Corrosion-fatigue under rainwater of a Q&T steel: experiments and probabilistic description

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Abstract

Corrosion-fatigue is one of the key failure modes of railway axles. We show the results of a series of corrosion-fatigue experiments under rainwater with a Q&T steel adopted for manufacturing railway axles. The process can be divided into the following phases by: i) an early formation of pits followed by ii) a pit-to-crack transition at approximately 30\textmu m diameter and iii) the growth of small cracks with a pronounced scatter. The variability of the different phases needs to be accurately described for achieving a realistic life prediction and a good comparison with full-scale experiments.

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1. Introduction

Corrosion-fatigue is a common \textit{failure mode} for railway axles [1], which is responsible for some recent axle failures [2]. The role of corrosion is acknowledged by standards (EN13261[3], BR-BASS 503 now superseeded [4]) that prescribe derating factors for fatigue strength of axles. However, these simple prescriptions do not allow to analyze the reliability of axle fleets in service and to optimize maintenance actions. Recent publications have clarified the role of atmospheric corrosion on fatigue properties of EA1N steel (a normalized carbon steel with UTS close to 600 MPa) [5–7], but there is a need to investigate how to correctly model the corrosion-fatigue process from a probabilistic point of view.

In this paper we analyze the corrosion-fatigue properties of EA4T, a Q&T carbon steel widely adopted for manufacturing railway axles of passenger coaches, high speed trains and locomotives. We describe an experimental campaign for the characterization of corrosion-fatigue under rainwater conditions and full-scale tests under the same conditions. The results from the latter tests have allowed us to understand that for a good prediction of the process at the level of full-scale components a random process model is required. In the following we will describe the small scale experiments together with the different phases of the corrosion-fatigue process and then the full-scale tests, together with an outline of the probabilistic models we have adopted.

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2. Corrosion-fatigue analysis by means of small-scale experiments

2.1. Material and experiments

The EA4T steel is a quenched and tempered low alloy steel, widely used in manufacturing railway axles. Its basic mechanical properties are: ultimate tensile strength $\text{UTS} = 705 \text{ MPa}$, 0.2% monotonic yield strength $S_y = 531 \text{ MPa}$, Young’s modulus $E = 206000 \text{ MPa}$ and elongation at failure $A = 22\%$. The 0.2% cyclic proof stress is equal to 422 MPa.

In order to investigate the evolution of corrosion fatigue damage of EA4T steel, series of corrosion-fatigue tests were carried out with small scale specimen under test conditions similar to those adopted by the authors earlier[6,8]. Specimens were hourglass shaped with a minimum diameter of 10 mm. After machining, they were polished with up to #1000 grit emery paper and then mirror polished with diamond paste. Tests were run at $R = -1$ using a four point rotating bending machine (capacity of 35 Nm) at 10 Hz frequency.

The stress levels of the corrosion-fatigue experiments were in the range $\Delta S = 180 - 400 \text{ MPa}$: this range has been chosen similar to the tests run for EA1N steel. Corrosion conditions were continuously applied to specimens by means of a dedicated dropping system with a dripping flow rate of 80 cc/min of artificial rainwater solution, characterised by pH = 6 [9]. Three types of tests have been carried out: i) complete corrosion-fatigue tests aimed at obtaining the S-N diagram under corrosion-fatigue especially at low $\Delta S$ levels; ii) interrupted fatigue tests for determining the evolution of pit size and the distribution of cracks on areas of 9 mm$^2$ (observations under SEM after mechanical polishing and chemical pickling); iii) tests for determining small crack growth rate by means of plastic replicas (gentle mechanical polishing on areas of 5 × 5 mm at specimen minimum section).

2.2. Pit formation and pit-to-crack transition

In terms of pit formation, the behaviour of EA4T is similar to the one of EA1N. In particular, the observations on the surface of interrupted tests have shown that the pits grow with a nearly hemispherical shape untile they reach a critical size for the pit-to-crack transition. The observations confirm that, similarly to EA1N steel [8], the formation of cracks is triggered by a secondary pit/crack at the bottom of the primary pit (Fig. 1). Our observations appear to differ from those of Turnbull et al [10] who found that cracks develop at the pit mouth. Since our experiments are carried out at low stress levels and the pit-crack transition is driven by plastic strains [11], it can be conceived that crack formation can be only triggered by the high stress concentration [12] at the tip of secondary pits. The average size of pits at the transition is approx. $d_{p\rightarrow c} = 35 - 40 \mu m$. The pit growth was described with a model of the type [13,14]:

$$d = K \cdot t^{(c \cdot \sigma_a + b)} \quad \text{for} \quad d < d_{p\rightarrow c} \quad (1)$$

where $d$ is the pit diameter, $\sigma_a$ is the stress amplitude, $t$ is the exposure time and $K, b, c$ are parameters determined from data obtained by interrupted tests.

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.
2.3. Propagation of small crack under corrosion-fatigue

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 $l_t = 600 \mu m$ due to crack coalescence. To describe this peculiar behaviour, we have adopted a crack growth model (an adaptation of the model by Murtaza & Akid [15], see [8] ) of the type:

$$\frac{dl}{dN} = B \cdot \Delta \sigma^\beta \cdot \ln l^n \quad \text{for} \quad l \leq l_t = 600 \mu m$$

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

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. Such a transition is shown in Fig.3.a for the different stress levels. The crack growth in air was modelled with the Nasgro propagation equation [16].

Fig. 2. Measurement of progressive damage: (a) observation of cracks propagating from pits; (b) the crack growth rate measured at $\Delta S = 400$ MPa.

Fig. 3. Model of crack growth: (a) transition from corrosion-fatigue to fatigue at the different stress levels; (b) estimation of the S-N diagram under corrosion-fatigue on small scale specimens.

2.4. Life prediction

The three stages of propagation (pitting + corrosion-fatigue + fatigue) have been modelled with a random variables approach within a Monte Carlo simulation for integrating the pit/crack growth equations, with the random variables
summarized in Tab. I. The simulation of the life of small-scale specimens gave a good prediction of the S-N diagram under corrosion fatigue for small scale specimens (Fig. 3.b), while the predictions for prospective full-scale axles were not in agreement with test results, as described in the following section.

Table 1. Probabilistic model (random variable approach).

<table>
<thead>
<tr>
<th>phase</th>
<th>equation</th>
<th>parameter</th>
<th>distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>pit growth</td>
<td>Eq. (1)</td>
<td>$K$</td>
<td>lognormal</td>
</tr>
<tr>
<td>pit-to-crack transition diameter</td>
<td>Eq. (1)</td>
<td>$d_{p-c}$</td>
<td>gaussian</td>
</tr>
<tr>
<td>small crack growth (corrosion-fatigue)</td>
<td>Eq. (2)</td>
<td>$B$</td>
<td>lognormal</td>
</tr>
<tr>
<td>fatigue crack growth</td>
<td>Nasgro propagation equation</td>
<td>$\Delta K_{th}$</td>
<td>gaussian</td>
</tr>
</tbody>
</table>

3. Full-scale experiments and model update

Full scale tests were carried out with two specimens tested at $\Delta S = 320 \text{ MPa}$ and $\Delta S = 240 \text{ MPa}$. The axles were tested, under a 3P bending bench [17], in conditions very similar to the ones adopted for small scale specimens. They were subjected to frequent stops in order to measure the distribution of propagating micro-cracks with the optical device [8], that was set up in the WOLAXIM project [18] (see Fig. 4 and Fig. 5). The two tests at $\Delta S = 320 \text{ MPa}$ and $\Delta S = 240 \text{ MPa}$ were then interrupted after $4.5 \times 10^6$ and $12 \times 10^6$ cycles respectively.

The application of the random variable approach for predicting the distribution of crack lengths showed that this method overestimates the scatter of cracks length. To improve the prediction, a random process model of the crack growth was implemented [19,20]. The crack growth rate $dl/dN$ is modelled as a lognormal process in function of the crack length $l$, whose correlation length was estimated from the data to be in the order of 1mm; for details see [21]. The explicit consideration of the random variability of the crack growth rate over the propagation phase leads to an averaging and hence to a reduction of the overall uncertainty compared to the random variable model. The differences in modelling the growth rate are illustrated in Fig. 7.

The results of the random process model have been very satisfactory in terms of prediction of the distribution of cracks on full-scale specimens and prediction of the prospective S-N diagram for axles (see Fig. 6).
Fig. 5. Measurement of progressive damage: (a) periodic oxide removal and preparation of the surface to be observed; (b) observation with the optical device.

Fig. 6. Prediction with different probabilistic models: (a) evolution of the crack distribution observed onto a full-scale specimen at $\Delta S = 240 \, MPa$; (b) prediction of the S-N diagram.

Fig. 7. Simulation of corrosion-fatigue crack growth at $\Delta S = 240 \, MPa$ with the two different probabilistic methods: (a) random variable approach; (b) random process approach.
4. Conclusions

We have shown the experimental results obtained on the corrosion-fatigue properties of EA4T, together with their statistical modelling. The process can be divided in different phases by: i) an early formation of pits with subsequent a pit-to-cracks transition at approx. 30 \( \mu m \) diameter; ii) the growth of small cracks with a pronounced scatter and iii) a coalescence that affects crack growth rate. The variability of the different processes needs to be accurately described for achieving a realistic life prediction: in particular the life of full-scale axle can be reasonably predicted only adopting a random process model for small crack growth.

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