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Temperature-dependent evolution of the cyclic yield stress of railway wheel steels

Johan Ahlström [a,*], Elena Kabo [a,b], Anders Ekberg [a]

[a] CHARMEC, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
[b] Qamcom R&T, SE-41285 Gothenburg, Sweden

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ABSTRACT

The evolution of the cyclic yield stress for a railway wheel steel (UIC ER7T) during cyclic plastic straining has been characterized at different temperatures from −60 to 600 °C. Different constant strain amplitude levels were examined and for temperatures above 200 °C, hold periods were included to study stress relaxation during constant compressive strain. The results are of use in predicting material deformation and damage. This is demonstrated by the application to improve a criterion for surface initiated rolling contact fatigue damage.

1. Introduction

Railway operations induce large mechanical and thermal loads on the surface of the wheels and the rails. Both are dynamic in nature, and both the loading and resulting material response for a certain position in the wheel or the rail are difficult to describe with high precision. It is well established though, that stress levels are high enough to plasticise the material, and that temperature levels can reach above 500 °C during normal freight operations. Stress cycles, as well as thermal cycles, lead to material responses that accumulate over time and cause both residual stress fields, and altered material behaviour. In addition the material accumulates damage that eventually leads to deterioration. To fully analyse this damage development, generally requires a combination of high resolution analyses combined with techniques that are simple enough to be possible to adopt throughout the long evolution from a virgin to a fully deteriorated state.

Surface initiated rolling contact fatigue (RCF) of railway wheels is commonly assessed using a shakedown map approach [1] that may be reformulated in the form of a "fatigue index" [2]

$$FI_{\mathrm{surf}} = f - \frac{2\pi abk}{3F_z} \qquad (1)$$

where f is the traction coefficient (tractive force divided by normal force), a and b the semi-axes of the Hertzian contact ellipsoid and F_z is the magnitude of the normal wheel–rail contact force (positive in compression). Material characteristics are here described by the yield stress in cyclic shear, k, commonly taken as a constant that should reflect the "steady state" response of the operating wheel. However a more precise definition is lacking.

A cyclic yield stress is commonly evaluated from linear fitting of the unloading part of the stress–strain loop from a low cycle fatigue (LCF) test, applying a strain off-set and then finding the intersection with the stress–strain loop. However, the actual unloading path is often found to be non-linear [3–8], and the slope is typically lower than the actual Young's modulus E as determined for example by (static) tensile tests. Both of these factors will add to a large ambiguity in identified cyclic yield stresses. In the current study, the method is therefore refined: second-degree polynomials are fitted to the tension and compression sides of each stress–strain loop. This allows for a well-defined assessment of the off-set of the cyclic yield stress. Parts of the technique and some experimental data are previously reported, e.g. in [3–9]. In the literature there are also other methods available for analysis of stress–strain loops to identify internal and effective stresses, for example the SAP method [10,11]. However, the chosen method is more suitable for the problem at hand, where the onset of large-scale plastic deformation after reversed loading is to be determined.

The current study focuses on the identification of a varying cyclic yield stresses as recorded from low cycle fatigue (LCF) tests run at constant strain rates at different temperatures, with and without hold

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* Corresponding author.
E-mail address: johan.ahlstrom@chalmers.se (J. Ahlström).

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times, and at different strain amplitudes. It further discusses the potential use of these results in evaluating surface initiated RCF.

2. Experiments

2.1. Material

The material examined is R7T, a near fully pearlitic railway wheel steel, which is defined by the standard EN 13262 under the name ER7 (chemical composition to be found in Table 1). However, the heat treatment of wheels carried out after rolling, with austenitisation of the entire wheel, followed by forced rim chilling by water spraying adds a "T" to the designation. The heat treatment gives a fine-lamellar pearlite in the machined rim surface, with some 10% pro-eutectoid ferrite. The rim hardness at 15 mm depth below the surface is around 270 HV10, decreasing slowly with increasing depth, ca 2.5% per 10 mm.

The microstructure of the material, ferrite content and pearlite lamellar spacing etc., are further described in [12].

2.2. Low cycle fatigue testing

Cylindrical specimens with gauge diameter 6.3 mm were taken out from virgin wheel rims some 15 mm below the running surface and gauge sections were ground with SiC paper from 320 down to 800 grit to remove remaining surface defects from machining. Low cycle fatigue tests were run in strain control at the strain ratio $R_\varepsilon = \varepsilon_{\min}/\varepsilon_{\max} = -1$ (to avoid ratcheting effects) with constant total strain amplitudes, $\Delta\varepsilon_t/2$:0.4, 0.6 and 1.0% with a triangular wave shape at a strain rate of $5 \cdot 10^{-3}\ \mathrm{s}^{-1}$. Peak/trough values of stress and strain at the turning points were recorded for every cycle, and full stress–strain loops recorded regularly during the lifetime. The number of cycles to failure, N_f, for the tests was defined as when the stress amplitude drops to 80% of the 24th cycle or when the peak load suddenly drops.

The machine was equipped with a furnace to perform isothermal tests at elevated temperatures from 200 °C to 600 °C. All tests were run under constant temperature until failure. Most tests at elevated temperature also included 30 min long hold times at regular intervals, where relaxation was obtained upon keeping the minimum strain level constant. These enabled characterisation of viscous effects that can be employed in advanced material modelling [13] and also examination of subsequent effects on the cyclic yield stress development. The full test scheme is given in Table 2.

2.3. Analysis of experimental results

After each load reversal, the measured unloading stiffness is non-linear. In addition, the maximum (initial) slope is typically lower than the Young's modulus, E. The relation between stress and strain during unloading to zero stress was here characterized using a second order equation,

$$\sigma = \langle E_0 \rangle \cdot \epsilon_{el} + \langle k \rangle \cdot \epsilon_{el}^2 \tag{2}$$

where σ is the stress and ε_{el} contains elastic and micro-plastic strains. Further, $\langle E_0 \rangle$ and $\langle k \rangle$ are material constants identified for tensional and compressive stress cycles by

$$E_0^+ \text{ and } k^+ \text{ at } \sigma > 0 \tag{3}$$

during unloading from peak tensile stress, and

$$E_0^- \text{ and } k^- \text{ at } \sigma < 0 \tag{4}$$

during unloading from peak compression stress.

Table 1
Chemical composition of ER7 wheel material, maximum levels, in wt%.

C	Si	Mn	Mo	Cr	Ni	S	P	V	Fe
0.52	0.4	0.8	0.08	0.3	0.3	0.015	0.02	0.06	Bal

Table 2
Tests done in current study.

ID	Temp (°C)	$\Delta\varepsilon_t/2$ (%)	Hold times	N_f
17	20	0.60	0	4688
18	200	0.60	1	2520
19	200	1.00	1	730
23	250	0.60	1	3469
05	300	0.40	0	9855
02	300	0.60	0	2935
11	300	0.60	1	1753
25	300	0.60	0	2195
03	300	1.00	0	836
04	300	1.00	0	928
28	350	0.60	1	2374
24	400	0.60	1	1706
09	500	0.60	1	1335
26	500	0.60	1	1228
29	500	1.00	1	486
27	600	0.60	1	970
30	600	1.00	1	191

Careful identification of $\varepsilon_{el} = 0$ was assured by fitting polynomials to a limited number of experimental data points to both sides of the stress–strain loop around the zero stress level. This procedure is important to get the constant term in the polynomial fits for tension and compression unloading close to zero.

The mathematical treatment sets out from [3]. However, in the current approach we distinguish between $\langle E_0 \rangle$ and $\langle k \rangle$ for the tension and compression sides. The differential elastic modulus is obtained by differentiating Eq. (2) as

$$E = \frac{d\sigma}{d\epsilon_{el}} = \langle E_0 \rangle + 2\langle k \rangle \epsilon_{el} = \left(\langle E_0 \rangle^2 + 4\langle k \rangle \sigma \right)^{1/2} \tag{5}$$

Once the slope of the stress–strain-curve was identified by Eq. (5), a small offset strain of 0.01% was subtracted/added to the peak/trough strain and the intersection with the parametrised stress–strain-curve was detected. Half of the stress range identified in this manner was defined as the cyclic yield stress. The procedure is illustrated in Fig. 1.

Cyclic yield stress after compression, as illustrated in Fig. 1. was used for the figures in the Results section. Except for slightly increased cyclic yield stress levels in the first cycles after a hold time, the cyclic yield stresses identified after compression and tension respectively are nearly identical for this material.

3. Fatigue damage model

There are several applications for the derived cyclic yield stress. One straightforward application is in shakedown-based prediction of surface initiated rolling contact fatigue. If the cyclic yield stress, k, is evaluated as a function of the current temperature, T, and the number of applied cycles, N, the fatigue index in Eq. (1) can be reformulated as

$$FI_{surf} = f - \frac{2\pi\, ab}{3F_z}\, k\,(T, N, \ldots) \tag{6}$$

where, at each load cycle, k is taken as a value that will depend on previous and current operational conditions. (Naturally also the parameters f, a, b and F_z are taken as their current values at each load cycle). In Eq. (6) dependence on the operational temperature, T, and on the number of load cycles experienced up to the current time, N, are explicitly stated. In addition there are more parameters that will affect the current magnitude of k as will be discussed below. It should

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