FATIGUE INVESTIGATIONS OF DAMAGED RAILWAY RAILS OF UIC 60 PROFILE

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Abstract: The development of procedures to calculate the service life of railway rails requires test results which describe the damage of rails thus affording their validation. Within the DEUFRAKO integrated project NOVUM, ten rail specimens were tested under constant and variable amplitude loads to investigate the propagation of lateral cracks and to ascertain the service life. The test conditions were based on real rail loading and were used in the 3-point-bending test frame under alternating stress. An eccentric notch was applied as pre-arranged damage in the 60 E1 (260) rail specimens. The notched rails showed a similar behaviour like rails with strong head checks damaged by rolling contact fatigue.

Keywords: railway rail, notch, service loading fatigue, crack propagation, bending, damage

1 INTRODUCTION

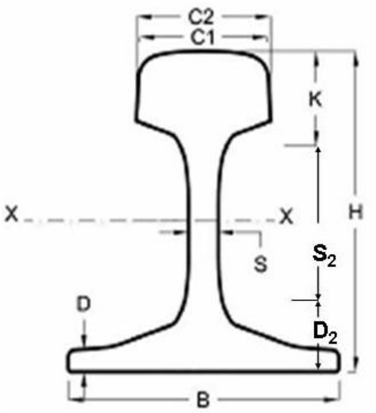
The BAM Federal Institute of Materials Research and Testing Berlin participated in the NOVUM integrated project “New methods for quantitative forecast of the transport capability of rail tracks with increasing load“ – a German-French DEUFRAKO project from 2004 to 2007 and dealt with fatigue tests of rail parts with profile 60 E1 (260). The main goal was to improve the performance of rails as an important component of the railway transportation system by improving damage prediction in rails.

Modern rails have high wear resistance that initiation of defects in the rail’s head range plays an important starting role to final failure of the component. The removal of defects or incipient cracks through grinding of rails delays their growth but it is cost-intensive and degrades the structure. Therefore it is essential to determine the optimal point in time balancing costs and risks. For this reason the knowledge of general principles of damage evolution and their modelling is the basis of developing a modern maintenance strategy.

BAM investigated the propagation of transverse cracks in rails. Crack propagation tests were also carried out on material specimens of S 900 A rail steel [1] [2]. The special goal was to obtain applicable data of crack propagation using by the project partners to validate their own computational procedures.

2 SPECIMENS AND MATERIAL

German Railway (DB) Systemtechnik AG in Kirchmoeser disassembled a passed track section to prepare specimens as cut rail sections of 1.2 m length. The head’s surface was smoothed by grinding. The material removal by wear and grinding was 10 mm, so the height of head K was 41 mm and the total height H was 162 mm (Fig. 1). The rails were produced by Thyssen AG, Duisburg in 1991 and 1992. They were marked as profile UIC 60 and quality S 900 A. These data correspond to the new marking 60 E1 (260). The material properties in Table 1 were given by rules and standards [3].



total height	H	172.00 mm
foot width	B	150.00 mm
head width top	C_1	72.00 mm
head width bottom	C_2	74.30 mm
web thickness	S	16.50 mm
head height	K	51.00 mm
foot thickness	D	11.50 mm
foot height	D_2	31.50 mm
web height	S_2	89.50 mm

Fig.1: UIC 60 railway rail profile with standard size [4]

The rail specimens were prepared with a circular shaped transversal notch at a distance of 10 mm from the longitudinal axis. The notch depth was 2.0 mm and the chord length was 12.0 mm. It was manufactured by an angular milling cutter simulating the incipient damage, the so-called head checks [5]. Head checks are cracks running near the gauge line on the head surface. First, they run nearly parallel to the surface and further on they bend down and propagate as transverse cracks. The notch was milled at an angle of 70°, therefore it has the shape of a sickle in Fig. 2. Rail material was taken from two different layers, both perpendicular and horizontal, in both cases transversally to the longitudinal axis. Accompanying investigation of crack propagation and determination of threshold values ΔK_{th} were performed on SE(B)-specimens (Fig. 3).

Tab. 1: Rail steel S 900 A – composition and characteristics [4]

Quality	Chemical composition in %						Mechanical characteristics	
	C	Si	Mn	P_{max}	S_{max}	Cr	R_m in MPa	A_5 in %
S 900 A	0.60 - 0.80	0.10-0.50	0.80-1.30	0.040	0.040	-	880 - 1030	>10

Fig. 2: Rail surface with notch

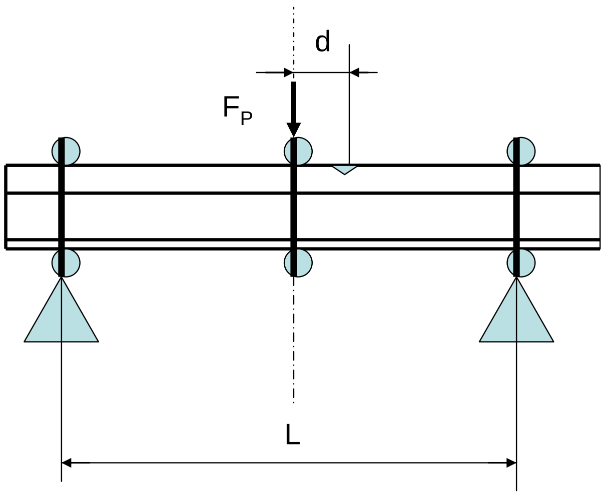
Fig. 3: SE(B) specimen
174.0 mm x 39.0 mm x 8.0 mm

3 EQUIPMENT – RAIL TEST RIG

A rail test rig for alternating loads was built in BAM to test undamaged rails up to failure by cyclic loading as well. The special feature is the zero crossing of load. Fatigue tests on rails were performed as compressive tests so far [6]. The test principle with central load application using three-point-bending is shown in Fig. 4.

The distance d between the notch simulating a defect and the load application was fixed in all tests at 75 mm. The relation between the test load F_P and the maximum bending stress σ_{bc} at the location of application was determined by the specimen's section modulus Z_{x2}. The corresponding nominal bending stress σ_b at d (place of notch) can be obtained from the ratio equation using the effective lever arm, so equation (1) gives the relation between test load F_P and bending stress σ_b at d:

$$F_P = \frac{2\sigma_b Z_{x2}}{L/2 - d} \tag{1}$$



L – distance of outer bearings: 1000 mm
d – distance centre – notch: 75 mm (notch at d)
F_P – test load (in the centre)
σ_b – max. (nominal) bending stress at d
σ_{bc} – max. (nominal) bending stress at centre point (place of load application)

roll diameter (bearings): 50 mm

Fig. 4: Test rig with three-point-bending

The bending table was built in a servo-hydraulic test machine (MTS) with 1 MN nominal load as displayed in Fig. 5. The hydraulic actuator is assembled within the cross head. A 5 MN load cell (Lebow) was used to measure the test load. It was calibrated in the range of -1250 to 1250 kN and assembled at the end of the piston.

The test machine worked in a closed loop load control with a sinusoidal load curve with a test frequency of 1.3 Hz. The controller was a TestStar-II Classic system (MTS). In addition, an adaptive controller (MAS-Link system based on Atari) was used as an external control loop for the service loading test with a load spectrum.

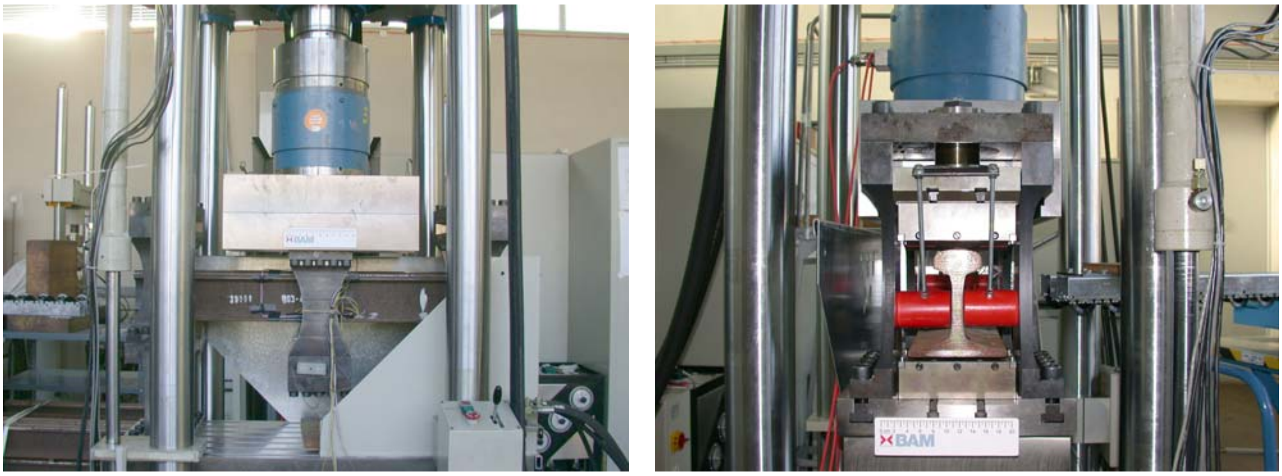


Fig. 5: Test rig for rails with centrical load transmission in an 1-MN testing machine and built-in specimen #24 (front and side view)

4 CONDUCTION OF LOADING CONDITIONS

The service load of the rail follows as superposition of the dynamical wheel forces, the thermally induced stresses and the residual stresses. The loading of a perfect rail during a roll-over did not result in a fatigue crack by alternating bending reclusively. Classical fatigue fracture begins in the rail foot initiated by inherent defects. The 60E1 (260) rail is classified as „rated for endurance strength“ under typical European loading conditions of mixed traffic tracks [7].

The aim was to ensure close-to-reality loading of pre-damaged rails in a test rig. Therefore, Deutsche Bahn AG (German Rail) provided exemplary load data as functions of time describing wheel and rail loads of an ICE train with 12 trailer vehicles and 2 traction units. The data were based on measurements on a track section called DAFUR equipped with instruments [8], at a train speed of 160 km/h during straight-ahead driving and their analysis by simulation of the dynamic behaviour.

Based on specified sleeper and wheel loads, the head stress had to be calculated. The multiple mounted bar model with different wheel positions was used for this calculation [9]. A simple roll-over by a trailer vehicle resulted in a cyclic load of ±33 MPa with a mean load of -16 MPa neglecting scatter and individual differences. Thereby the representative fundamental loading of the rail by bending resulted in the following approach to the constant amplitude loading:

$$\sigma_b(t) = -16MPa + 33MPa \cdot \sin(\omega t) \qquad (2)$$

However, at first the applied load was increases by a factor of 4.3 based on the results in [6]. This was necessary in order to obtain a crack growth and a service life within less than two million cycles using alternating bending only. This factor was gradually decreased during the constant amplitude loading test schedule while the mean load was kept constant.

The total variation of the turning points of the load function of the ICE train was taken into account in the investigation and the corresponding bending stresses were calculated. The original load spectrum included the overall maximum of 16 MPa and the overall minimum of -68 MPa. The number of turning points was 572 resulting in 285 cycles as repeatable subsequences. The subsequence represented one train passage and included 56 roll-overs by one wheel axle. The initial load spectrum was increased to the interval -189 MPa to 108 MPa ensuring sizeable crack propagation and a connection to the constant amplitude loading tests. The transformation was made by an amplitude factor of 3.45 and a mean load offset by +44.3 MPa. So the used constant amplitude loads of ±141 MPa and ±113 MPa were classified as maxima of individual roll-overs in the transformed load spectra very well.

5 TEST RESULTS – SERVICE LIFE

All tests were carried on until failure. The results of valid constant loading were transformed using the Haigh diagram to the load ratio R = -1 (see details in [1]) in order to compare with data from the literature [6]. The mean load effect was assumed to be 0.18. It was a possible value for this material class given by [10]. The resulting S-N curve is shown in Fig. 6. The NOVUM results were in very good agreement with the sequence of head checks, especially of extensive head checks.

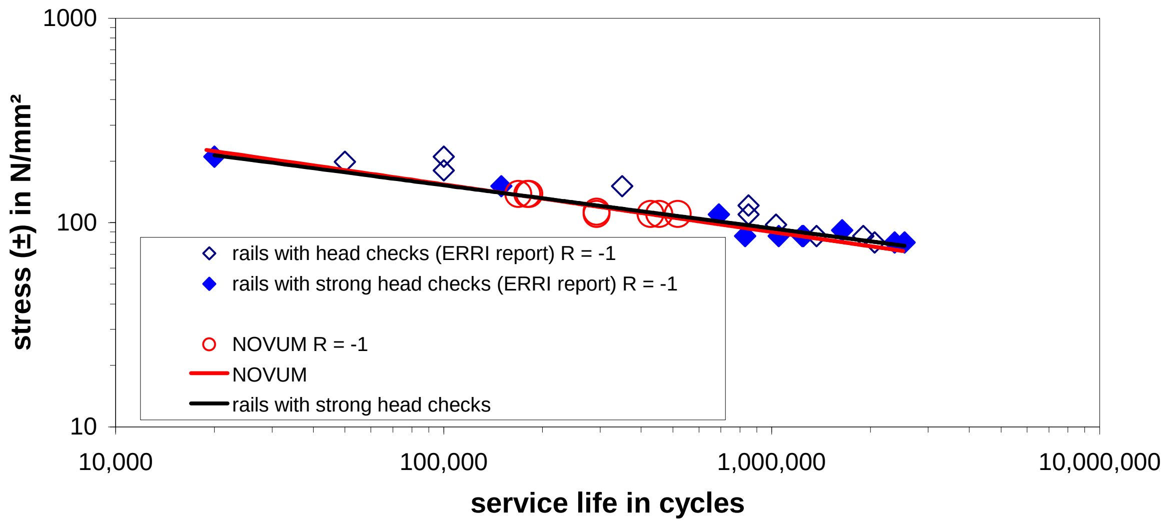
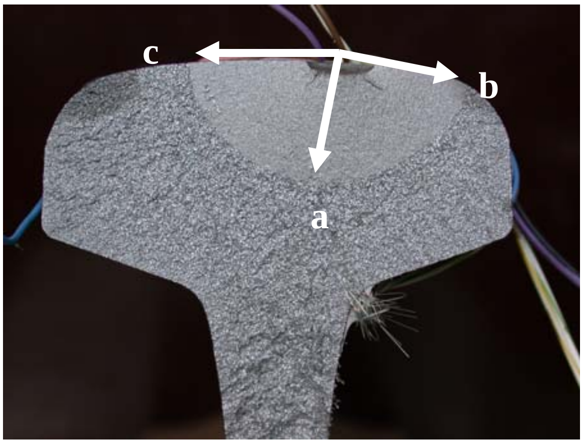


Fig. 6: Transformed S-N curve of 60 E1 (260) rails with pre-arranged damage under bending for R = -1 with M = 0.18

The resulted service life of the service loading test of 1 922 900 cycles corresponded to 6747 train passages including 377 833 roll-overs by one wheel axle. The last number of roll-overs as lifetime conformed to a constant amplitude loading of about ±115 MPa.

6 TEST RESULT – CRACK PROPAGATION

Since geometrically similar semi-elliptical or quasi circular crack fronts were observed (Fig. 7), the crack depth was estimated by the propagation of the surface cracks, see equation (3). The crack length on the head surface was measured by crack gauges.



Approximate crack depth:

$$a = (b + c)/2 \tag{3}$$

Fig. 7: Fracture surface and crack variables (specimen #35)

Fig. 8 shows all test results with the crack depth being given by equation (3). The maximum error was assumed to be +2 mm based on a comparison between surface measurement and crack front after cracking.

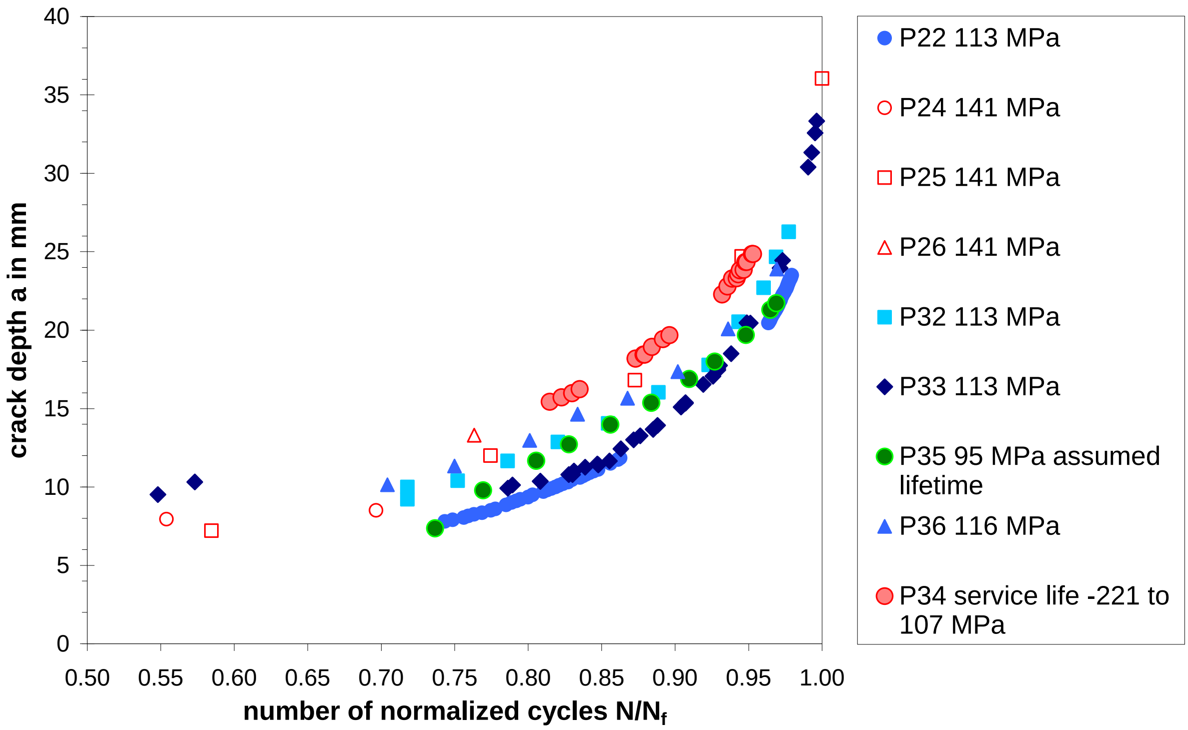


Fig. 8: Crack depth versus crack propagation

The service loading test (# 34) fits well to the overall results. Specific conclusions were not possible because of the small number of tests and the scatter in service life. However, it was assumed that greater loads caused an earlier crack initiation and were associated with bigger crack depths.

The data of crack propagation in rails can be compared with the results of material specimens directly, the procedure is explained in detail in [11] and [1]. It was possible to determine the rail's stress intensity factor according to Budnitzki and Edel [12] in the simple well-known way if the crack was not deeper than a special crack depth corresponding to the critical crack depth of 35 mm. Fig. 9 shows a crack-propagation diagram with regression lines without transformation of the R ratio and the Paris exponent m. The regression lines of both kinds of specimens will approach each other more closely if the different R ratios and the excessive size of the measured crack depths of rails are taken into account.

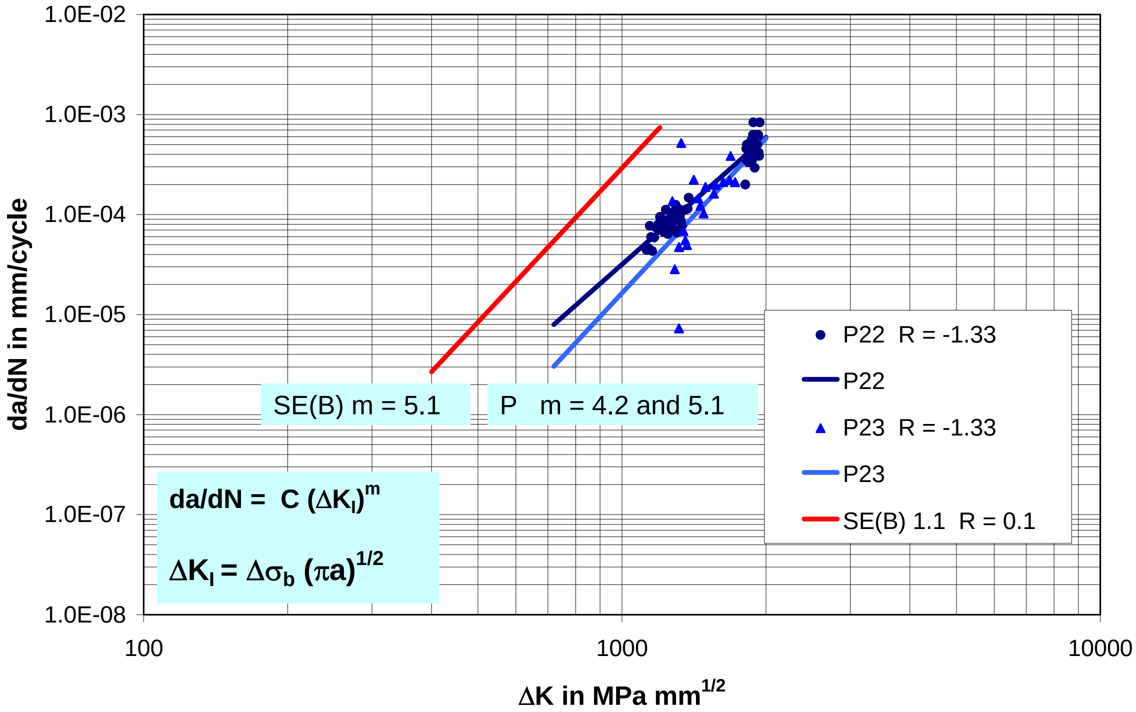


Fig. 9: Comparison of crack growth rates of rail and material specimens

7 CONCLUSIONS

The notch effect of head checks is similar to milled notches with respect to lifetime as a function of loading within the C-N curve in Fig. 6. The investigation verifies the result in [5] that transverse cracks caused by head checks propagate according to the rules of linear-elastic fracture mechanics. The asymmetry of the notch had no bearing on the crack development. The reason was the dominant mode I loading. The following two aspects seem to be important to come closer to real loading, especially at the beginning:

- taking into account the thermal-induced stresses
- implementation of a non-stationary load application

The service fatigue test performed was a preliminary test. It enabled the conclusion that the major part of damage was caused by the maximum amplitude of every individual roll-over. Based on the number of roll-overs and the obtained crack depth to failure, the amplitude of an assumed constant loading test was found to be ±115 and ±110 MPa, respectively, using the C-N curve. So a practical damage equivalent to the load spectrum was found. Further tests with different load spectra are necessary to obtain data that can be generalized.

The test rig has proved for the alternating bending load tests with constant and variable amplitude loading and enables the investigation of fatigue properties of different rail qualities with and without pre-arranged damage.

ACKNOWLEDGMENT

We would like to thank the Federal Ministry of Education and Research (BMBF) for the financial support to the project. The funds were provided under the support code 19 S 4024B. The authors are responsible for the content.

Furthermore we thank all colleagues for their help to successfully completing this project.

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