COMPARISON OF FATIGUE CHARACTERISTIC AND CRACK PROPAGATION TESTS PERFORMED ON STANDARD AND INDUCTION HARDENED AXLES PRODUCED FROM STEEL GRADE EA4T

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Abstracts

A new surface induction hardening technology was for the first time in Europe designed in Bonatrans Group a.s. Company for the purpose of increasing the safety and resistance of railway axles to fatigue damage. The operation of railway axles should fulfill two main demands: safety and low operation costs. A significant part of operation costs is given by frequency of regular inspection intervals which should reveal potential fatigue cracks in railway axle. For the safety, the existence of potential initial crack should be considered on the axle surface and residual fatigue lifetime (RFL) should be conservatively determined for this case. Reliable procedure of fatigue lifetime estimation should take into account real geometry, material characteristics and loading of the railway axle. This document shows methodology for determination of RFL and presents a part of technological benefit such as hardness profile and fatigue characteristics and compares their values with standard heat treated railway axles.

Keywords: Railway axles, wheelset, fatigue crack, lifetime

1. INTRODUCTION

The main reason for the development of new axle design concepts giving higher resistance to fatigue crack initiation and its propagation is fatigue damage of railway wheelset axles. Because fracture failure of axles due to gigacyclic fatigue may be initiated by much lower stress amplitude than the fatigue limit for 10^7 cycles, the consideration of fatigue strength must always be accompanied by considerations of fatigue damage tolerance in order to ensure axle safety. The fatigue damage tolerance therefore takes into account not only the minimum crack size detectable using NDT methods but also suitable intervals between inspections, set depending on the location and period of operation. For the operators of rail vehicles, surface hardened axles reduce the number of essential ultrasound inspections of fatigue damage tolerance. All trials presented in this document were carried out on specimens of commercially produced grade of steel (EA4T). One technology applied in order to increase axle fatigue strength is surface induction hardening (IH). The fatigue limit is significantly increased, and short fatigue cracks in surface layers are hardly able to propagate.

2. ESTIMATION OF WHEELSET LIFETIME USING FEM CALCULATION

The critical position of considered crack is found on the axle surface using finite element analysis. The highest probability of fatigue crack initiation is in the location close to the railway wheel seat (see **Figure 1**). Then the number of load blocks necessary for fatigue crack propagation from initial defect to the critical crack length is evaluated in the framework of linear elastic fracture mechanics.

2.1. Critical position of the initial crack determination

For the RFL estimation of the axle it is necessary to determine location of the most probable crack initiation and following propagation. The approach used considers crack of initial size in different locations of selected section and corresponding stress intensity factor of the crack is determined. Location of the crack with the highest value of the stress intensity factor is the critical one. For determination of critical position an initial crack with length a = 2 mm and shape close to semi-circular was considered. Using this analysis the critical position was determined for L = 1768 mm (see **Figure 2**).

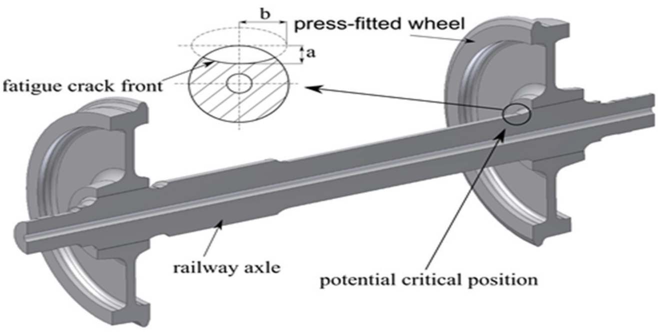

Figure 1 Scheme of the railway wheelset considered

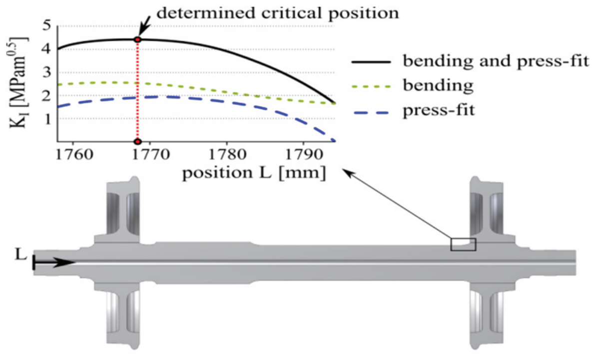

Figure 2 Dependence of the stress intensity factor on the initial crack location for initial crack length a=2mm

2.2. Determining the stress intensity factor

As soon as the critical location for the crack initiation is known the stress intensity factor K_I as a function of the crack length a is determined. The stress intensity factor is evaluated using optimized crack front shape obtained by the special procedure described in the document [1], see **Figure 3**. The K_I-a dependence is determined for the case of bending loading as well as for the load caused by press fitted wheel. The total stress intensity-ty factor is given by superposition of bending and press-fit loading.

The values of the stress intensity factor caused by bending monotonically increase with increase of the crack length a, however the values of stress intensity factor caused by pure press-fit loading increase to the peak value at about 9 mm from the surface and subsequently decrease for longer cracks.

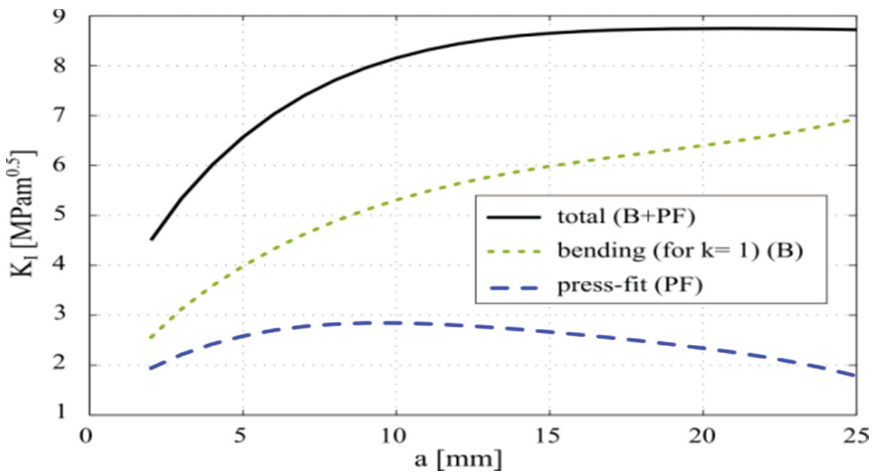

Figure 3 K_I of the semi-elliptical crack caused by bending loading (B), loading of the press-fit (PF), total one

2.3. Load spectrum of railway axle

The stress intensity factors were calculated for loading of railway axle corresponding to ride on straight track. However, the trains also go to curved track, over switches, crossovers, etc. These events commonly increase the basic level load caused by weight of the vehicle. Real load spectrum of railway axles [2] with sorted load amplitudes in histogram is given in **Figure 4.** The spectrum is sorted into 36 load levels, which are described by dynamic coefficient k. The static load correspond to k = 1, however some events during operation can lead to load amplitude peaks up with k = 2.9.

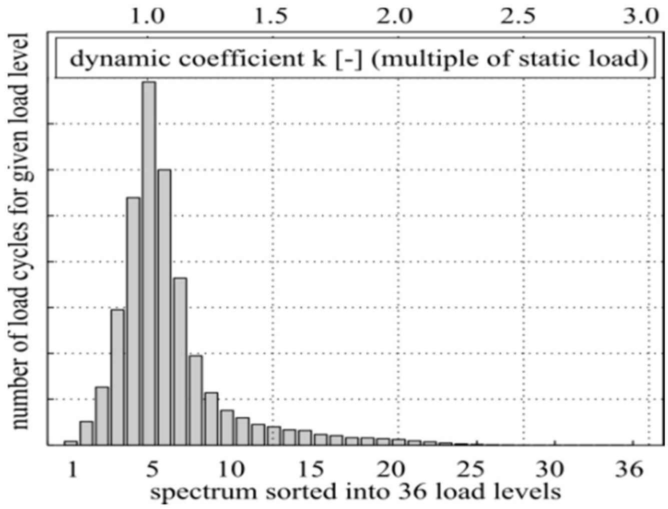

Figure 4 Load spectrum of railway axle [2]

2.4. Fatigue crack growth rate determination

Fatigue crack propagation rates were evaluated experimentally based on fatigue tests of middle tension (M(T)) specimens. Own experimental measurements were performed to obtain material data of EA4T steel.

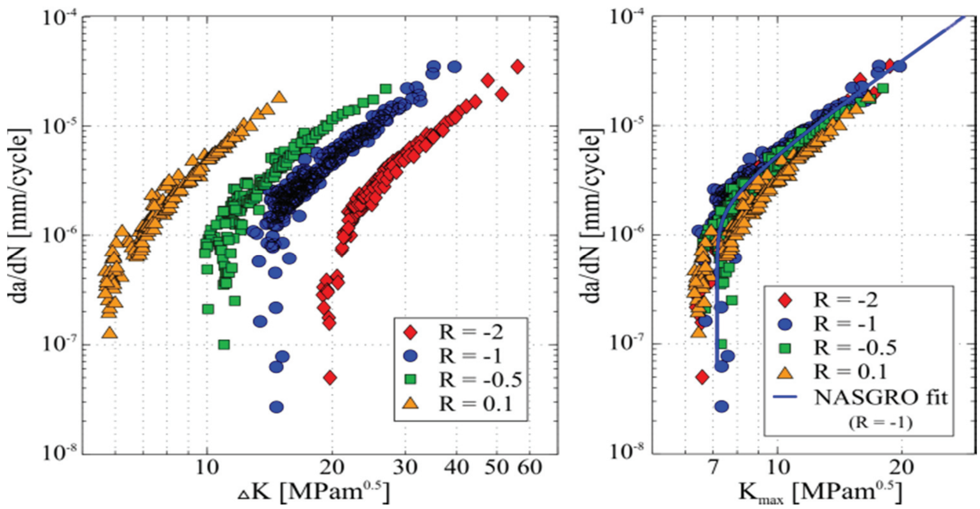

Figure 5 Experimentally obtained *v*-K curves of EA4T steel for stress ratios *R* with NASGRO fit

The measured *v-K* curves were obtained for stress ratios R = -2, -1, -0.5 and 0.1. Measured *v-K* data are shown in **Figure 5**. The figure shows dependence of stress intensity factor range ΔK and maximal value of stress intensity factor $K_{max.}$ on crack propagation rate $v = da/dN$. It is evident, that for v-$K_{max.}$ expression, the measured curves fit each other quite well. Based on this fact, the fatigue crack propagation rate can be sufficiently described just by one v-$K_{max.}$ curve. Due to this fact that the v-$K_{max.}$ curve for stress ratio R = -1 (see Figure 5) was chosen for following calculations. The v-$K_{max.}$ curve was fitted by NASGRO relationship [3]. Due to results of experiments obtained the NASGRO equation can be expressed in the simplified form:

$$\frac{\Delta a}{\Delta N} \cong \frac{da}{dN} = C\left(K_{I,max.}\right)^{n}\left(1 - \frac{K_{th}}{K_{I,max.}}\right)^{p} \tag{1}$$

where C, n and p are material constants, $K_{I,max.}$ is maximal value of stress intensity factor in load cycle, K_{th} is threshold value for R = -1. Note that maximal value in load cycle is given by superposition of bending and press-fit contributions of loading:

$$K_{I,max.} = kK_{I,bending} + K_{I,,press-fit} \quad (2)$$

where k is dynamic coefficient, respecting load spectrum. If $K_{I,max.}$ is larger than threshold value K_{th}, then the crack increment Δa is given by (1):

$$\Delta a = C\left(K_{I,max.}\right)^{n}\left(1 - \frac{K_{I,th}}{K_{I,max.}}\right)^{p}\Delta N \quad (3)$$

By the calculated crack increment is extended the crack length from previous step. The calculation runs till the crack length will not reach the defined final crack length 25 mm. However, the contribution of crack growth from 25 mm to critical length to the residual fatigue life is negligible due to rapid crack propagation in this area.

2.5. Estimation of RFL without considering of surface treatment

Calculated RFL for different considered initial crack lengths according to Eq. 1 is shown in **Table 1**. These values represent basic estimations of RFL. The effect of surface treatment on RFL will be taken into account in the following.

Table 1 RFLs [thousand km]

Initial crack length	1.5 mm	2 mm	3 mm
RFL	1 308	128	44

2.6. RFL estimation with considering of surface treatment

Manufacturing process of railway axle usually contains surface treatment. Compressive residual stresses of magnitude 20-60 MPa are developed after application of such treatment. These compressive residual stresses close fatigue crack and help to resist to propagation of fatigue cracks. Calculated stress intensity factor caused by surface treatment (with maximal residual stresses 24 MPa) is shown in **Figure 6.** This stress intensity factor reduces the total one. By consideration of residual stress the estimations of residual lifetimes quite rapidly increase, see **Table 2.**

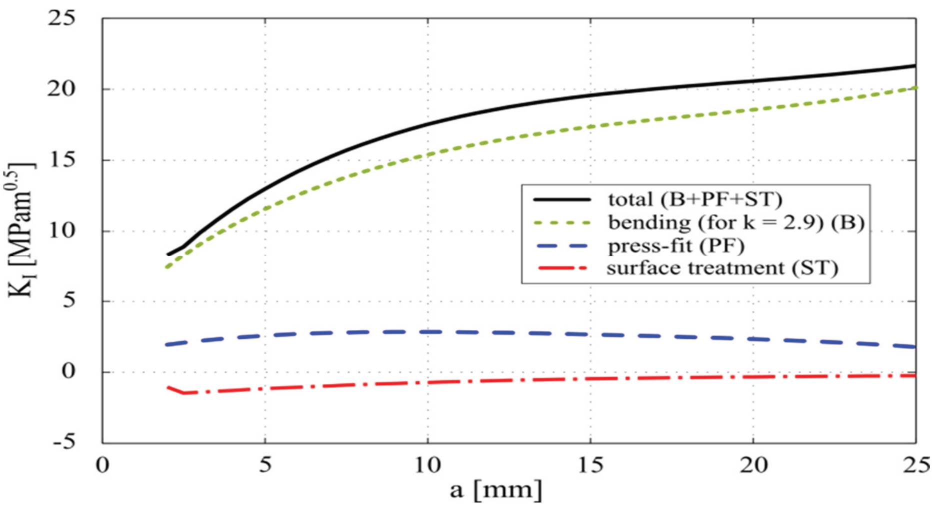

Figure 6 Stress intensity factors with consideration of effects of surface treatment

Table 2 RFL with effect of surface treatment [thousand km]

Initial crack length	1.5 mm	2 mm	3 mm
RFL	35 201	2 696	153

3. RFL OF INDUCTION HARDENED RAILWAY AXLE

The effect of compressive residual stresses can be amplified by IH, which causes strong and compressive residual stresses (more than 800 MPa) under railway axle surface. The calculations performed show that the magnitude of residual stresses don´t allow the propagation of formerly considered initial fatigue cracks of lengths 1.5, 2 and 3 mm, even with consideration of maximal load amplitude of the load spectrum (with dynamic coefficient $k = 2.9$). According to **Figure 7** the total stress intensity factor (considering maximal bending amplitude from load spectrum $k = 2.9$) overcomes threshold value just for crack length a longer than 22.7 mm. The **Table 3** shows calculated dynamic coefficient k, which should lead to crack propagation (note that maximum coefficient of load spectrum is $k = 2.9$) in IH axles.

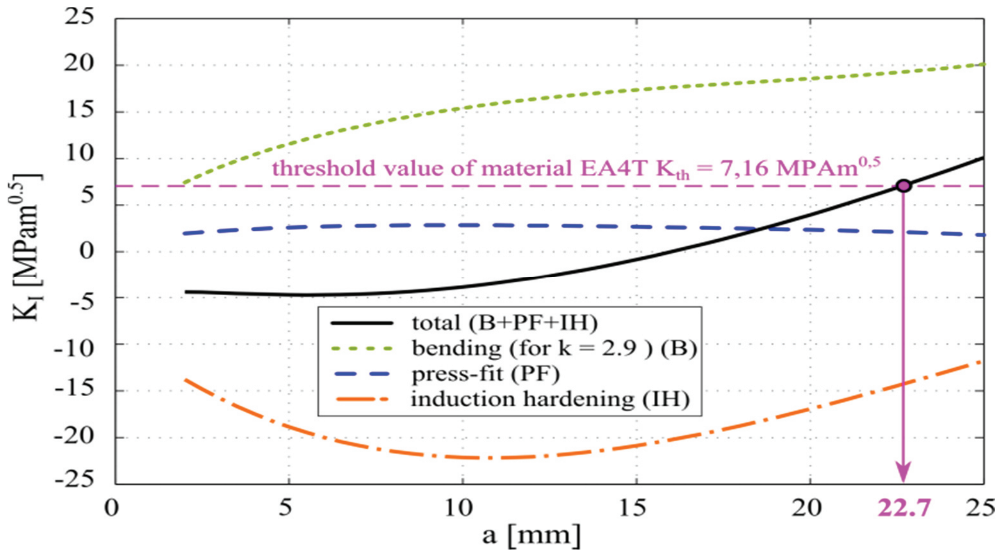

Figure 7 Stress intensity factors of crack in IH railway axle

Table 3 Calculated dynamic coefficients k leading to fatigue crack propagation in IH axle

Crack length	**1.5 mm**	**2 mm**	**3 mm**
Coefficient k	8.1	7.4	6.6

4. EXPERIMENTAL TRIALS

4.1. Crack propagation test on real axles EA4T and EA4T+IH

For verification of calculation results were organized with cooperation with DB Systemtechnik Prüfstelle in Minden crack propagation test with a spark-eroded notch in the transition radius on one standard axles of the steel grade EA4T and one axles of the grade of steel EA4T with IH surface. The tested object was “half wheelsets” with diameter of axle body 185 mm and diameter on wheel seat press fit area 215 mm. The artificial elliptical defect, with typical length 3.75 mm, and depth 1.5 mm, were placed in the transition radius R75/R15 at a distance 34 mm from wheel seats.

The test of standard axles of the steel grade EA4T started with crack initiation on testing amplitude of nominal stress 112 MPa which correspond 134 MPa of local stress. At this level, a crack length of 5.7 mm was measured after 8.10^5 load cycles. After verification of omission of low amplitude load cycles the fatigue crack growth testing started with the defined test load spectrum. After a distance covered of 500.000 km, the crack length determined on the crack measurement strain gauges had grown from 5.7 mm to 6.6 mm.

Totally different behavior was occurred during test of IH axles EA4T steel quality. The test started with crack initiation on testing amplitude of nominal stress 200 MPa and was applied 5.10^6 load cycles. Then the testing amplitude was increased on 240 MPa / 5.10^6 load cycles, 280 MPa / 0^7 load cycles and 300 MPa / 10^7 load cycles. During application 340 MPa there was a problem with testing equipment power which prohibitive next test continuation. If we compare these results with results from standard EA4T axle we can say that 2.6 multiple value of nominal stress, which causes on standard steel quality EA4T crack initiation from artificial notch, is not for IH axles with artificial notch with defined geometry damaged. For the other hands EA4T steel quality shall fulfil according standard EN 13261 10^7 cycles during fatigue testing axle on real scale on nominal testing stress 240 MPa and we apply on IH axles nominal stress 300 MPa without crack initiation from artificial notch.

4.2. Fatigue characteristic of full size axles

Bonatrans Group a.s. tested 6 drive axles with wheel seat diameter/axle body diameter ratio D/d = 207/180 = 1.15 and with standard R75/R15 transition radius design. The **Table 4** shows only result for one standard axle produced from EA4T steel quality and one axle from EA4T+IH surface. Fatigue strength increased minimally about 58 % (418/264) compared to the standard grade of steel EA4T and about 74 % compared with EN 13261 standard, which cannot be achieved by any other technologies.

Table 4 Test stress levels to which the full scale axles were exposed

	Local stress [MPa]	Nominal stress [MPa]	Stress on press fitted area [MPa]	No. of cycles
EN 13261	-	240	145	10^7
Standard A4T	285	243	156	10^7
	310	264	170	10^7
	335	286	183	$6.3.10^6$
A4T +IH surface	400	372	241	10^7
	450	418	271	10^7
	500	467	301	$4.2.10^6$

*) High test stresses and raised temperature made it impossible to continue testing on the test assembly

5. CONCLUSION

Main benefit of the technology of surface IH of EA4T and advantages of this technology are:

High internal compressive residual stress on axle surface which taking impossibility of propagate a short fatigue crack in surface layers and significantly decelerate a growth of long fatigue cracks. Practically impossible create on axle surface initiation defect from which fatigue crack can propagate on real load spectra measured in maintenance. Significantly increase the fatigue limit minimally about 58 %. Possibility protected all length of axle not only wheel seat as in case Mo coating technology. There is impossibility of seizure axle during repeated assembly and disassembly during maintenance. Possibility of reproofing wheel seat and axle body with preservation of all positive property as a compressive residual stress, hardness etc. are real.

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