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An experimental approach to determining the residual lifetimes of wheelset axles on a full-scale wheel-rail roller test rig

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ABSTRACT

The paper describes an experimental method for determining the residual lifetime of wheelset axles which was developed and proved. The procedure includes all necessary steps: crack initiation from an artificially generated surface defect, monitoring of crack growth, and specification of the end-of-test criterion. The crack propagation tests described in this paper were carried out on a complete wheelset that was installed on a full-scale wheel-rail roller test rig using a measured load spectrum. During both the test planning and test implementation phases, considerable attention was paid to the complex processes involved in crack propagation in wheelset axles. In addition to axle material and design issues, important factors that have to be taken into account include sequence effects, the reliability of load cycle omission strategies to reduce the overall duration of testing, static stresses introduced by press-fitting procedures and residual stresses caused by manufacturing processes, and crack closure effects. The results obtained indicate that the method produces reliable results that are of practical relevance. Examples were also presented that indicated how far experimentally determined residual axle lifetimes could still differ from lifetimes calculated using current fracture mechanics modelling techniques.

1. Introduction

On 9 July 2008, the axle shaft on a driving wheelset of an ICE3 multiple unit fractured as the train was leaving Cologne Central Station causing the vehicle to derail. As a result of the accident, the inspection intervals between ultrasonic testing (UT intervals) were significantly shortened for ICE3 axles. Prior to the accident, powered axles from the first production series manufactured from the higher-strength quenched and tempered (QT) steel 34CrNiMo6 were inspected every 300,000 km; after the accident, the inspection interval was reduced to 30,000 km. The inspection intervals for powered axles from the second production series and for unpowered axles, both of which are fabricated from EA4T grade axle steel (25CrMo4 QT), were shortened from 300,000 km to 60,000 km, as neither axle type had shown any irregularities while in service.

The principal issue that arose after the accident was how axle inspection intervals should be specified. Clearly, inspection intervals have to be sufficiently short so as to prevent an axle failure. However, other factors also have to be taken into account when stipulating axle inspection intervals, such as their effect on the vehicle system as a whole, on vehicle availability and on the overall life cycle costs of a wheelset.

Previously, the inspection intervals used throughout the European rail sector were specified mainly on the basis of operating experience. Even today, there is no national or international standard that establishes a recommended procedure for stipulating axle inspection intervals. Establishing a verifiable quantitative procedure for determining residual axle lifetimes is still the subject of scientific study [e.g. 1,2]. This may well be a reflection of the fact that some of the factors and time-dependent mechanisms that influence crack growth in train axles are still not sufficiently well understood or sufficiently well quantified. However, this knowledge represents the basis on which inspection or testing intervals are specified. The objective is to express the residual lifetime as accurately as possible in terms of either number of stress cycles or kilometric performance, i.e. how long an axle with a propagatable incipient crack of length $2c_{th}$ or depth a_{th} will last until the crack has reached the critical dimensions (a_{crit}, $2c_{crit}$) at which residual (forced) fracture under load can occur (see Fig. 1). Factors affecting crack initiation are not considered.

Uncertainty regarding such elements as the actual load spectrum acting over the entire service life of a train axle, or regarding material behaviour, residual stresses, environmental factors and the occurrence of crack closure effects means that it is still very

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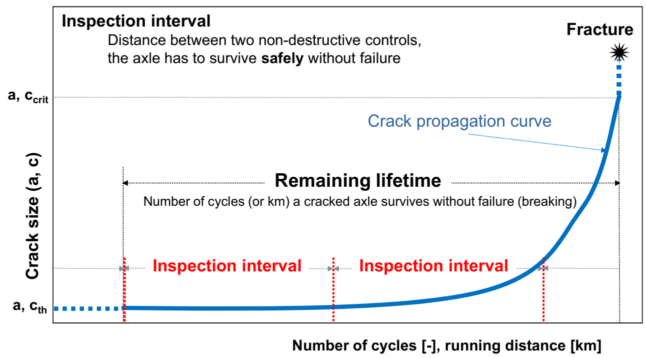

Fig. 1. Schematic plot showing residual axle lifetime and inspection intervals.

difficult to perform a "mechanistic modelling" that underlies any quantitative determination of the residual axle lifetime for a particular vehicle. If a parameter is not known with sufficient accuracy, a conservative estimate will generally be made of its magnitude, which can result in very short calculated residual lifetimes. If the residual lifetime calculated in this manner is further decreased by dividing by a given safety factor and this factor is comparably high (in an effort to accommodate the possibility that non-destructive testing may fail to detect the crack), the resulting inspection intervals will be of little practical use.

This paper presents the results of experimental determinations of the residual lifetimes of train axles that have been conducted since 2006 using full-scale testing on a wheel-rail test rig.

2. Axle cracks and fractures – what has been learnt from damage analyses

In Europe, the occurrence of cracks or fractures in wheelset axles is an extremely rare event relative to the total number of vehicles in service. This is plausible as axles have for decades been designed and dimensioned in accordance with a set of uniform European standards [3–5]. The part of the axle that is subjected to the greatest stress is generally that at which there is a change in the axle cross-section from the main axle shaft to the wheel seat (the "transition radius"). If the requirements of the standards [3–5] are met, cracks will therefore not occur on the undamaged (smooth) surface of the shaft. For cracks to appear, there must be a significant increase in local stresses in those cross-sectional zones subjected to the greatest stresses. These large increases in stress are caused by the presence of surface defects or flaws from which incipient fatigue cracks can arise.

As investigations and analyses of cracked and fractured wheelset axles for a variety of German and European clients have shown that besides engineering design deficiencies, axle corrosion is by far the most common cause of the surface defects that lead to the formation of fatigue cracks, particularly corrosion occurring at the transition radius (due, for example, to inadequate adhesion of the paint applied during wheelset manufacture or maintenance). Particularly in highly stressed axles made from higher-strength QT steels (42CrMo4, 34CrNiMo6, 30NiCrMoV12), incipient cracks often occured as conventional corrosion fatigue cracking. At a more advanced stage of crack growth (crack depth of several millimetres), crack propagation was shown to be driven by a purely mechanical mechanism [6]. The next most common cause of surface defects or flaws is flying ballast, frequently accompanied by corrosion that arises because of the localised damage to the protective coating on the axle surface. Surface flaws caused by martensitic transformations induced by arcing in the axle shaft (due to a faulty traction current return path) are increasingly becoming a thing of the past. Finally, fatigue cracks can also arise from surface roughening at the wheel seat due to fretting corrosion. These findings agree well with those of other authors in the field [1,7].

In the light of these findings, if crack propagation studies are to be carried out on full-scale axles, artificial surface defects in the form of notches have to be machined into the axle at the most highly stressed locations on the axle surface known from calculations and/or at those crack initiation locations identified in practice. This allows cracks to form and grow under controlled conditions in order to be able to determine their residual lifetimes (Fig. 1).

3. Determining the residual service life of axles on a wheel-rail roller test rig

Most of the results presented here were acquired from studying powered axles made from 34CrNiMo6 steel and unpowered axles made from EA4T. The mechanical properties are given in Table 1.

The individual steps in the investigation are described below for the case of an unpowered axle.

3.1. Preparing the test axles

In order to maximise the information obtained from each of the time-consuming bench tests, not one but two semi-elliptical notches are machined into opposite sides of the axle (angular displacement: 180°) on the section of the axle that is subjected to the highest stresses. Each test therefore generates two residual lifetime plots.

The semi-elliptical notch has an aspect ratio a/c of 0.8, which in experience from own fracture surface investigations of broken axles is the average a/c ratio found at least at and a few millimetres under surface. The notch was machined into the surface using a spark erosion technique.

The maximum stress in the notch plane (i.e. in the axle cross-section subjected to the greatest load) is the resultant of the maximum bending moment, the rise in stress due to the change in the axle cross-section (form factor) and the mean stresses arising from the press-fitted wheel. Both axle types (powered, and non-powered) had the same diameter in the highest stressed cross-section.

In order to determine a residual axle lifetime, an initial crack depth a_{th} (Fig. 1) must be specified, and this is best expressed in terms of a fault parameter that can be reliably detected by the chosen inspection method. At the ICE maintenance depots, the automated ultrasonic testing facilities for inspecting axles with drilled shafts can reliably detect faults with a depth of 2 mm. An initial crack depth of 2 mm was therefore selected. However, before the actual crack propagation test can be carried out an incipient crack that begins at the base of the notch and that can be detected by means of non-destructive testing methods has to be initiated. The notch depth was therefore chosen to be as small as 1.2 mm (e.g. a notch length of 3.9 mm) so that after crack initiation a fatigue crack front extending to a depth of 2 mm was achieved (see Fig. 2).

Table 1
Mechanical properties of test axle materials.

Steel grade	Standard	Yield strength, MPa	Tensile strength, MPa	Elongation, %
EA4T = 25CrMo4	EN 13261	⩾420	650–800	⩾18
34CrNiMo6	EN 10083-3	⩾700	900–1100	⩾12