Fracture Mechanics Assessment of Railway Axles Based on Experimental and Computational Investigations

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Abstract. In this paper the results of the ongoing joint research project - Safe and Economic Operation of Running Gears - aiming at developing validated fracture mechanics assessment procedures for railway axles are presented. The paper includes material characterisation for the commonly used axle steel 25CrMo4 (A4T) and the high strength steel 34CrNiMo6. Fatigue crack growth parameters are experimentally determined both in the range of stable crack propagation and near the threshold. The results are employed for predicting fatigue crack growth for cracks initiating at the axle shaft. For the computational modelling of fatigue crack propagation a generally applicable solution for stress intensity factors has been derived. Furthermore, the influence of variable amplitude loading (block loading) on the crack propagation behaviour has been studied and is discussed. The computational results are compared with experimental data determined on standard fracture mechanics specimens as well as down-scaled and geometrically similar axle specimens.

Introduction

Railway axles are safety relevant components designed for infinite life. However, in a technical system the initiation of damage due to corrosion or ballast impact can't be completely avoided. It is a common practice to withdraw railway axles from operating service if a defect or crack has been detected by visual inspection or NDT techniques. In such a case fracture mechanics tools can be reasonably applied to assess inspection intervals for identically constructed axles. The overall goal of this project is to contribute to further improvements of technical standards based on validated experimental and theoretical analyses; see also [1-3].

In Fig. 1 the main modules of the fracture mechanics assessment concept - material data describing fatigue crack growth behaviour, loading state and defect model - are schematically shown. For the following analyses a railway axle which largely matches the service conditions of a solid leading trailer axle, as they are used for commuter trains with speeds up to 160 km/h, is chosen. The axle cross section to be evaluated is the shaft (cylindrical axle section). However, the same methodology may be applied to fillets (transition radii, e.g. of the inner wheel press fit to the free axle surface).

During service railway axles are subjected to rotating bending. To calculate crack propagation, the stress state in the crack free component cross sections were determined by FE analyses. At shaft positions these stresses are distributed linearly with respect to the axle cross section, whereas the stress distributions at the position of the fillets are non linear (as indicated in Fig. 2). As an appropriate crack model, a semi-elliptical surface crack is considered. The fatigue crack propagation can be calculated using numerically or analytically determined stress intensity factors, as well as experimentally measured crack growth rates. Unfortunately, validated material data and generally applicable stress intensity factor solutions are hardly available in the literature. A particular aim of the project is therefore to create a defined reference case together with a validated data base. The achieved results are introduced in the following sections.

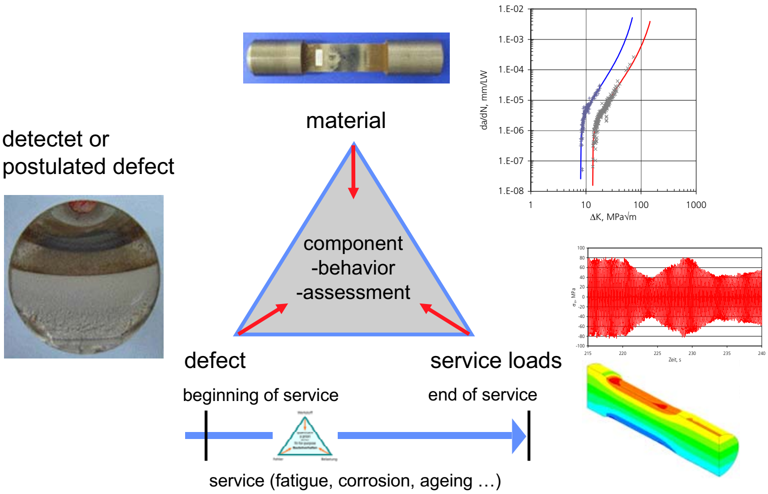


Figure 1: Fracture mechanics assessment concept.

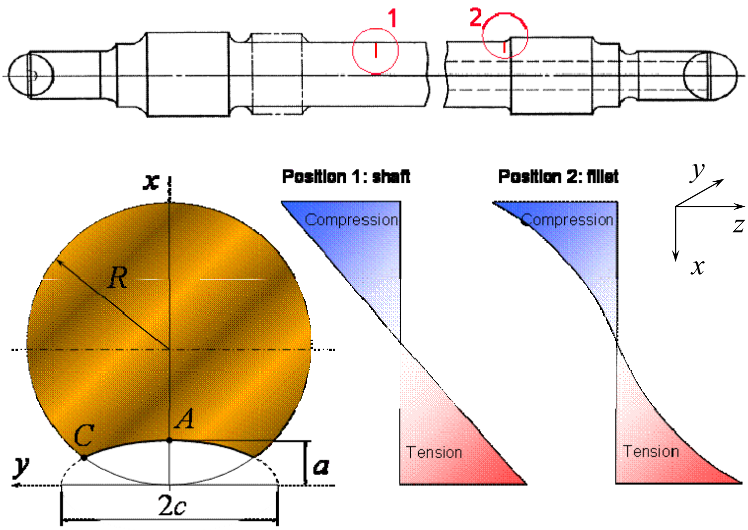


Figure 2: Schematic representation of the reference axle and stress distribution at selected cross-sections.

Fracture Mechanics Material Characterization under Constant Amplitude Loading

The widely used quenched and tempered steel 25CrMo4 (A4T) and the high strength steel 34CrNiMo6 were chosen as materials for the reference case. For the fracture mechanics characterization, M(T) specimens were machined from full scale railway axles. Crack propagation tests were performed under fully reversed tension/compression loading (stress ratio of $R = -1$, analogous to the shaft loading during service) and in the tension regime at a stress ratio of $R = 0.1$. The cross-section of the M(T) specimens tested was 24 mm x 10 mm. Due to the applied reversed loading the M(T) specimens had to be dimensioned to exhibit a sufficient stiffness, thus avoid bending effects during testing. This was monitored via strain gauges applied to the front and back surfaces of the specimens. The starter notches were machined by means of wire-cut EDM (electrodischarge machining). The testing and evaluation has been performed according to ASTM E647-05 [4]. Further details about the specimen geometry and the testing procedure are given in [5].

The determined crack propagation rates da/dN for both axle materials (25CrMo4 and 34CrNiMo6) are shown in Fig. 3 as a function of the stress intensity range, ΔK. Note, that the full range of the stress intensity factor $\Delta K = K_{max} - K_{min}$ is considered.

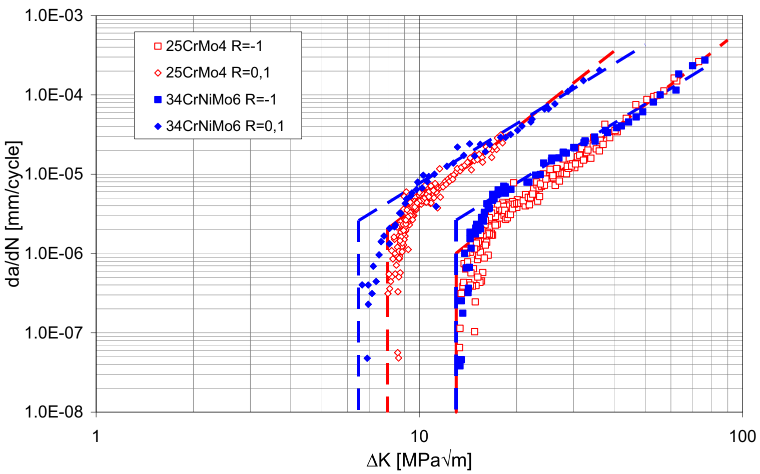


Figure 3: Comparison of crack propagation data of 25CrMo4 and 34CrNiMo6 at R=-1 and R=0.1.

All curves represent the results of several specimen tests. The parameters C and m of the Paris-Erdogan law, $da/dN = C \cdot \Delta K^m$, were determined based on the data within the linear range of the curve. In case of the material 25CrMo4 the 50% mean value of all measured data point above $da/dN \geq 3 \cdot 10^{-6}$ mm per load cycle have been considered, whereas for the material 34CrNiMo6 the limit of $da/dN \geq 6 \cdot 10^{-6}$ mm per load cycle was chosen.

The threshold value ΔK_{th} was estimated using data corresponding to the crack growth rates between 10^{-7} and 10^{-6} mm/cycle. Here the limit lines represent a linear fit with respect to the envelope values. The threshold value ΔK_{th} is determined as the intersection of this linear fit with the da/dN value of 10^{-7} mm/cycle. All derived fracture mechanics parameters are summarized in Table 1.

The crack propagation curves of the axle materials 25CrMo4 ($R_{P0,2} \approx 550$ MPa) and 34CrNiMo6 ($R_{P0,2} \approx 950$ MPa) show relatively small differences. However, in the regime of moderate ΔK-values, which are relevant for the assessment under service conditions, higher crack growth rates were determined for the high strength steel. The scatter of the ΔK-values is larger for 25CrMo4.

material	stress ratio R	C	m	ΔK_{th} [MPa√m]
25CrMo4 (A4T)	-1	2.74E-10	3.2	13
34CrNiMo6	-1	4.32E-09	2.5	13
25CrMo4 (A4T)	0.1	2.65E-09	3.2	7.5
34CrNiMo6	0.1	2.42E-08	2.5	6.5

ΔK in MPa√m, da/dN in mm/cycle

Table 1: Material properties for the axle steels 25CrMo4 and 34CrNiMo6.

Validation Tests under Constant Amplitude Loading

In order to analyse the transferability of the crack propagation behaviour determined on M(T) specimens to full scale railway axles subjected to service loading a sequence of validation steps are foreseen during the course of the ongoing project. The idea is to stepwise increase the complexity of the geometry and the applied loads and thus to apply the analysis tools for cracks at arbitrary locations in the axle. The influences of the geometry are investigated by testing component-like specimens with a scale of 1:3 and 1:1, respectively. The effect of loading modes e.g. in-plane and rotating bending is quantified by means of numerical analyses [5]. Finally, the effect of variable amplitudes are to be investigated using M(T) and component-like specimens.

To determine the geometry of the scaled specimens the radial stress distribution of the reference full size axle was analysed in the cross section of interest. With this knowledge specimens with a scale of 1:3 and 1:1 were designed. The hub diameter of the 1:3 scale specimens is 60 mm, whereas the full size examples have a diameter of 160 mm. The hub to shaft diameter ratio D/d was kept constant at 1.156. The radius combination of R15/R75 was also adopted and it was ensured that the position of the maximum stress and the stress gradients in axial direction were identical to the full-size counterpart. A near identical distribution of the first principal stress is crucial for similar crack growth behaviour, as this stress causes the opening and closing of the crack in mode I, which is the predominant mode for the crack propagation in axles. The 1:3 scale specimens are tested under in-plane and rotating bending and the full size specimens are tested under in-plane bending loading.

In Fig. 4 propagation rates derived from tests of scale 1:3 component-like specimens are shown as a function of ΔK. The left curve represents the crack propagation behaviour determined on M(T) specimens, as already given in Fig. 3 for the 25CrMo4 material, R = -1. The data determined for the scale 1:3 specimens exhibit a pronounced scatter. This can be attributed to the fact that the measurement of the crack depth growth is more difficult in the case of the scale 1:3 specimens. Namely, beach marks which have been produced by decreasing the stress amplitudes were difficult to identify. Moreover, it was difficult to assign the crack length visual at the surface to the corresponding crack depths.

A comparison of the linear regression of the M(T) data and the scale 1:3 data shows that for the component-like specimens lower crack propagation rates have been determined. This difference is currently being analysed. In particular, the stress distribution in the crack plane has to be reanalysed considering the real boundary conditions in the test rig. Apparently, the M(T) curve represents a conservative limit with respect to the crack propagation behaviour of the scale 1:3 specimens. Further tests at lower ΔK values will be performed to confirm this trend in the service relevant regime.

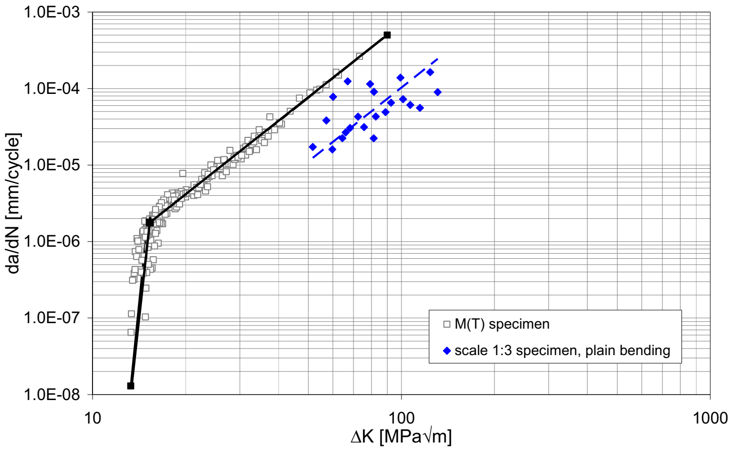
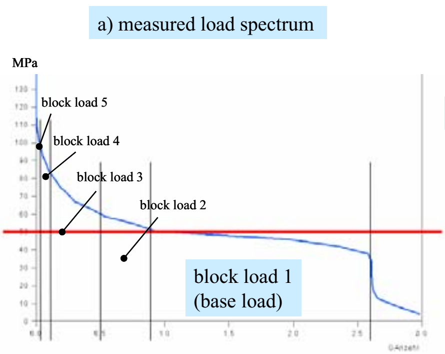


Figure 4: Comparison of crack propagation rates determined for M(T)-specimens and scale 1:3 component-like specimens under fully reversed loading, R = -1.

Crack Growth Rates Determined under Variable Amplitude Loading

During service railway axles are subjected to characteristic variable amplitude loading sequences which have to be taken into account. Following the fracture mechanics concept depicted in Fig. 1 extensive field tests have been performed in cooperation with Deutsche Bahn AG. Stress-time histories were determined via strain gauge measurements at selected positions of the reference wheelset axle. From the measured data specific load spectra could be derived as a function of typical operational modes. In Fig. 5 an extrapolated load spectrum, covering 30 years of service, which has been calculated with the assumption of 260000 km service per year is shown. The evaluated measuring position was situated in the shaft region of the axle. For a transfer to lab tests the load spectrum was divided into 5 different block loads (the base load and 4 differently high overload blocks). Based on the five block loads the *reduced* block load spectrum shown in Fig. 6 was derived keeping constant the portions and the overload ratios of the *original* block loads. Thus, the complete number of load cycles per block was reduced to 26000 km. The reduced block load spectrum was used for M(T) specimen tests.



b) *derived* load block spectrum

	block load ratio	cycles absolut	cycles in %
block load 1	1.0 (base load)	1.7E+09	65.4
block load 2	1.2	4.0E+08	15.4
block load 3	1.7	4.0E+08	15.4
block load 4	2.2	9.0E+07	3.4
block load 5	2.8	1.0E+07	0.4
		2.6E+09	100.0

Figure 5: Measured load and *derived* load block spectrum.

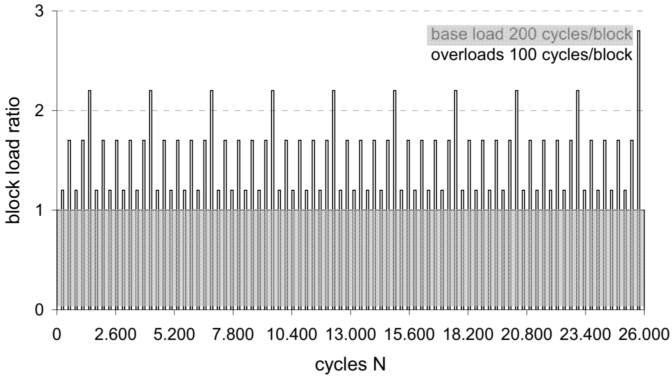


Figure 6: *Reduced* block load spectrum.

In Fig. 7 measured and calculated crack propagation curves of both materials are shown as a function of load cycles. The experimental data is represented by symbols whereas for the calculated results lines have been chosen. No load-interaction effects were considered in the analytical calculation. All M(T) specimen tests started with a crack depth of 3 mm. Tests with two different base load levels have been performed. As a first base load level $\Delta F = 28.8$ kN ($F = \pm 14.4$ kN) was chosen, which corresponds to the stress intensity range $\Delta K = 12$ MP$\sqrt{}$m and a net section stress of $\Delta\sigma = 120$ MPa. The other base load level was higher and was defined to be $\Delta F = 48$ kN ($F = \pm 24$ kN), which corresponds to the stress intensity range $\Delta K = 20$ MP$\sqrt{}$m and a net section stress of $\Delta\sigma = 200$ MPa. In both cases relatively high net section stress levels were selected to achieve all data points within the Paris range of the fatigue crack growth curve.

A comparison of the experimental and computational results at the base load level of $\Delta F = 28.8$ kN ($F = \pm 14.4$ kN) shows that the calculated curves significantly underestimate the test data. The difference is more pronounced for the material 34CrNiMo6 (factor of appr. 2.5) than for 25CrMo4 (factor of appr. 1.5). This can be attributed to the fact that a linear-elastic crack propagation approach has been applied which doesn't account for crack closure and load sequence effects. Nevertheless, the calculated results can be interpreted as a conservative estimation of the crack growth behaviour.

At the higher base load level of $\Delta F = 48$ kN the material 34CrNiMo exhibits a similar behaviour. However, the extent by which the experimental data is underestimated by the computational results is reduced to a factor of 1.8. A qualitative change in behaviour was observed for 25CrMo4. Here the calculated curve slightly overestimates the crack growth behaviour determined in the M(T) tests. Bearing in mind that the tensile yield strength of 25CrMo4 is significantly lower than for 34CrNiMo6 this experimental finding suggests that the load interaction effects observed under variable amplitude loading essentially depend on the load level. Under low or moderate stress levels, overload cycles usually result in crack retardation which is often attributed to plasticity induced compressive residual stresses, crack tip blunting and closure or plastic zone shielding. In contrast, at high levels of applied load, overload cycles seem to produce a pronounced material damage ahead of the crack tip which leads to an overall accelerated crack propagation.

The results of a fracture mechanics assessment of the reference axle geometry are shown in Fig. 8. The calculations were performed assuming semi-elliptical cracks in the shaft section of the axle with a diameter of 160 mm. The initial crack depth and length were selected to be $a = 2$ or 4 mm and $2c = 8$, 16 or 32 mm, respectively. All curves are normalised with respect to the crack propagation curve for the initial defect size of $a \times 2c = 4 \times 8$ mm^2. The service loads have been applied according to the actually measured stress time history depicted in Fig. 5. Thus, the crack depth propagation as a function of the vehicle distance has been calculated. Using these results, NDT requirements can be specified.

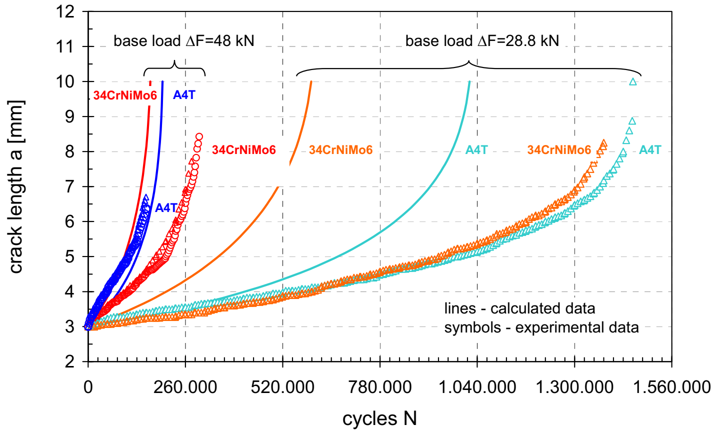


Figure 7: Crack propagation of 25CrMo4 (A4T) and 34CrNiMo6 axle steels under variable amplitude loading (reduced block loading) determined with M(T) specimens.

Due to the fact that automated inspection systems are in the most cases hardly available and that uncertainties in the probability of detection have to be accounted for, the introduction of appropriate safety factors or an integration of the analysis results in a risk based assessment tool is advisable. The definition of safety factors is a difficult task as it depends on the exact knowledge of the probability of detection which can be reached during inspection. As a consequence 50% of the calculated theoretical inspection interval is often chosen. Note, that the consideration of cracks positioned in fillets or other transition zones may lead to reduced inspection intervals, as compared to cracks in a cylindrical part.

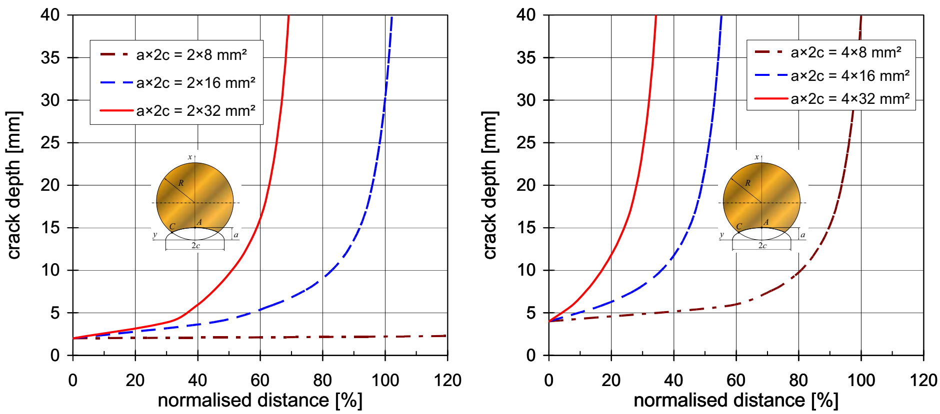


Figure 8: Normalised fatigue lives for different initial flaws in the shaft (here 100% fatigue life corresponds to the initial crack size of a×2c = 4×8 mm^2).

Summary and Conclusions

Important aspects related to the application of fracture mechanics methodology for predicting inspection intervals of railway axles under in-service conditions have been studied. These include material characterisation, computational modelling of fatigue crack propagation, influence of characteristic variable amplitude loading and validation experiments with component-like specimens. Up to date the following status has been reached:

- a reference wheelset axle (fully described technical reference case) has been created and will be used for further investigations,
- fatigue crack growth properties (C, m and ΔK_{th}) have been experimentally determined for the railway axle steels 25CrMo4 (A4T) and 34CrNiMo6 under fully reversed loading (R = -1) using M(T) specimens,
- validated solutions for stress intensity factors (K_I) were developed for a general use, including arbitrary 2D stress distributions in components (e.g. shaft and fillets) with cracks,
- a data base of crack growth experiments with 1:3 and 1:1 scaled specimens, varying crack positions (shaft and fillet) and loading regimes has been established,
- track trails have been performed with an instrumented non-powered axle of a commuter train and data stress amplitude histograms were derived for different axle positions.

In the following project phase investigations focused on the transfer of crack propagation behaviour of small scale specimens to full scale railway axles will be emphasized. Special interest will be placed on the influences and effects of characteristic variable amplitude loading scenarios.

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