

Effects of predeformation on torsional fatigue in R260 rail steel

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Abstract

Rolling contact loading induces severe plastic deformations and initiates cracks near the rail surface. Prevention of such rolling contact fatigue cracks requires a better understanding about the mechanical behavior of the deformed material in this region. Even so, current rail standards do not consider the plasticity-induced changes to mechanical behavior. They only evaluate the mechanical performance of virgin rail steels under uniaxial loading conditions, which is not representative for the material's performance after years of service. This study proposes a new method for fatigue life evaluation of deformed material under loading conditions similar to rolling contact loading. Both virgin and predeformed test bars with a circumferential notch were subjected to strain-controlled torsional fatigue loading to evaluate the influence of axial loading, predeformation, and torsional loading direction. Superimposed compressive axial loads increase the fatigue life without affecting the torque response. The predeformed test bars exhibited longer lives, an effect we attribute to the combination of different torque responses, hardening, and anisotropy.

Keywords: Torsional fatigue; Axial-Torsion; Pearlitic steel; Large plastic deformation

1 Introduction

In service, the repeated rolling contact loading of rails causes the material to deteriorate over time. The small contact patch area, through which the wheel load is transferred, causes a very high contact pressure. In addition, frictional loads caused by e.g. traction, cornering, and braking generate shear stresses. If the frictional loads are high and the traffic predominantly unidirectional, then ratcheting occurs i.e. accumulation of shear strain [1]. The material close to the railhead becomes severely deformed, and its material properties and mechanical behavior are significantly changed due to work hardening and microstructure alignment, see e.g. [2], [3], [4] and [5]. Cracks are often initiated in the severely deformed layer [6], [7]. These cracks typically propagates along the direction

of the microstructure alignment in the severely deformed surface region under mixed mode loading. However, most fatigue tests reported in the literature have been conducted on undeformed material under uniaxial loading and this is not representative for the material performance after years of service. Understanding the material behavior of the severely deformed surface material is a key factor for mitigating rolling contact fatigue (RCF).

Pearlitic steels are the most widely used material for railway rails. Such steels offer a good combination of wear and strength with respect to cost and their properties can be tailored to fit the operating conditions. The material state in the top of the rail has previously been replicated by high pressure torsion (HPT) [8], equal channel angular pressing (ECAP) [9] and axial-torsion [3]. In these methods, the material is severely deformed by applying large shear deformation under large compressive hydrostatic stresses, similar to the contact loading at the rail surface. Wetscher et al. [9] deformed the pearlitic rail steel R260 by ECAP to three different equivalent shear strain levels ranging from 0.67 to 2. Later, even higher equivalent shear strains (up to $\gamma = 30$) were achieved in rail steel R260 by Kammerhofer et al. [10], Hohenwarter et al. [8] and Leitner et al. [11], [12], by using HPT. The experimental results from these studies showed that the strength in terms of fracture toughness and fatigue crack propagation rate under mode I loading strongly correlate with the direction of microstructure alignment relative to the crack plane. The lowest strength was measured when the crack plane was parallel to the microstructure alignment, i.e. parallel to the cementite lamellae, and the highest strength when the crack plane was perpendicular to the microstructure alignment. The main limitation of ECAP and HPT as methods for replicating the severely deformed surface layer is that the extracted specimen size must be small for the material state to be well defined. Axi-symmetric test bars required for fatigue testing cannot be produced with ECAP and are very difficult to obtain with HPT. To overcome this limitation and enable fatigue testing Meyer et al. [3] developed a new method to replicate the material state at the rail surface by twisting cylindrical test bars under a compressive axial load. This method can reach shear strains up to 2.3. The replicated material corresponds to the material state at greater depths beneath the rail surface as compared to HPT, which can achieve larger shear strains.

Recently, Schnalzger et al. [13] conducted fatigue crack propagation experiments under mode II loading on pearlitic rail steel R260 using hollow cylindrical test bars. Solid cylindrical test bars were predeformed by the method proposed by Meyer et al. to $\gamma = 1.6$ and a new, modified HPT method to $\gamma = 3.5$. Coplanar crack growth was observed for the test bars predeformed by HPT. The crack followed the microstructure alignment and the crack propagation rate was higher at lower loads than the undeformed material and material predeformed by compression-torsion. Gren et al. [14] conducted stress-controlled uniaxial fatigue crack propagation experiments, predeformed to different levels by compression-torsion. It was reported that the crack propagation resistance of the predeformed material was higher than for the undeformed material. The increased crack propagation resistance was attributed to differences in plastic deformation whilst the effect of microstructure alignment was considered to be limited. The results from previous studies highlights the importance of fatigue testing in predeformed material. Fatigue crack propagation experiments of replicated surface material under strain-controlled cyclic torsional loading have not

been conducted to the authors' knowledge. This study aims to investigate how previously accumulated shear strains affect the fatigue behavior during rolling contact-like loading by using test bars predeformed by compression-torsion. The study also aims to investigate how the direction of the applied shear load affects the fatigue behavior of the predeformed test bars.

2 Materials and Methods

2.1 Material

Torsional fatigue crack initiation and early crack propagation in the pearlitic rail steel R260 have been studied. The microstructure is almost fully pearlitic with a nominal chemical composition according to Table 1. The material was received as cylindrical rods, extracted close to the railhead surface of virgin rails. Test bars were machined from these cylindrical rods with the geometry and dimensions from the drawing in Figure 1.

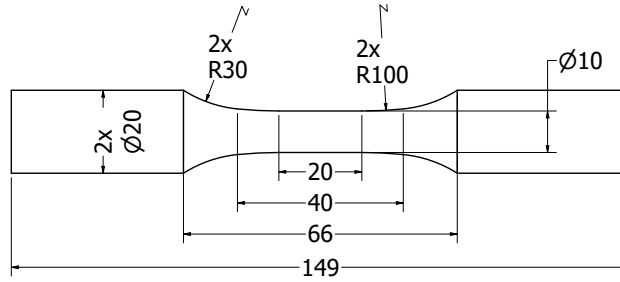


Figure 1: Geometry and dimensions of the test bars used for predeformation in [mm].

Table 1: Nominal chemical composition of the R260 steel.

C	Si	Mn	P	S	Cr	Al	V	N	Cu
0.72	0.31	1.04	0.006	0.010	0.02	<0.002	<0.005	0.006	0.018

2.2 Test bars

The material state close to the surface of highly deformed railheads was replicated with the predeformation method developed by Meyer et al. [15], as illustrated in Figure 2a: test bars are repeatedly twisted 90° under a constant compressive force. In this study, the compressive force was set to give an initial nominal compressive stress of 500 MPa. One deformed material state, corresponding to twisting $3 \times 90^\circ$ (PD3) was investigated, see Figure 2b. The direction of the torsional load (green arrow) during predeformation is throughout the paper denoted as loading along the direction of predeformation.

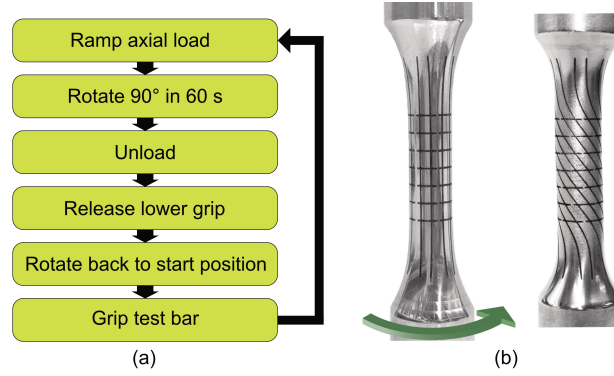


Figure 2: Predeformation method. (a) flowchart of the predeformation process and (b) visualization of shear deformation resulting from twisting $3 \times 90^\circ$.

Predeformation decreases the length of the test bar and increases the gauge section diameter. A new gauge section, symmetric at the center of the predeformed test bars, with a length of 40 mm and diameter of 10 mm was therefore re-machined by turning. At the center of the new gauge section, a circumferential notch was made, with dimensions according to the drawing in Figure 3. The test bar in Figure 3 shows the test bar geometry and dimensions for undeformed material.

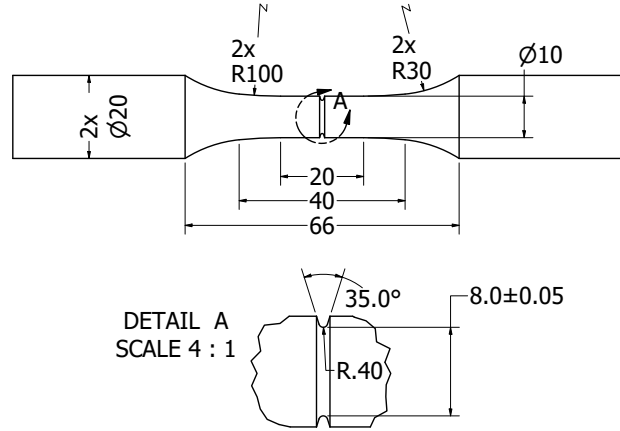


Figure 3: Geometry and dimensions of undeformed and notched test bars.

The geometry differences between the undeformed test bars and reprofiled predeformed test bars do not influence fatigue testing as the strains are measured across the notch where the geometries are identical. The gauge section was ground in steps to P1200 abrasive paper to remove the grooves from machining and make the surface suitable for the extensometer.

Gren et al. [14] measured the surface shear strain of PD3 test bars to 0.74 ± 0.05 , which equates to a shear strain of 0.56 at the notch root of the predeformed test bars used in the present study.

2.3 Experimental

2.3.1 Design of experiments

The fatigue crack propagation experiments were conducted under pulsating cyclic loading in order to investigate the influence of load direction on the fatigue behavior of predeformed material. The fatigue experiments were strain controlled to avoid ratcheting which would have increased the loading difference between the material states and loading directions. The torsional strain was controlled by the rotation angle $\theta = 0.0132 \pm 0.0044$, measured by a biaxial extensometer over its gauge length $L = 12$ mm, as illustrated in Figure 4. The waveform of the torsional load was sinusoidal and the frequency was set to 1 Hz. The strain interval was experimentally determined to achieve an initial torque response of 0 to 50 Nm for undeformed material i.e. a nominal maximum shear stress of about 800 MPa at the notch root, see figure 5.

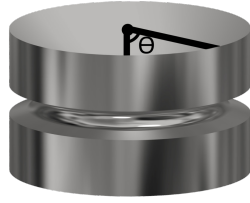


Figure 4: Illustration of the rotation angle used for controlling the fatigue experiments.

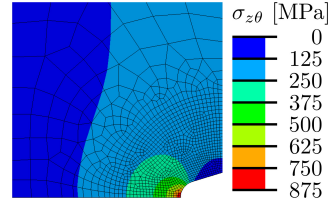


Figure 5: Elastic shear stresses around the notch, simulated with finite elements for a 50 Nm torque.

The test matrix for the fatigue experiments is given in Table 2. The direction of the torsional load was either along or against the direction of predeformation, with or without a superimposed compressive axial load of -100 MPa. To investigate the fracture surface after fatigue testing the test bars were rapidly opened in tension.

Table 2: Test matrix.

Predeformation	Direction	Axial load	No. of test bars
PD0	Along	-100 MPa	3
PD0	Along	0 MPa	3
PD3	Along	-100 MPa	2
PD3	Along	0 MPa	2
PD3	Against	-100 MPa	2

The second test of the load case where a PD3 test bar was subjected to torsional loading against the direction of predeformation was restarted after running a few cycles with a frequency of 1 Hz. The test became unstable and was therefore interrupted by the narrow strain limits set in the control software. To avoid further interruptions it was decided to make the test more robust by restarting the test at a lower frequency of 0.4 Hz.

2.3.2 Fatigue life definition

Axial and torsional stiffness were used as a comparative measurement of the material damage evolution during fatigue testing. This method is easy to implement, allows continuous measurements, and relates to changes in mechanical behavior. An alternative approach that can be used is potential drop as was done by Tanaka et al. [16] during torsional fatigue loading of notched test bars. This method requires careful calibration and is limited by electrical shortening between the fracture surfaces [17].

Stiffness measurements were conducted every 1000th cycle and the fatigue life was defined as the number of cycles until a 5% drop from the initial axial stiffness. The fatigue life was based on axial stiffness as the influence of crack face friction in the torsional stiffness measurement cannot be determined. Equations (1) and (2) define the axial and torsional stiffness, using the measured quantities described in Figure 6. These quantities were time averaged under 2 seconds to reduce measurement noise.

$$\text{Torsional stiffness} = \text{abs} \left(\frac{T_1 - T_2}{\theta_1 - \theta_2} \right) \quad (1)$$

$$\text{Axial stiffness} = \text{abs} \left(\frac{F_1 - F_2}{\epsilon_1 - \epsilon_2} \right) \quad (2)$$

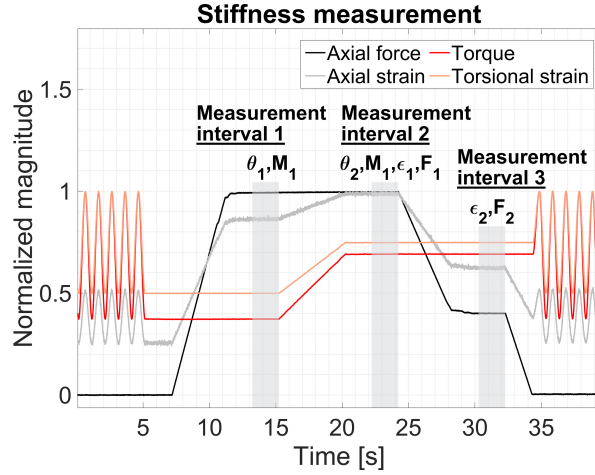


Figure 6: Measurement of axial and torsional stiffness.

The torsional stiffness was measured under a nominal tensile stress of 50 MPa at $\theta_{\min}$ and at θ_m . The axial load was applied to reduce the influence of crack face contact. At measurement intervals 1 and 2, the average magnitude of the torque, T , and the torsional rotation, θ , were measured. These magnitudes are denoted as T_1 , T_2 , θ_1 and θ_2 for respective measurement interval. The axial stiffness was measured in unloading at interval 2 and 3, between a tensile stress of 50 MPa and 20 MPa to avoid influence of plasticity. The lower limit of the axial force was set to 20 MPa to reduce the influence from crack closure. At each interval, the average force F and average strain ϵ were measured, denoted as F_1 , F_2 , ϵ_1 , and ϵ_2 .

The axial load applied during the stiffness measurements was chosen to be low to limit its influence on the fatigue life. Using such a low load implies small axial strains, making the axial stiffness measurements very sensitive to internal and external effects such as vibrations, temperature, and crack interactions. These issues were partly mitigated by time averaging before the stiffness calculation.

3 Results

3.1 Mechanical response

As previously mentioned, the torsional strain was controlled by the rotation angle $\theta = 0.0132 \pm 0.0044$ [rad] and the axial loading was load-controlled to give a nominal stress of either 0 or -100 MPa. Due to different stress-strain behavior, depending on predeformation state and loading direction, the torque response differs between the test cases. Consequently, the local stress state is not the same in each test case.

Figure 7 shows that all test bars have a similar torque range. The undeformed test bars have a slightly higher torque range due to their higher initial stiffness, as discussed in Section 3.2.

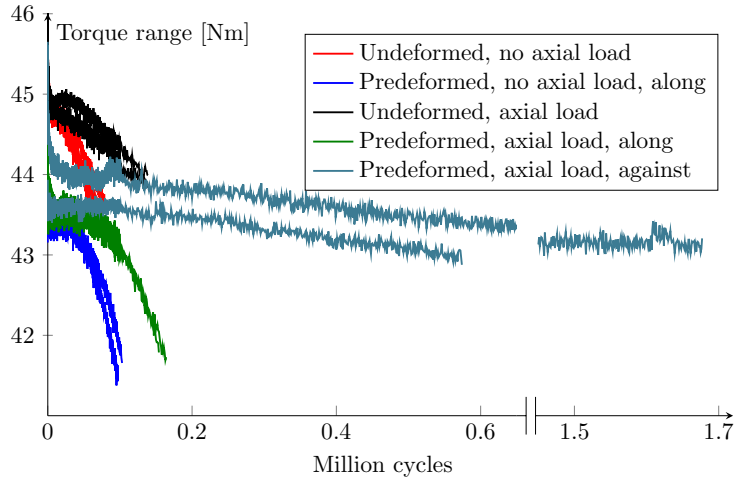


Figure 7: Torque range for each test bar. The graph has been split for improved clarity. The torque range (predeformed, axial load, reversed) linearly decrease in between the split.

Figure 8 shows the mean torque evolution. The mean rotation was chosen to give an almost pulsating torque for the undeformed test bars, resulting in the torque being approximately 20 ± 22 Nm for these cases. However, the mean torque differs between material states and loading directions. For loading against the predeformation direction, the absolute value of the mean torque is much lower than along. The latter gives a torque of approximately 45 ± 22 Nm, while the former yields $T = -7 \pm 22$ Nm. The influence of axial load on the torque response is negligible in comparison.

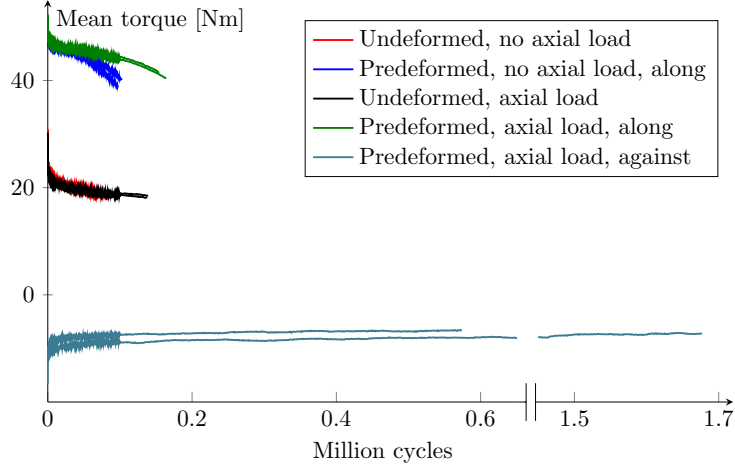


Figure 8: Mean torque for each test bar. The graph has been split for improved clarity. The mean torque (predeformed, axial load, reversed) remains constant in between the split.

Rolling contact fatigue is often attributed to plastic deformations in the contact patch, cf. e.g. Johnson [18]. To observe differences in plasticity between samples, we investigate the accumulated work during the experiments, W . Below, we motivate that the major part of W is the plastic work. Thereafter, the accumulated work in Figure 9 is presented.

The work, w_i , during a torsional cycle from time t_{i-1} to t_i is

$$w_i = \int_{t_{i-1}}^{t_i} [T\dot{\theta} + F\dot{u}] dt \quad (3)$$

where T is the torque and θ is the rotation angle over the gauge length, $L = 12$ mm. The axial contributions are the force, F , and the axial displacement, u (change of L). However, as F is constant and u remains small, the axial contribution is negligible. Finally, the accumulated work, W , is then given as the sum of all cycles, $W = \sum w_i$.

For an elastic material, $w_i = 0$, as the torque, T , only depends on the rotation angle, θ , and $\theta(t_{i-1}) = \theta(t_i)$. Hence, w_i is a measure of the inelastic work in cycle i . In this section, we motivate why this inelastic work is primarily due to plastic deformations: The reversible elastic work from the valley to the peak is about $w_{\text{elastic}} = 0.36$ Nm. In comparison, the inelastic work per cycle, w_i , is between 0.005 and 0.013 Nm after the first few cycles. Different sources contribute to the inelastic work, such as crack formation, crack face friction, and plastic deformations. The accumulated work due to crack formation under strain-controlled loading is limited to the elastic work in the first cycle. Hence, it must be less than $0.05W_{\text{elastic}} \approx 0.02$ Nm due to the 5 % stiffness reduction. The inelastic work due to crack face friction is expected to be affected by the axial load, but no strong influence is observed. Furthermore, the work due to crack face friction should increase as damage evolve, but no such increase in inelastic work is observed. Based on these indications, we will assume that plasticity is responsible for most inelastic work.

In Figure 9, no significant effects of axial forces or torsional direction are observed. The latter may seem inconsistent with the yield asymmetry reported in [19] that showed a lower yield limit in the reversed loading direction. However, those results only apply to the first loading after predeformation and not the cyclic response. Considering the undeformed test bars, these have a higher work accumulation than the predeformed bars. Figure 7 showed that undeformed test bars had a higher torque range, which may seem contradictory to more plastic work. While those test bars have 6% higher torsional stiffness, the torque ranges after the first initial cycles are only 3% higher. This difference explains why the undeformed test bars experience more plastic deformations. Furthermore, the work in each cycle, w_i , is approximately constant for the predeformed test bars. For the undeformed test bars, w_i decreases during the experiment but remains higher than for the predeformed test bars.

In summary, the undeformed test bars sustain about twice the amount of accumulated plastic work compared to the predeformed bars after the same number of cycles.

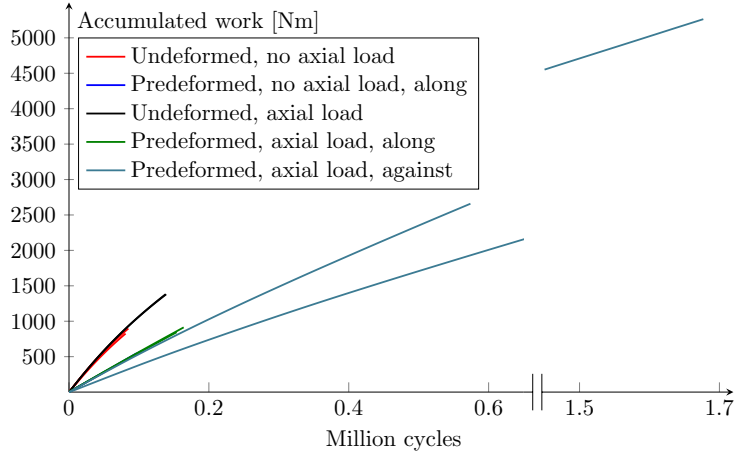


Figure 9: Accumulated work, $W = \sum w_i$. The graph has been split for improved clarity. The accumulated plastic work (predeformed, axial load, reversed) increases linearly in between the split.

3.2 Fatigue life evaluation

The initial stiffness of the undeformed and predeformed test bars, calculated as the average of the 10 first measurements are given in Table 3.

Table 3: Initial stiffness according to Equations (2) and (1) (average of first 10 measurements) and standard deviation between samples.

Direction	Undeformed	Predeformed	Unit
Axial	14.59 ± 0.05	14.27 ± 0.06	MN
Torsional	5.38 ± 0.02	5.06 ± 0.01	kNm

Compared to the predeformed material, the initial axial stiffness of the undeformed material is approximately 2% higher and the initial torsional stiffness is 6% higher. It was expected that the undeformed and predeformed material would have different initial stiffness. Meyer [19] measured the shear modulus and Young's modulus of both undeformed and predeformed tubular test bars of the pearlitic rail steel R260. It was reported that the shear modulus and Young's modulus of undeformed material were 3% respectively 1% higher than for material predeformed to $\gamma = 0.6$. The present study uses solid cylindrical test bars with a notch that induces an inhomogeneous stress field. In addition, the predeformed test bars have a shear strain gradient as opposed to the hollow test bars in [19]. Consequently, only the same qualitative differences in initial stiffness between undeformed and predeformed test bars are expected.

The stiffness measurements were filtered by a modified running average, as the standard running average will shift the data in the curvature direction. Each data point is calculated as the value predicted by a fitted 2nd order polynomial to 10 additional data points in both directions. With this method, the scatter for axial stiffness measurement was significantly reduced. Furthermore, no shift in the torsional stiffness measurements was observed. The filtered axial and torsional stiffness measurements are presented in Figures 10 and 11, respectively.

The axial stiffness measurements have a large scatter, as shown by the standard deviation (wrt. the difference between filtered and unfiltered data). For the torsional stiffness, the scatter is much lower and barely visible. This difference stems from the lower axial strain amplitude compared to torsional strain amplitude during the stiffness measurements. However, the variation between each repeated test is lower than the difference between different tests. The axial stiffness measurements are therefore sufficiently reliable. From Figure 11 it is observed that torsional stiffness initially slightly increase for predeformed material. However, it cannot be seen in the axial stiffness measurements if this effect is present due to the measurement noise, see Figure 10.

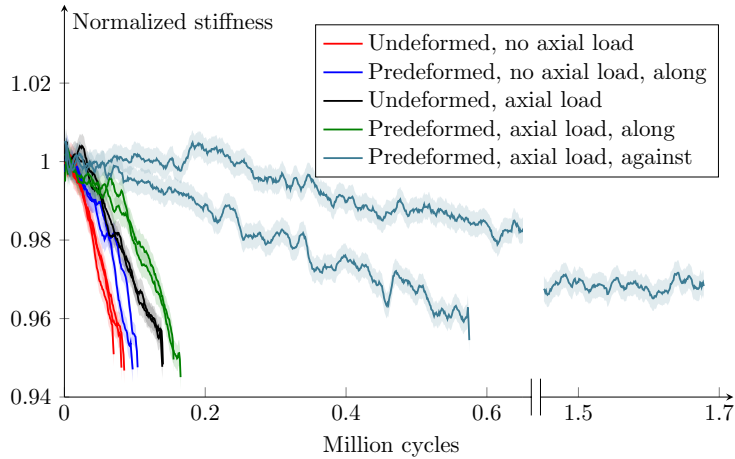


Figure 10: Axial stiffness evolution for different material and loading conditions. The colored areas show $\pm$ one standard deviation. The graph has been split for improved clarity.

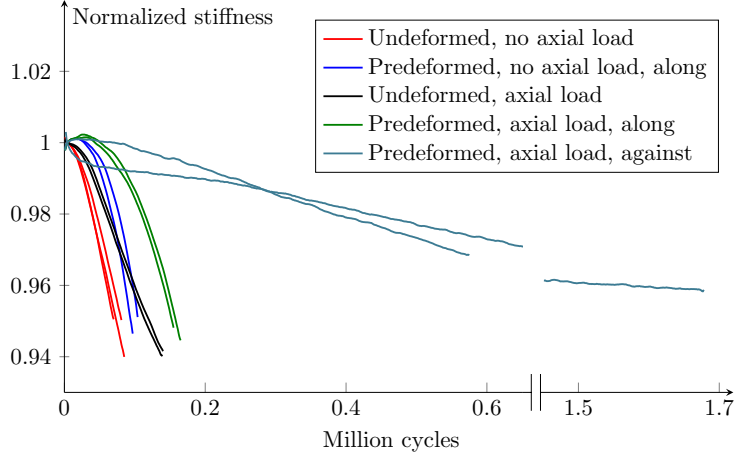


Figure 11: Torsional stiffness evolution for different material and loading conditions. The graph has been split for improved clarity.

The fatigue life was longer for predeformed material and increased when a compressive axial load was applied. The compressive load influences the fatigue life more than the material state, and the effect was similar for both material states. Reversing the direction of the torsional load increased the fatigue life of the predeformed material the most. These results were unexpected as cracks then grow along the predeformed microstructure, see Section 3.3. This effect is further discussed in Section 4. It should be noted that the duplicate test endured more than three times the number of cycles. Moreover, due to computer memory constraints, the duplicate test was interrupted before a 5% reduction from initial axial stiffness was reached. Nevertheless, the trend is significant as also discussed in Section 4.

3.3 Fractography

The fracture surface was investigated for the different material states and loading conditions. The crack paths and shape of the fracture surface depend on the material state and loading condition. In all experiments, the fatigue zone represents the growth of multiple cracks initiated along the circumference of the notch. Moreover, the fatigue zone is characterized as a complex crack network. The crack growth plane varies around the circumference, and multiple cracks have grown beneath the observed fracture surface. In addition, the crack growth direction was observed to be either predominantly inclined clockwise or counterclockwise for torsional loads along respectively against the direction of predeformation. The fraction of cracks growing in the predominant direction was estimated by counting the cracks extending outside the notch.

The fracture surfaces of the undeformed samples, with and without a superimposed axial load appear similar. In Figure 12, a representative fracture surface for undeformed samples is shown. The fatigue zone is mainly continuous with a rather uniform depth, but regions with no apparent fatigue cracking exist, see Figure 12b and c. Characteristic for the fracture surface of undeformed material is the factory roof shape resulting from primarily mode I crack growth [16]. The factory roof is mainly asymmetric and the average fraction of cracks in the predominant direction was estimated to 65%.

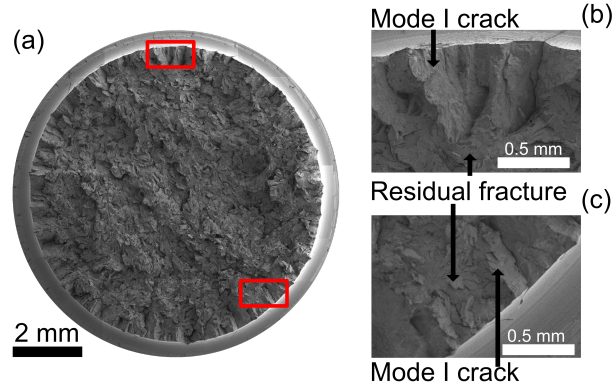


Figure 12: Representative fracture surface of undeformed test bars cyclically shear loaded with and without a static compressive load. (a) overview, (b) and (c) detailed view.

The fracture surface of a predeformed sample subjected to torsional loading against the direction of predeformation is shown in Figure 13. The fatigue zone is mainly continuous but not as uniform along the radial direction as for undeformed material. Similar to the undeformed material, the factory roof topology characterizes the fracture surface, for detailed view see Figure 13b and c. The factory roof is mainly asymmetric and the average fraction of cracks in the predominant direction was estimated to 63%.

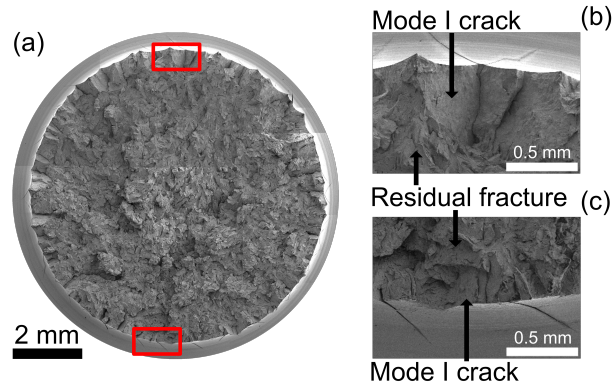


Figure 13: Representative fracture surface of predeformed test bars cyclically shear loaded against the direction of predeformation with a static compressive axial load. (a) overview, (b) and (c) detailed view.

The fracture surface of predeformed test bars, subjected to torsional loading along the direction of predeformation, is markedly different from the fracture surface of the undeformed material. Representative fracture surfaces of predeformed material, with and without a compressive load, are shown in Figures 14 and 15 respectively. The fatigue zones are heterogeneous and the crack path varies greatly around the circumference of the notch. The factory roof shape is not evident, instead, the fracture surfaces are characterized by a inclined crack growth in the clockwise direction. The fractions of cracks in the predominant direction were estimated to be 87% and 86% with, respectively without, an axial load.

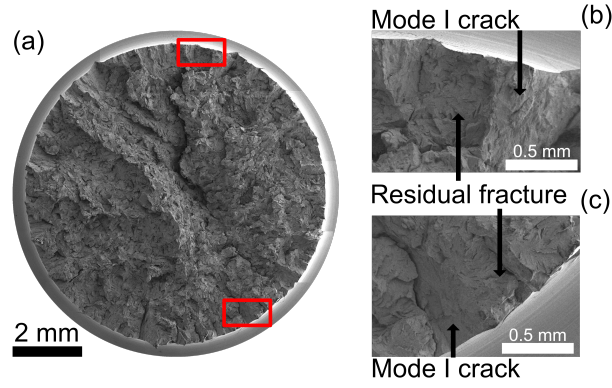


Figure 14: Representative fracture surface of predeformed test bars cyclically shear loaded along direction of predeformation without a static compressive axial load. (a) overview, (b) and (c) detailed view.

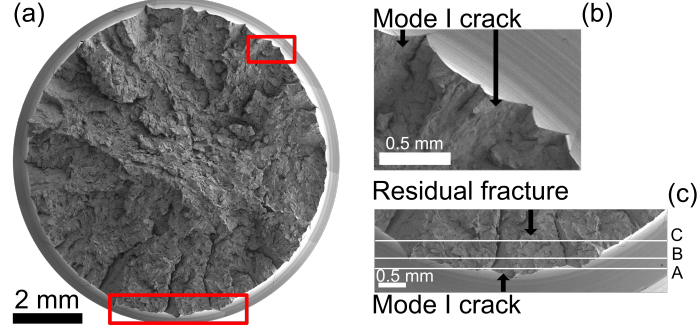


Figure 15: Representative fracture surface of predeformed test bars cyclically shear loaded along the direction of predeformation with a static compressive axial load. (a) overview, (b) and (c) detailed view. The corresponding micrographs for the transverse sectioning lines in (c) are shown in Figure 16.

The topography of the fracture surface does not capture the complete crack growth behavior as many cracks are concealed. The crack network was examined in more detail by transverse sectioning at different depths on the predeformed test bar in Figure 15. The transverse lines A-C in Figure 15c corresponds to the micrographs A-C in Figure 16. The micrographs reveal crack growth underneath what is observed as a residual fracture on the topography. These cracks are observed to mainly grow against the direction of predeformation and thus along the direction of maximum remote principal stress, as illustrated and discussed in Section 4.

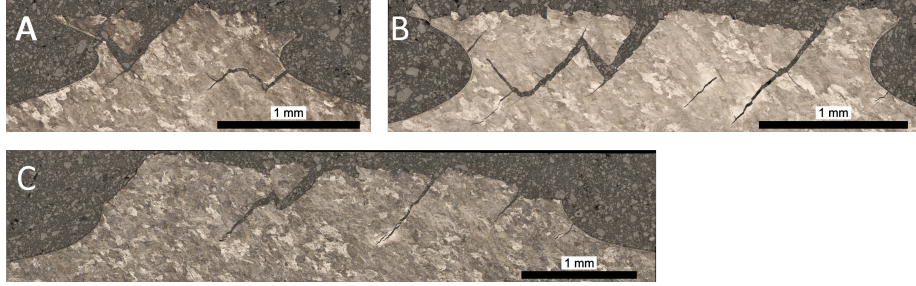


Figure 16: Radial view of crack network of the predeformed test bar in Figure 15 at different depths from the notch root (A) $51\ \mu\text{m}$ (B) $234\ \mu\text{m}$ (C) $547\ \mu\text{m}$.

4 Discussion

4.1 Simplified analysis of predeformation and cyclic stress state

As reported in Section 3.2, a compressive axial load increases the fatigue life. This finding is in accordance with common fatigue life estimation models, see e.g. the Dang Vang [20] (high cycle fatigue) and Jiang and Sehitoglu [21] (low cycle fatigue). The presented results show that the fatigue life is longer for predeformed test bars. The difference is very large when the loading direction is reversed compared to the predeformation direction. To better understand the interplay of changes in material behavior, anisotropy and fatigue life, a simplified analysis of the predeformation and the cyclic stress state is presented first.

The bars are predeformed in the negative shear direction, as illustrated in Figure 17. The initially vertical green lines slant to the left, illustrating the alignment of the microstructure (noting that the specific rotation angle is just for illustrative purposes). During testing, the material in the lower left is subjected to a negative shear strain for a positive torque (loading along with the predeformation direction). Without an axial load and for a uniform test bar, the principal stress directions are then inclined 45° (along $\hat{x}$ and $\hat{y}$) as illustrated in the lower right illustration. The stress magnitudes are then proportional to the applied torque. Hence, if the torque is positive and pulsating, $T = \Delta T \pm \Delta T$, the stress along the aligned microstructure is pulsating in tension. The stress transverse to the aligned microstructure is then pulsating in compression.

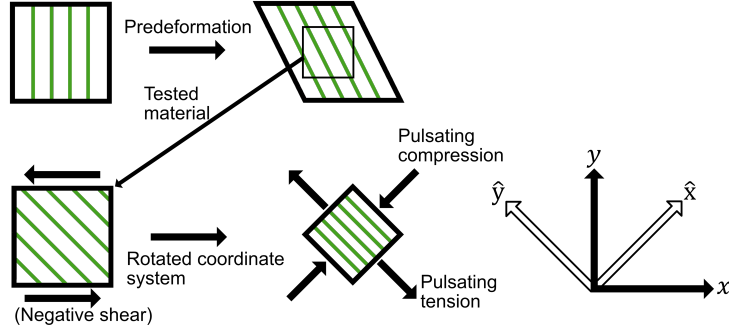


Figure 17: Predeformation and cyclic stress state.

Wetscher et al. [9] studied mode-I fatigue crack growth rates of the same R260 steel after Equal Channel Angular Pressing (ECAP) predeformation. They used Compact Tension (CT) samples in two different directions, one transverse to the microstructure alignment and one in the neutral direction. The latter corresponds to the radial direction in the present study.

Figure 7 in [9] shows crack propagation rates at different stress intensity factors, ΔK . For the present study, the samples after one ECAP pass (1A and 1B) are of particular interest since the predeformation shear strain, $\gamma = 0.67$, is similar to $\gamma = 0.56$ in the present study. For $\Delta K \in [7, 10] \text{ MPa}\sqrt{\text{m}}$, the transverse crack propagation rate (Sample 1B) was about twice that in the neutral direction (Sample 1A). Crack propagation relative the microstructure alignment in Sample 1B is comparable to the case in Figure 17 for pulsating tension transverse to the microstructure alignment. Whilst when pulsating tension is along the microstructure alignment the crack grows along a more difficult path than in Sample 1A. Based on these results, it is expected that the life should be shorter for pulsating tension transverse to the microstructure alignment in Figure 17. However, when the load direction was changed, a significantly longer life was observed.

As described in section 2.3.1 the complementary test of the load case torsional loading against the direction of predeformation was restarted. The mechanical response as presented in 3.1 shows a similar mechanical behavior with only small differences in the torque range and mean torque. Whilst a notable difference is observed in the plastic work. Based on the similar mechanical response it is thought that the complementary test strengthens the finding that fatigue life strongly correlates with the direction of the applied load where torsional loading against the direction of predeformation significantly increases the fatigue life. However, as the test was restarted after several weeks with a lower frequency there exists a larger uncertainty in fatigue life as compared to the first test. It cannot however be concluded why a much longer fatigue life was observed in the complementary test as several factors can be contributing e.g. frequency dependence, static strain ageing and natural variability.

4.2 Effect of mean torque on crack path and fatigue life

While the torque ranges are similar for all test cases, the mean torque differs significantly between predeformation states and torsion directions. Considering

the undeformed test bars, the approximate torque, $T \approx 20 \pm 22$ Nm gives the case depicted in the lower right part of Figure 17 (without the aligned microstructure). The majority of the cracks in Figure 12 grow in the $\hat{x}$ direction. As shown in Figure 9, plastic deformations occur during the cyclic loading, which causes residual stresses. In combination with the notched sample geometry, this implies that the stress state is more complicated than that depicted in Figure 17 which may explain why there are also cracks growing in the $\hat{y}$ direction.

For torsional loading in the predeformation direction, the fracture surfaces are very different from the other test cases. In this case, the mean torque is much higher, $T \approx 45 \pm 22$ Nm, resulting in high tensile stresses along $\hat{y}$ and high compressive stresses along $\hat{x}$. This will strongly promote crack growth in the $\hat{x}$ direction. However, the results in Wetscher et al. [9] show that crack growth is slower in this direction. This may partly explain why a longer life is observed in these predeformed cases despite a much higher tensile stress. The fracture surfaces in Figures 14 and 15 also show much larger fatigue cracks along the $\hat{x}$ direction compared to the undeformed test bar in Figure 12. These larger cracks result in a more irregular fracture surface. There are also very few cracks growing in the $\hat{y}$ direction.

When the torsional loading is reversed for predeformed test bars, a very different torque, $T = -7 \pm 22$ Nm, is observed. In the simplified analysis above, such a torque response gives almost fully reversed tensile stresses in both $\hat{x}$ and $\hat{y}$ directions. Without an aligned microstructure, much longer fatigue lives can then be expected, if analyzed by using e.g. the Jiang-Sehitoglu [21] criterion. Even with the aligned microstructure, the same effect is clearly observed in the present study. The distribution of crack growth directions in Figure 13 is, however, similar (but reversed) to the undeformed case. Hence, more cracks grow along the aligned microstructure than expected based on the stress state. This result is in accordance with the findings in [9].

The effect of mean torque has been investigated by Wang et al. [22] and McClaffin et al. [23] in isotropic medium carbon and high strength steel respectively. It was reported that mean shear stress has a detrimental effect on the fatigue life. The principal tensile stresses that are highest for predeformed material subjected to torsional loading along the predeformation direction. Thus, the fatigue life should be shorter as compared to underformed material but the opposite was observed. Hence, we conclude that the predeformation extends the fatigue life for torsional loading in this direction. Loading against the direction of predeformation yields a much lower mean torque and based on the simplified stress analysis it should have the longest fatigue life which was also observed. Thus, it cannot be concluded whether predeformation has a beneficial effect when subjected to loading against the direction of predeformation.

4.3 Outlook for proposed method

The proposed method is suitable to evaluate fatigue of predeformed material during shear-dominated loading. In comparison to e.g. Wetscher et al. [9] and Schnalzger et al. [13], we observe a complex crack pattern. Our method is thus unsuitable to calibrate discrete crack propagation models. However, the results are useful to calibrate diffuse damage models, such as phase-field damage models (see e.g. Ambati et al. [24]). An additional advantage of the proposed method is the relatively simple sample preparation, not requiring hollow samples. This

feature makes the method suitable to evaluate the performance of materials under predeformed conditions. Even though crack growth in rails occurs under predeformed conditions, such tests are not included in the rail material quality standard EN13674-1:2011 [25].

5 Conclusions

A new fatigue test method of rail steels under conditions similar to rolling contact loading, accounting for the large accumulated shear strains close to the surface, has been proposed. The method has been applied to investigate the influence of accumulated shear strains, compressive stresses, and loading direction in the R260 rail steel. The main findings are:

- The torque range is similar for all cases, but the mean torque depends on predeformation and load direction.
- A compressive axial load prolongs the fatigue life while having negligible influence on the torque.
- The predeformed material sustains more cycles, even though loading along the predeformation direction increases the mean torque.
- Loading against the predeformation direction increases the fatigue life even though cracks grow in a weaker microstructural direction. This result was attributed to the lower mean torque.
- The crack growth direction correlates strongly with the mean torque.
- Complex crack networks, similar to those observed in rail field samples, form around the notch.

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