Crack initiation and growth in full scale railway axle in A1T mild steel have been studied, under three points rotating bending loading conditions and artificial rainwater as corrosive environment. A surface plastic replication technique has been used along with optical microscopy and Scanning Electron Microscopy to monitor the environment assisted fatigue at various stages. A modified Murtaza and Akid empirical model has been employed to predict the corrosion fatigue crack growth rates and a reasonable agreement has been found between experimental and calculated lifetime.

"Keywords: A1T steel; Railway axles; Corrosion-fatigue; Crack Growth;"
In the present paper corrosion fatigue tests in presence of artificial rain water will be carried out on full scale axles and the predictive model for fatigue crack growth assisted by corrosion of rainwater will be applied to estimate the corrosion fatigue life of the axles.

2. Crack Growth Model

To set a suitable model for prediction of the corrosion fatigue life of railway axles, crack growth rate measurements were performed during crack propagations tests under correlate fatigue and corrosion on A1T small scale specimens [4]. Experiments at $\Delta \sigma = 400$ MPa, $\Delta \sigma = 320$ MPa, $\Delta \sigma = 240$ MPa, have been run. The load configuration is four points rotating bending, $R = \sigma_{\text{min}} / \sigma_{\text{max}} = 1$, under continuous dropping of aerated artificial rainwater. The composition of the artificial rainwater is Ammonium sulfate 46.2 mg/l; Sodium sulfate 31.95 mg/l; Sodium nitrate 21.25 mg/l; Sodium chloride 84.85 mg/l. During testing the PH value of the artificial rainwater is measured on daily basis and adjusted to a value between 5.7 and 6.3; the conductivity and the temperature of the artificial rainwater are monitored in order to verify that their initial values are maintained; and the free corrosion potential ($E_{\text{corr}}$) is plotted vs. the number of cycles. The results of the tests for each stress level are shown in the Figure 1(a).

To predict the corrosion fatigue lifetime of the A1T railway axles the Hobson-Brown model, modified in the work of Murtaza and Akid [10], is proposed. The model allows us to account for a crack growth rate dependent on the applied stress level. The corrosion fatigue crack growth rate may be described by the following equation [4]:

$$\left( \frac{da}{dN} \right) = B \left( \Delta \sigma \right)^\beta a^n \quad \rightarrow \quad \frac{da}{a^n} = B \left( \Delta \sigma \right)^\beta dN$$

where:
- $B$, $\beta$, and $n$ are the material constants (in most cases $n = 1$);
- $\Delta \sigma$ is the stress range.

The results of the model for each stress level are shown in the same Figure 3(b).

Fig. 1. (a) Corrosion fatigue on small scale specimens: crack growth experimental data and interpolation for each of the three stress level. (b) Corrosion fatigue SN diagram and description in term of corrosion fatigue crack propagation.
By adopting equation (1), we are also able to propose a description of the S-N diagram in terms of propagation of corrosion fatigue cracks from the transition length from short crack to long crack ($d_m$) to the final crack length ($a_f$). As can see in figure 1(b), if $d_m$ is assumed equal to the material grain size (20 μm) and the final crack length corresponding to failure is assumed $a_f=3$mm, the prediction of the adopted model describes the median S-N diagram fairly accurately.

3. Full-scale experiments

The present study involves corrosion-fatigue tests on full scale specimens representative of common designed hollow railway axles for passenger trains in service in the Central Europe railways net. The geometry of the specimens is detailed in figure 2(a). The nominal inner and the outer diameters are the same as in axles. The press-fitting is reproduced one time in the middle of the specimens as the loading configuration, also marked in figure 2(a), is a three point bending. Smooth hour-glass shape has been designed close to the press-fitting zone for local corrosive environment application.

The material is A1T steel, widely used in the manufacture of railway axles. The matrix consists of a ferritic-pearlitic microstructure with a 20-40 μm ferritic grain size. The resultant mechanical properties are of the following order: ultimate tensile strength (UTS) 620 MPa, yield strength 390 MPa, Young’s modulus 206 GPa and elongation 14.8 %.

Two full scale specimens have been tested. The experimental conditions and the corrosive environment are the same as in the small scale case. The schematic of the experimental set up and a detail of the corrosion cell are visible in figure 2(b). The press-fitting is reproduced one time in the middle of the specimens as the loading configuration, also marked in figure 2(a), is a three point bending. Smooth hour-glass shape has been designed close to the press-fitting zone for local corrosive environment application.

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The evolution of the fatigue corrosion damage, pits formation, cracks initiation and growth, has been monitored by surface replication, of small areas each 45° along the circumference at the center line of the hourglass. Corrosion causes localized pitting of the surface, and these pits serve as stress concentrations to triggers fatigue crack initiation. A high density of small cracks is observed on the surface exposed to artificial rainwater, in the early stage of the corrosion fatigue tests. Figure 3(b) shows examples of cracks initiation from corrosion pits for the test at variable amplitude, when the number of cycles is $3.2 \times 10^6$ cycles, about 10% of the predicted life. The synergetic action involved in the mechanics of corrosion fatigue make the threshold stress intensity factor of short cracks initiated at corner pits lower and the crack growth faster when compared to the laboratory air conditions [4]. When the number of cycles increase, the crack length increases due to the propagation of single cracks or due to the coalescence of a small number of individual cracks. The coalescence of propagating cracks results a key factor in the development of the damage and in the formation of a typical zig-zag path of the crack.

The constant amplitude test is terminated with the final failure of the specimens at $9.4 \times 10^6$ cycles. Magnetic particles examination of the broken specimen reveals two very long cracks, the main is about 110 mm and shows the before mentioned, zig-zag path, and a large populations of uniformly distributed cracks which length is of order of millimeters (figure 4(a)). The morphology of damage found confirmation in literature [1], where a real case of corrosion fatigue failure of railway axle is documented.
Fig. 2. (a) Full-scale specimen and load configuration; (b) Schematic of the experimental test set up for full-scale corrosion fatigue experiments and detail of the corrosion cell.

Fig. 3. (a) Free corrosion potential vs. the number of cycles for the full scale test under constant amplitude loading. (b) Cracks initiation from corrosion pits. Surface of the specimen tested at variable amplitude at $3.2 \times 10^6$ cycles, about 10% of the predicted life.
The main fracture reveals a semielliptical crack (Figure 4(b) with a depth of approx. 20 mm and with some other minor cracks near the ends. SEM observation of the ‘nucleation’ region reveals pits with a depth 50-100 μm. A section of the axles along its axis, reported in Figure 5, clearly shows a transgranular crack that in the first stage propagate inside an oxide path (interaction between corrosion and mechanical load) and in the second stage propagate more quickly that the oxide formation (mechanical effect is dominant). The variable amplitude test has been run with the load spectrum reported in Figure 6(a). The test has been interrupted at 14.6 10^6, about 50% of the estimated life. At this stage, magnetic particles examination reveals numerous clusters of cracks having length of the order of millimeters, still not uniformly distributed.

4. Validation of the corrosion fatigue model

According to eq. (1) a prediction of the corrosion fatigue life of the full scale tests described in the previous paragraph can be also performed. For the constant amplitude full scale tests \( \Delta \sigma = 320 \) MPa, the corrosion fatigue lifetime predicted by the model is of 6.3 \( 10^6 \) cycles. The difference between the calculated and the experimental lifetime is less than the experimental scatter of data observed on small scale corrosion fatigue tests [4]. If the second experiment is considered, a prediction of the crack size vs. the number of cycles can be obtained according to the equation (1) and with the applied load spectrum reported in figure 6(a). In practice, the crack size is expressed in terms of depth \( a \), with an appropriate correction assuming an aspect ratio of 0.85 as established in both in small and full scale experimental tests. The result is shown in figure 6(b). As previously said, in this case the estimated life is about 30 \( 10^6 \) cycles and the test has been run for 14.7 \( 10^6 \) cycles (half-life). At this stage the model predict a corrosion fatigue crack length, on the surface of the specimen in the circumferential direction, of about 1.4 mm, while the experiment has shown the formation of a coalescence of small cracks about 1.5 mm long.

Conclusions

Two full scale corrosion fatigue tests of railway axles have been carried out. Crack growth rate measurements, enables us to set a modified version of a model proposed by Murtaza and Akid for the fatigue corrosion life prediction of railway axles. The corrosion–fatigue crack growth model enables us, also, to obtain a fairly precise prediction of the S–N diagram of A1T steel under corrosion–fatigue sustained by the free corrosion of the material.
Fig. 5. Section of the axles along its axis direction. (a) Transgranular path of the crack. (b) First stage of the crack growth inside a path of oxide and second stage more quickly of the oxide formation.

Fig. 6. (a) Load spectrum applied to the variable amplitude full scale test.; (b) Crack growth rate, as predicted by the proposed model for the load spectrum of figure 8(a).

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