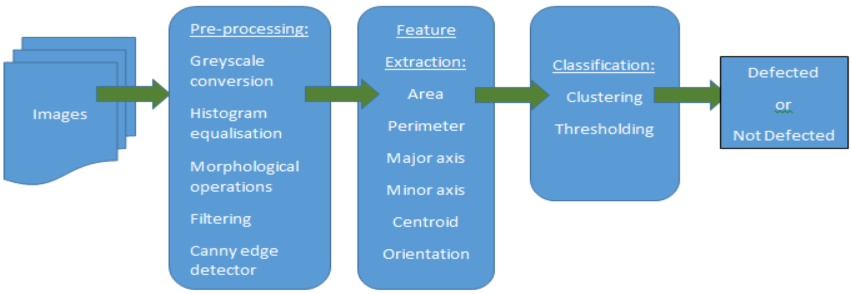


Fig. 6. Basic stages of the detection system.

Real images include a lot of noise. Some images contain pits and some contain cracks and pits. It can be seen from Fig. 7 that the system has managed to display the location of the surface features by highlighting them in the enhanced image. The system also produces a text file with all the measurements, some of which include the flaw length, perimeter and area for each flaw counted.

The performance of the algorithm will be compared to an expert-made ground-truth image for machine learning purposes. This will quantitatively evaluate in terms of three measurable metrics: (i) sensitivity, (ii) specificity, and (iii) accuracy. These metrics are based on a simple measure of the true positive TP, the true negative TN, the false positive FP, and the false negative FN. Mathematically they can be defined as follows:

$$Sensitivity = TP/(TP + FN) \quad (2)$$

$$Specificity = TN/(TN + FP) \quad (3)$$

$$Accuracy = (TP + TN)/(TP + TN + FP + FN) \quad (4)$$

3.3. Life prediction software

The life prediction software has been elaborated following the results already obtained by Moretti et al. (2014), who showed that an accurate description of the distribution of surface cracks could be only obtained adopting a random

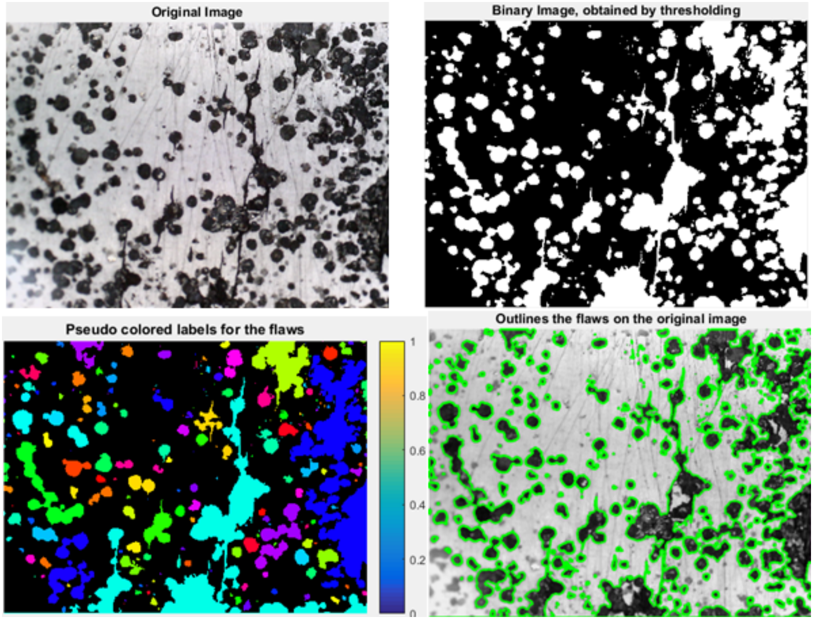


Fig. 7. Resultant processed images by the system.

process. In detail, a lognormal process has been adopted for the small crack growth under corrosion fatigue according to the model by Moretti (2013). For describing the phase when cracks become sufficiently long (corresponding to $\Delta K > \Delta K_{th}$), fatigue crack growth has been described by the *NASGRO* propagation equation, by taking ΔK_{th} as a lognormal random variable as suggested by Beretta and Carboni (2006). An example of the prospective growth rate corresponding to a few simulations is shown in Fig. 6.a

The crack growth models have been incorporated into a Monte Carlo software suite able to simulate corrosion-fatigue crack propagation under a randomized service stress spectrum starting from initial crack sizes equal to d_{p-t-c}. The activity has been concentrated onto a fine tuning of the parameter $\mathcal{B}$ in Eq (1) in order to correctly reproduce a series of measurements of corrosion-fatigue damage obtained on full-scale axles subjected to constant amplitude loading. The result of the simulation tools is shown in Fig. 6.b, where the simulated distribution of surface cracks perfectly matches the crack detected on a full-scale axle made of A4T.

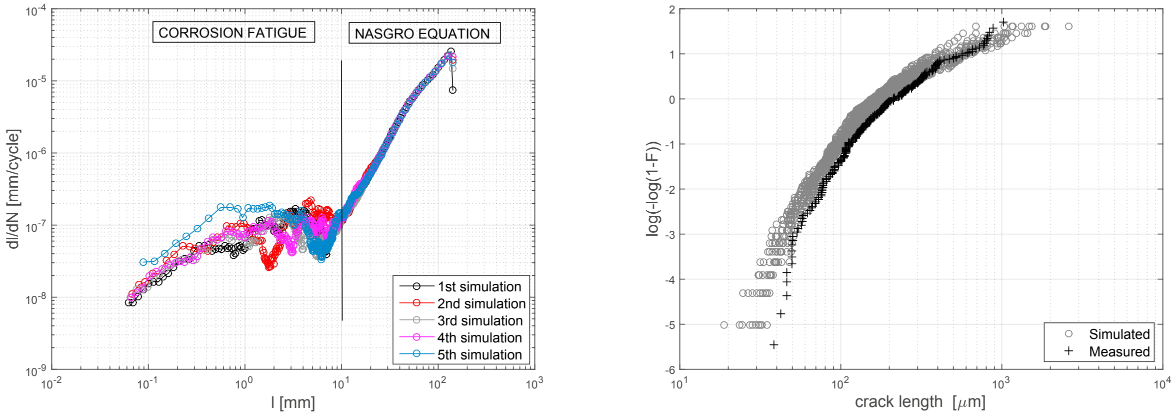
Table 1. Probabilistic model .

phase	equation	parameter	description
pit-to-crack transition diamater	d_{p-t-c}	μ_{ptc}, σ_{ptc}	gaussian
small crack growth (corrosion-fatigue)	$\frac{dl}{dN} = \mathcal{B} \cdot \Delta\sigma^{\beta} \cdot l^{n}$	$\mathcal{B}$	lognormal process
fatigue crack growth	Nasgro propagation equation	ΔK_{th}	lognormal random variable

4. Concluding remarks

The novel method for estimating the residual service life of a corroded axle, developed with the RAAI project, is the combination of new automated scanner plus a new software tool able to accurately reproduce results so far obtained on full-scale corrosion-fatigue experiments.

The combination of surface damage quantification (observations + surface measurements of the distribution of pits/cracks) and life predictions has been successfully applied in trials for assessing series of axles exposed to corrosion during their service. The results (in terms of residual service lifetime), that could not be obtained in previous projects, look to be interesting for for new NDT services and maintenance planning.



(a) (b)

Fig. 8. Life prediction software:(a) five simulations of crack growth rate evolution for the same initial crack considering both corrosion fatigue (random process) and in-air (NASGRO) regime; (b) comparison between simulated and measured crack length populations after a determined number of cycles.

Acknowledgements

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