Engineering Fracture Mechanics 131 (2014) 587–601

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

An investigation about the influence of deep rolling on fatigue crack growth in railway axles made of a medium strength steel

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ARTICLE INFO

Article history:
Received 17 December 2013
Received in revised form 1 August 2014
Accepted 29 September 2014
Available online 7 October 2014

Keywords:
Railway axles
EA4T
Deep-rolling
Crack propagation
Residual stresses

ABSTRACT

Over the last years, deep rolling has been adopted to improve the fatigue strength of railway axles, but very few scientific analyses and studies of this phenomenon are available in the literature. For this reason, the present research investigates some aspects related to the influence of this technological process on fatigue crack growth in railway axles made of EA4T steel grade.

Firstly, special full-scale specimens were prepared applying the industrial deep-rolling process. The measurement of the resulting compressive residual stress field was then performed by X-ray diffraction and prompted an experimental crack growth campaign, on small-scale SE(B) and SE(T) specimens, to investigate the behavior of the material at very negative stress ratios.

Crack growth tests were then carried out on full-scale specimens and the results successfully compared to those obtained by a simple no interaction predictive model built up considering both the characterized behavior of the material and the measured residual stress field.

1. Introduction

Railway axles are usually designed against the fatigue limit [1,2], but, due to their very long service life (30 years or 10^7 km) and to in-service damages like corrosion [3,4] or ballast impacts [5], the traditional design is complemented by a damage tolerant approach [6–8]. From this point of view, the presence of cracks in running axles is accepted and they must be periodically inspected by non-destructive testing (NDT) methods. The problem so switches to the determination of the appropriate inspection interval, based on crack growth life predictions and the adopted non-destructive testing technique [9]. Usually, a 2 mm deep initial defect, which corresponds to a conservative assumption for the damage induced by ballast hits [5], is adopted. Simulations of crack propagation are then performed, based on the knowledge of several factors as the crack propagation behavior of the material, the in-service loads acting on the component and the stress intensity factor (SIF) of the considered geometries. After the estimation of crack growth life, the inspection interval is defined by calculating the failure probability of the axle starting from the ‘‘Probability of Detection’’ (POD) curve of the adopted NDT method [10] (an alternative method is to define the NDT specifications for a chosen length of the inspection interval [11]).

Considering the possible methods to improve crack growth life of mechanical components subjected to fatigue, several surface mechanical procedures have been more and more adopted [12–15], over the last few decades, to increase their

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http://dx.doi.org/10.1016/j.engfracmech.2014.09.016
0013-7944/

Nomenclature

a	crack depth
a_0	initial crack depth
c	surface semi-crack length
c_0	initial surface semi-crack length
A–D	parameters of the Shiratori weight function
K_0–K_3	contributions to the SIF due to the ith polynomial approximation
K_I	mode I SIF
M	dimensionless SIF
R	stress ratio
t	thickness of the plate
Δa	crack depth increment
Δc	surface semi-crack length increment
ΔK	SIF range
ΔK_{max}	maximum SIF range applied at the beginning of a given test and corresponding to the highest stress level of the stress spectrum
ΔK_{th}	threshold SIF range
Φ	elliptical integral for the Shiratori weight function
σ_0	nominal stress
σ_{max}	maximum stress level of the load spectrum

service durability and reliability. Nevertheless, while some scientific analyses were recently dedicated to the investigation of the beneficial effects of compressive residual stresses onto fatigue life [16–19] and crack propagation [20–24] in specimens made of aluminum and steel, no investigations were found in the literature about the effects of deep rolling onto fatigue crack propagation in real components. Since deep rolling is the technological process traditionally adopted by axle producers, and the damage tolerant approach is the design methodology, the focus was here pointed onto this particular procedure for life extension of railway axles. Deep rolling [25] is basically performed pressing a roller against the rotating axle and applying a certain amount of pressure in order to induce plastic deformation at the surface and, consequently, the compressive residual stresses. The roller translates along the whole surface of the axle or just along those regions where compressive residual stresses are required. The relevant technological parameters, depending on the desired magnitude of residual stresses and their maximum depth, are the geometry of the roller at the contact region, the longitudinal feed (i.e. the step of advancement along the axle) and the applied contact force [25].

In order to deepen the subject, the MARAXIL ("Manufacturing Railway Axles With Improved Lifetime") Project, supported by Regione Lombardia (Italy) [26], was launched in order to experimentally and theoretically investigate the effect of deep-rolling onto the in-service life of railway axles made of EA4T steel, one of the standardized grades [1,2] for the production of axles.

Compressive residual stresses, in addition to the typical rotating bending stress state, modify the in-service stress ratio of axles from the typical value ($R = -1$) to the very negative region ($R = 10$ or even below). For this reason, the crack propagation behavior of the material, in the unexplored region of the very negative stress ratios, was firstly experimentally characterized.

In order to verify the enhancement in propagation lifetime, full-scale specimens were designed for variable amplitude (VA) crack propagation tests on a test bench with a 250 kNm capacity: three full-scale crack growth tests were performed considering different initial notch depths.

Full-scale experimental results were compared to simulated predictions carried out by a crack propagation algorithm, where residual stresses were superimposed to bending ones and crack growth rate was modeled by Nasgro's propagation equation [27].

2. Characterization of the material to crack propagation

The material considered in this study is the EA4T (quenched and tempered 25CrMo4) steel grade, one of the standardized steels used for the production of railway axles [28] running in Europe.

Due to the superposition of the very high compressive residual stresses, expected as the consequence of the deep-rolling technological process, and the stresses due to the in-service rotating bending, the stress ratio acting at the surface of the axle will be different, in particular much lower, than the typical $R = -1$ value due to rotating bending alone. From this point of view, a dedicated experimental campaign was carried out, in order to investigate the crack propagation behavior of the A4T grade in the not-yet-explored region of very negative stress ratios. In particular, two different shapes of specimen were tested: