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Corrosion fatigue lifetime assessment of high-speed railway axle EA4T steel with artificial scratch

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ABSTRACT

The effects of environment (in air and 3.5 wt% NaCl solution) and artificially-induced surface scratches are investigated on the fatigue properties of railway EA4T (also called 25CrMo4) alloy steel. This steel is found to be markedly sensitive to the chloride-containing environment, with cracking at stresses two thirds of the in-air fatigue limit (+/−326 MPa) under rotating bending (Wöhler) tests. The scratched specimens show even shorter lifetime at stresses below 300 MPa and no fatigue limit is found down to 100 MPa. The fracture surfaces are characterized by the initiation of cracks from multiple sources and intergranular cracking. The fatigue failure of smooth specimens tends to initiate from localized corrosion pitting, while the corrosive environment facilitates crack initiation without pitting for scratched specimens. The fatigue crack growth rate in NaCl solution is slightly higher than that in air. Within the framework of defect-tolerant design, El-Haddad modified Kitagawa-Takahashi (KT) diagrams are constructed to explore the variation in fatigue strength and the defect assessment for both conditions. The modified KT model, which takes the short crack behavior into account, is in better agreement with the experimental results than the original KT diagrams.

1. Introduction

There have been significant developments in high-speed railway technology with the normal operating speed of the China “Fuxing” bullet trains reaching 350 km/h in 2017. As a result, the service safety and reliability of critical components have become a significant structural integrity concern. Among these, the railway axles (comprising alloy steel EA4T or medium carbon steel S38C) experience various types of surface damage during maintenance and applications, such as scratches, dents, impact defects and fretting wear [1,2]. These surface defects can have a negative effect on the rotating bending fatigue response because they are the potential crack nucleation sites [3–5].

Detailed investigations have shown that scratches account for around 40% of the surface damage and negatively influence the...
fatigue resistance of railway axles [3,4]. Based on previous studies, scratches are mainly located between 830 mm and 1050 mm from the end of the axle opposite the gearbox [3]. Longitudinal scratches smaller than 200 μm in depth are frequently generated on the wheel and gear seat when the assemblies are disassembled for magnetic powder inspection. Circumferential scratches can occur due to hard objects entering the gearbox and rubbing against the axle surface during high-speed rotating [5]. Compared to the scratch angle and the curvature radius of the scratch tip, the scratch depth is the most critical factor influencing fatigue crack initiation and short crack propagation [4]. For example, the maximum scratch depth found on the in-service railway EA4T hollow axles extends to around 128 μm [5].

It has been argued that in this case surface scratches can cause a considerable reduction in fatigue life (of up to almost 98% [5]). Multiple cracks were initiated from the scratch root in the early-life period and further coalesced to form a primary crack [6]. A model to quantify the influence of small defects on the fatigue strength was formulated in terms of the hardness of the material and the size and location of defect [7]. It is found that the fatigue limit decreases with increasing scratch depth, particularly so when the scratch is larger than a critical value [5]. In the case of an artificially scratched axle EA4T, the critical safe scratch depth under ambient conditions has been tentatively proposed to be less than about 10 μm according to a modified Kitagawa-Takahashi (KT) fatigue diagram [5].

During routine operations, railway axles are exposed to a variety of environments, from humid air through rainwater. The coupling effect of a corrosive environment and cyclic loading can promote premature failure far below the in-air fatigue limit [8,9]. Previous studies have reported that artificial rainwater can eliminate the fatigue limit of railway EA1N steel (the disappearance of the knee-point of fatigue S-N curve), primarily due to pitting damage and much faster short crack growth than in air [9–12]. Further, oxide-induced crack closure can contribute to a larger scatter in fatigue life of railway EA4T steel (by one or two orders of magnitude) under various humidity conditions [13].

To avoid corrosion attack, protective coatings (thickness of ~20–30 μm) can be applied to the railway axles. However, peeling has been frequently observed during routine operations under complex environments. Moreover, the surface defects accidentally introduced during regular operations and maintenance activities can damage the coatings locally. The combined effects of the stress concentration due to the defect and the environment access to a localized area can cause corrosion-fatigue failures. To date, very few papers have been reported the influence of the corrosive environment on the fatigue performance of scratch-affected railway axles.

This study aims to evaluate the effect of scratch depth on the fatigue performance of railway EA4T steel as a function of environmental condition. To this end, rotating bend high cycle fatigue (HCF) tests have been carried out on both smooth and artificially scratched specimens in air and 3.5 wt% NaCl solution. The fatigue strength and damage mechanisms are compared in terms of the measured S-N fatigue curves and post-mortem fractography. Within the framework of defect-tolerant design, El-Haddad modified Kitagawa-Takahashi diagrams including the short crack growth behavior [14] are constructed to explore the variation in fatigue strength and the defect assessment for both conditions.

2. Experimental procedures

2.1. The material

The material studied here is medium-strength EA4T alloy steel grade, which is widely used in the manufacture of high-speed railway hollow axles in both Europe and China. As shown in Fig. 1, the matrix primarily comprises bainite and martensite having an average grain diameter of around 7.2 μm [15].

Fig. 1. Microstructure at the center of the EA4T railway axle from (a) optical microscopy image and (b) inverse pole figure (IPF) from electron backscattered diffraction (EBSD).
It has been reported that the very fine microstructure and small grain size to plastic zone ratio of railway EA4T steel contribute to a low level of roughness-induced crack closure [13,16]. The nominal mechanical properties of the matrix were measured as follows: elastic modulus of 209 GPa, the ultimate tensile strength of 726 MPa, yield strength of 591 MPa, engineering strain to failure of 19% and a Vickers hardness of 240 HV [3].

2.2. Scratch preparation

Scratches (see Fig. 2) were introduced into the gauge section of hourglass-shaped specimens using a mini turning machine in order to simulate their detrimental effect on the fatigue and corrosion fatigue life of modern railway axle EA4T steel. The scratch depth can be exactly controlled by the blade feed pressure. Based on the post-mortem fractographic of the failed specimens using scanning electron microscope (SEM), three depths of scratches were imposed, namely 140 μm, 300 μm and 500 μm. The scratch widths were determined by the width of the blade (335 μm).

2.3. Fatigue resistance tests

Fatigue crack growth (FCG) tests were performed on the center-cracked specimens excised from the axle body (see Fig. 2) using an Amsler-HFP5000 testing machine. The load ratios were 0.1 and −1. The frequency was 120–150 Hz and 2 Hz for testing in room air and 3.5 wt% NaCl solution, respectively. An increasing stress intensity factor (SIF) loading procedure was adopted to determine the FCG rate. A decreasing SIF loading procedure was used to estimate the threshold stress intensity factor range (ΔKth).

To examine the fatigue strength, rotating bending HCF tests were performed on both smooth and artificially scratched hourglass-shaped specimens in room air and 3.5 wt% NaCl solution. All the specimens were carefully ground and polished before testing, producing a surface roughness of ~0.6–0.8 μm. The surface quality is exactly the same as that of real railway axles. They were pre-exposed to NaCl solution for 30 min. The flow rate of corrosion solution was set to 850 l/h. During fatigue loading, the corrosion solution was dripped onto the specimens at a rate of 1.6 ml/min. Sinusoidal loading was applied with the stress ratio R of −1 at 3300–3600 revs/min, which approximately equals to the running velocities of 300–350 km/h of high-speed railway trains and the equivalent loading frequency. The runout limits were set to 5 × 10⁷ cycles and 10⁷ cycles for smooth and artificially scratched specimens, respectively. A FEI Quanta FEG 450 SEM was used to examine the fracture characteristics of failed specimens.

Fig. 2. Schematic of the sampling location for fatigue resistance tests (unit in mm), the geometry of hour-glass (blue) and center-cracked (yellow) specimens, alongside SEM images showing the nature of the scratches.
3. Experimental results

3.1. Smooth specimens

Rotating bending HCF testing was first performed on the smooth surface specimens (see Fig. 2). The fatigue life results in air and 3.5 wt% NaCl solution are plotted on the $S$-$N$ fatigue diagrams (see Fig. 3) in terms of stress amplitude, $S_a$, and the total number of cycles to failure, $N_f$ [17].

It is evident that the corrosive environment significantly degrades the fatigue resistance of the EA4T steel, especially in the long fatigue life regime. The fatigue life data in corrosive environment is one to two orders of magnitude lower than that in room air under the same applied stress. Moreover, the fatigue failure is observed at a stress (200 MPa) well below the in-air fatigue limit (+/−326 MPa). The fatigue life of the smooth specimens shows a larger scatter when exposed to 3.5 wt% NaCl solution. In our previous studies, the conditional probability density function (CPDF) has been applied to the statistical fatigue life assessment of smooth and foreign object damaged EA4T steel. Here we examine its validity in the statistical assessment of corrosion-fatigue life. The CPDF is used to describe the probability density distribution (PDD), $f$, of fatigue life at different stress levels [18,19]:

$$f(x|S) = \frac{1}{\sigma(S)\sqrt{2\pi}}\exp\left\{-\frac{(x-\bar{x(S)})^2}{2\sigma^2(S)}\right\}$$

(1)

where $x$ is the logarithm of fatigue life ($x = \log (N_f)$), $S$ is the applied stress, $\bar{x}(S)$ and $\sigma(S)$ are the mean and standard deviation of $x$ under a given stress amplitude, respectively.

For the smooth surface specimens tested in 3.5 wt% NaCl solution, the $\bar{x}(S)$ and $\sigma(S)$ at five stress amplitudes plotted in Fig. 3 are listed in Table 1.

The relationships between $\bar{x}(S)$, $\sigma(S)$ and $S$ in Table 1 can be approximately fitted by the classical Basquin equation and the empirical reciprocal model [18], respectively:

$$\bar{x}(S) = \log(C) - m\log(S)$$

(2)

$$\sigma(S) = (a + bS)^{-1}$$

(3)

where $C$, $m$, $a$ and $b$ are the fitting parameters. In our case, $\log(C) = 17.8699$, $m = 4.9167$, $a = -4.5914$ and $b = 3.272 \times 10^{-2}$.

By combining Eqs. (1)-(3), the CPDF for smooth surface specimens in 3.5 wt% NaCl solution can be determined as a function of stress amplitude:

$$f(x|S) = \frac{0.033S - 4.5914}{\sqrt{2\pi}}\exp\left\{-\frac{(x + 4.9167\log(S) - 17.8699)^2(0.033S - 4.5914)^2}{2}\right\}$$

(4)

The CPDF surface is plotted in Fig. 4 with the probability density function capturing the increasing scatter in fatigue life with decreasing stress listed in Table 1.

It is noteworthy that the probabilistic analysis of corrosion-fatigue life is limited by the test conditions. This paper only aims to provide a feasible probability density function to describe the feature that the corrosion-fatigue life and the scatter in lifetime increase with decreasing stress levels. It is critical necessary to consider the influence of time dependent variable on the probability analysis of corrosion-fatigue life in future works.

Post mortem fractography provides an insight into the environmentally-assisted fatigue damage mechanisms. Multiple active crack
initiation sites are visible on the fracture surfaces of the smooth specimens tested under NaCl conditions (see Fig. 5). It is found that the environmentally induced cracks tend to initiate from localized corrosion pitting. The randomly distributed pits contribute multiple crack initiation sources, as previously observed in other systems by time-lapse computed tomography [20].

The corrosion pits of around $10 \mu m$ were observed on the fracture surfaces at the crack nucleation region, as shown in Fig. 5 (c). It may be due to that the cracking of the inclusions or second phases occurs during cyclic loading and then the corrosive solution flows into the damaged sites to form the corrosion pitting. The pit size of $10 \mu m$ is simply a consequence of the testing conditions adopted rather than the limiting size for the testing. The crack propagation region is characterized by intergranular cracking. Moreover, Fig. 5 (d) reveals the broken oxide layer and the dense interconnected nest-like oxides and salts, which originate from the infiltration of the corrosive solution into the cracks as they form. These may serve as a chemical facilitator for intergranular cracking under a joint electrochemically and mechanically driven process [21].

Railway axles are susceptible to pitting damage, particularly when exposed to a chloride-containing environment [22]. Unsurprisingly, the detrimental effect on fatigue strength of railway EA4T steel is more pronounced at stresses below the in-air fatigue limit (see Fig. 3). The pit growth stage is believed to occupy a large portion of fatigue life at low stress levels [11]. In this case, the corrosive

<table>
<thead>
<tr>
<th>Stress amplitude $S_a$/MPa</th>
<th>Fatigue life $N_f$/cycles</th>
<th>Log ($N_f$)</th>
<th>Mean value $\mu(S)$</th>
<th>Standard deviation $\sigma(S)$</th>
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![Fig. 4](image.png)

**Fig. 4.** The conditional probability density function surface and probability density curves for smooth surface specimens in 3.5 wt% NaCl solution.
medium plays a dominant role in the corrosion-fatigue failure as compared to the mechanical effects [11,23]. Clearly, the low fatigue strength and large scatter in fatigue life at low stress levels present a challenge from a structural integrity, and requires further characterization.

Fig. 5. Typical fractography for a smooth specimen exposed to NaCl environment at a stress amplitude of 200 MPa (fatigue life of 456,100 cycles): (a) the crack initiation and stable propagation region and sudden fracture region are marked with green and yellow dotted lines respectively, (b) a magnified view of crack nucleation, (c) corrosion pitting, (d) oxide cracks.

Fig. 6. Fatigue life results for specimens artificially scratched to depths of 140 μm, 300 μm and 500 μm tested in air.
3.2. Scratched specimens

Surface scratches are commonly observed on in-service railway axles. These scratches can degrade the fatigue properties because they act as potential crack initiation sites. The depth, width, length and orientation of the scratch combined with the curvature radius of the scratch tip are the critical factors controlling the fatigue performance of scratched materials [4,24]. The effect of scratch depth, which is the most critical geometric parameter [4], is explored in this study through the specimens artificially scratched to depths of 140 μm, 300 μm and 500 μm. Fig. 6 shows the fatigue life of these specimens tested in air. Unsurprisingly, as the scratch depth increases, both the fatigue life and fatigue limit decrease. The scratches tend to introduce a high-stress concentration that facilitates the nucleation of small cracks and the reduction in crack initiation life.

The relationship between the stress concentration factor, $K_t$, associated with defects, and crack initiation life, $N_i$, can be estimated by [25,26]:

$$K_t \Delta \sigma \left(1 - \frac{r^*}{\rho} \right) - \Delta \sigma_c \right) \rho_{\text{f}} = \zeta$$

(5)

where $\Delta \sigma$ is the stress range, $r^*$ is the distance ahead of the scratch dominated by crack initiation, $\rho$ is the curvature radius of the scratch tip, $\Delta \sigma_c$ is the fatigue limit, $\zeta$ is the fatigue life coefficient, and $\alpha$ is the fatigue life exponent. The evolution curves of $K_t$ dependent on the notch geometry have been determined previously [27]. The deeper defects lead to the higher $K_t$ and a shorter crack initiation life according to Eq. (5).

Clearly the surface scratches acting as a stress concentrator have a detrimental influence on the fatigue resistance of the materials. Moreover, the corrosive environment can facilitate the crack initiation arising from the formation of corrosion pitting (see Fig. 5). This can be especially problematic in the case of localized damage to coatings caused by scratches. In such case, the in-service performance of railway axles is compromised by the two damaging factors, namely the surface scratches and the exposure to the corrosive atmosphere. Fig. 7 summarizes the fatigue life results of scratched specimens in air and 3.5 wt% NaCl solution as a function of stress amplitude.

Based on Fig. 7, it is evident that the fatigue strength of scratched specimens under 3.5 wt% NaCl environment is significantly lower than those in air. The variation in fatigue life is sensitive to the corrosive atmosphere, displaying a sharp degradation in the lifetime with increasing stress amplitude. The corrosive solution also markedly lowers the fatigue limit for scratched specimens, leading to fatigue failure at a stress less than 1/3 that of the in-air fatigue limit (+/−326 MPa). This poses a significant threat to the safe-life design of railway axles. In order to better understand the mechanism by which the fatigue failure is affected by the surface scratches and the corrosive environment, the fracture surfaces of a failed scratched specimen with a scratch depth of 140 μm tested in 3.5 wt% NaCl solution are analyzed, as shown in Fig. 8.

It is evident from Fig. 8(a) that the fatigue failure originates from multiple sources. These initiation sites include the scratch root and the specimen surface. Small cracks from the scratch root and specimen surface further lead to coalescence steps due to the intersection of different crack propagation planes. No corrosion pits are observed at the scratch root or on the specimen surface. However, that is not to say that the environment cannot aid crack initiation despite the absence of pits as observed previously [28]. The secondary cracks are observed in Fig. 8(c) after chemical cleaning using a solvent consisting of 100 g oxalic acid and 900 ml distilled water for 120 min. The broken oxide layer and dense interconnected nest-like corrosion products (including the oxides and salts) are found at the crack propagation region in Fig. 8(d), which are similar to the observations for smooth specimens in Fig. 5. Fig. 9 compares the long crack growth in air and 3.5 wt% NaCl solution.

The classical Paris equation $d a/d N = C \cdot (\Delta K)^m$ is adopted in Fig. 9, where $C$ and $m$ are the fitting parameters. In our case, we have log$C = -11.18$ and $m = 2.78$ in air, and log$C = -10.94$ and $m = 2.84$ in 3.5 wt% NaCl solution. The long crack growth rate in NaCl...
solution is slightly higher than that in air. It is indicated that the corrosive environment has a detrimental effect on the crack propagation. Therefore, the degraded fatigue strength of the scratched specimens tested in NaCl solution may be attributed to the fact that the environment facilitates crack nucleation and crack propagation.

Fig. 8. Typical fracture surfaces of an artificially scratched specimen with total cycles 755,200 to the failure) having a scratch depth of 140 μm tested in 3.5 wt% NaCl solution: (a) full view of the fracture surface showing the crack stable propagation region and the catastrophic static fracture region marked with green and yellow dotted lines, respectively, (b) crack nucleation site, (c) secondary cracks and (d) oxide cracks.

Fig. 9. Fatigue crack growth rate data tested in air and 3.5 wt% NaCl solution alongside the fitted Paris curves based on measured data.
4. Defect-tolerant fatigue diagram

4.1. In-air fatigue safe-life assessment

Railway axles are usually operated over a service life of more than 30 years and are subjected to an extremely high number of loading cycles ($\sim 6 \times 10^9$ or more) [2]. However, any surface scratches accidentally introduced during maintenance and applications can degrade the fatigue resistance of railway axles. It is therefore critical to quantify the influence of scratch depth on the fatigue strength of railway axles for the safe-life design and defect assessment.

The classical Kitagawa-Takahashi diagram is widely used for describing the variation in fatigue limit with defect size. The KT diagram of railway EA4T steel is represented by a horizontal line and a slanting line, as denoted by the solid blue lines in Fig. 10.

The horizontal line exhibits the fatigue limit range of smooth surface specimens, $\Delta \sigma_{th0}$. Here, the conditional fatigue limit range corresponding to $5 \times 10^7$ cycles in Fig. 3 is adopted and $\Delta \sigma_{th0} = 652 \text{ MPa}$. The slanting line in the KT diagram describes threshold stress range, $\Delta \sigma_{th}$, as a function of scratch depth, $a$ [7,29–31]:

$$\Delta \sigma_{th} = \frac{\Delta K_{thL}}{Y\sqrt{\pi \text{area}}}$$

(6)

$$\sqrt{\text{area}} = \sqrt{10 \cdot a}$$

(7)

$$\Delta \sigma_{th} = \frac{\Delta K_{thL}}{Y\sqrt{\frac{\pi}{a}}}$$

(8)

where $\sqrt{\text{area}}$ is the Murakami parameter, which is defined as the square root of the projected area of the scratch vertical to the loading direction [7]. $Y$ is the geometric factor and $Y = 0.65$ in the case of surface defects [7]. The threshold stress intensity factor range for long crack propagation, $\Delta K_{thL}$, is determined by the FCG rate testing, as shown in Fig. 11. Here, $\Delta K_{thL} = 15 \text{ MPa} \sqrt{\text{m}}$.

A critical safe scratch depth of approximately 125 $\mu$m is defined by the intersection of the slanting and horizontal lines in Fig. 10. Scratches smaller than the critical value would not be expected to have a negative influence on the fatigue limit of the material. The fatigue limit of the specimens with these defects is similar to that of the defect-free material. Conversely, fatigue performance is increasingly degraded with increasing scratch depth. A safe-life region corresponding to fatigue life of $5 \times 10^7$ cycles is bordered by the horizontal and slanting lines. Conventionally specimens within this region would have a fatigue life of $5 \times 10^7$ cycles and defects within this region are defined as the safe defects, which is consistent with previous investigations [32]. To verify the validity of the safe-life region, the failure and runout data collected from Fig. 6 and the reference [5] are plotted in Fig. 10. It is found that some failed specimens with the fatigue life less than $10^7$ cycles are located within the safe-life region defined by the original KT model indicating that the classical KT diagram is non-conservative for the evaluation of a safe-life regime and safe scratch depth of railway axle EA4T steel.

The classical KT model has been modified by El-Haddad [14] by introducing an intrinsic defect size $a_0$:

$$\Delta \sigma_{th} = \frac{\Delta K_{thL}}{Y\sqrt{\pi (a + a_0)}}$$

(9)

Numerically, $a_0$ equals the critical safe scratch depth in Fig. 10 and can be estimated by:

$$a_0 = \frac{1}{\pi} \left( \frac{\Delta K_{thL}}{\sqrt{\Delta \sigma_{th0}}} \right)^2$$

(10)

Fig. 10. Comparison of the original KT and improved model proposed by El-Haddad, alongside failure and runout data for tests undertaken in air.
The KT diagram modified by the El-Haddad model is also plotted in Fig. 10, as denoted by the dash-dot green lines. With this reformulation, the safe-life regime becomes smaller such that all the failed specimens lie outside this region. It is noteworthy the fatigue limit decreases with the increasing scratch depth. The El-Haddad model indicates that even a small scratch can still reduce the fatigue limit of the material and there is no critical safe scratch depth, which is questionable since in the case of defects smaller than the surrounding microstructure, the failure originates predominantly from the structural features [33,34].

Short cracks can benefit from locally well oriented structure and they have not built up the full level of closure. These effects allow crack growth in a regime which would not normally allow it. The crack resistance increases with increasing length, and threshold value \( \Delta K_{th} \) increases from an effective threshold \( \Delta K_{th, eff} \) to that for a long crack \( \Delta K_{th, L} \) [35,36]. A new critical scratch depth can be defined according to Chapetti model, as formulated below [37]:

\[
a_{\text{eff}} = \frac{1}{\pi} \left( \frac{\Delta K_{th, eff}}{\Delta \sigma_{th0}} \right)^2
\]

\[
\Delta K_{th, eff} \approx \chi \cdot 10^{-2} \cdot E
\]

where \( \chi \) is a correlation factor (\( \chi = 1.64 \) [38]). \( E \) is the Young’s moduli and \( E = 209 \) GPa. The value of \( \Delta K_{th, eff} \) according to Eq. (12) is 3.43 MPa \( \cdot \sqrt{m} \), which is in a reasonable agreement with the experimental result of 3.0 MPa \( \cdot \sqrt{m} \) [16].

According to the Chapetti model, the estimated critical scratch depth dramatically reduces from \( \approx 125 \) \( \mu \)m (KT model) to \( \approx 7 \) \( \mu \)m, which is similar to the average grain size (7.2 \( \mu \)m) of railway EA4T steel. The surface damage has been carefully quantified for 46 in-service railway axles. Around 90% of the scratches are deeper than the critical size of \( \approx 7 \) \( \mu \)m [5]. Consequently, the above analysis suggests that these scratches will have significantly lowered the fatigue strength of railway axles. In practice, this effect could potentially be mitigated, for example, by introducing near-surface compressive residual stresses [39].

### 4.2. Probabilistic corrosion-fatigue analysis

In view of the sensitivity of fatigue to the corrosive environment observed in Fig. 3, it is important to assess the degree to which corrosion alters the modified KT response. However, this presents a challenge because the corrosive medium appears to eliminate the fatigue limit (the disappearance of the knee-point of fatigue S-N curve [10]). Therefore, a theoretical fatigue limit based on a low probability event is adopted in this study [18].

The definition of a low probability event needs to be clarified. For the PDD of fatigue life under a given stress amplitude, as the peak value of the probability density curve \( f(x|S)_{\text{max}} \) tends to be 0, the probability that \( x \) falls within the finite interval \( \Delta x = x_2 - x_1 \) will always be \( P(x_1 \leq x < x_2) = \int_{x_1}^{x_2} f(x|S)dx \to 0 \). Such an event has a low probability. Fig. 4 indicates that the peak value of the probability density (i.e., the probability of the most likely fatigue life) decreases as the stress amplitude decreases. Supposing \( f(x|S)_{\text{max}} \) is small enough, the failure would not occur. The theoretical fatigue limit can be then determined to be the stress amplitude when the fatigue failure is a low probability event.

The statistical corrosion-fatigue life under 3.5 wt% NaCl solution has been assessed by means of the CPDF (see Section 3.1). Here, the peak probability occurs when the logarithm of fatigue life \( x \) equals the mean value \( \bar{x}(S) \), i.e., \( x = \bar{x}(S) \):

\[
f(x|S)_{\text{max}} = \frac{1}{\sigma(S) \sqrt{2\pi}}
\]

It is clear that \( f(x|S)_{\text{max}} \) varies with the stress amplitude because the peak value, the stress amplitude and the standard deviation are coupled. If the hatched area enclosed by the probability density curve \( f(x|S) \) and interval \( \Delta x \) is very small, both the peak value \( f(x) \)
$S_{\text{max}}$ and the stress amplitude $S$ are small whereas the standard deviation $\sigma(S)$ is large. Correspondingly, an extremely small $P(x_1 < x < x_2) = \int_{x_1}^{x_2} f(x|S)\,dx$ corresponds to a low probability event and can be determined by the infinite scatter in lifetime $\sigma(S) \to \infty$. According to Table 1, the relationship between $\sigma(S)$ and $S$ is fitted to Eq. (3) as below:

$$\sigma(S) = (3.272 \times 10^{-2} \cdot S - 4.5914)^{-1}$$

(14)

Thus, the theoretical fatigue limit of EA4T steel in NaCl solution is approximately determined as 140 MPa from Eq. (14). This method of determining the fatigue limit makes full use of the failed specimens and is not restricted by the runout limit, such as $10^7$ cycles. The El-Haddad model modified KT corrosion-fatigue diagram of EA4T steel is plotted in Fig. 12 by using the theoretical fatigue limit of 140 MPa.

It is clearly observed from Fig. 12 that the safe-life region becomes much smaller or narrower in the corrosive environment due to the reduction in the fatigue limit from 326 MPa (air) to 140 MPa (corrosion) and the threshold limit of 140 MPa. The El-Haddad based Kitagawa-Takahashi diagrams were constructed for the fatigue strength design and defect assessment for air and corrosive environment. The following conclusions can be drawn:

5. Conclusions

The effects of environment and surface scratches were investigated on the fatigue properties of modern railway axle EA4T steel. Rotating bending fatigue testing was conducted using both smooth and scratched specimens in air and 3.5 wt% NaCl solution. Within the framework of a defect-tolerant methodology, El-Haddad based Kitagawa-Takahashi diagrams were constructed for the fatigue strength design and defect assessment for air and corrosive environment. The following conclusions can be drawn:

(1) The EA4T steel is markedly sensitive to the chloride-containing environment. The corrosive environment accelerates failure at stresses two thirds of the in-air fatigue limit (+/−326 MPa) of EA4T steel. A conditional probability density function can be adopted for the statistical assessment of corrosion-fatigue life.

(2) The fatigue strength and life gradually decrease for the specimens scratched to depths from 500 μm to 300 μm to 100 μm. For the specimens scratched to a depth of 500 μm, the corrosive environment can induce failure at a stress less than one third of the in-air fatigue limit (+/−320 MPa).

(3) The environmentally induced cracks tend to initiate from localized corrosion pits for smooth surface specimens. However, no corrosion pits are observed at the crack nucleation sites for scratched specimens and the environment facilitates crack nucleation without pitting. The fracture surfaces are depicted by the crack initiation from multiple sources and intergranular cracking for both conditions.

(4) The classical KT diagram provides a non-conservative estimation of the safe-life region because most failed specimens are located inside. The safe-life region becomes smaller based on a KT diagram improved by the El-Haddad model, which considers the short crack growth behavior.
(5) Based on the Chapetti model, the critical safe scratch depth of EA4T steel in air decreases from approximately 125 µm to 7 µm, which is similar to the average grain size of EA4T steel. Scratches smaller than the critical safe scratch depth would not be expected to show a negative impact on the fatigue limit.

(6) The theoretical fatigue limit of +/−140 MPa based on a low probability event is adopted for corrosion-fatigue assessment, which is significantly less than +/−326 MPa in air. Although this is only a theoretical estimation, this value can be used for the modified KT diagram and to draw conclusions about the effect of defect size on the fatigue performance in corrosive environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


