TECHNICAL ARTICLE—PEER-REVIEWED

Comparison of Rail Head Checks Using Destructive and Non-Destructive Examination Methods

Tamás Máté · Péter T. Zwierczyk

Abstract The development of railway transportation requires increased vehicle speeds and axle loads. The enhanced effects from the vehicle side and the new harder steel rails used in tracks lead to increased Rolling Contact Fatigue (RCF) crack initiation and propagation. One of the most frequently occurring RCF defects is the Head Checks (HC) around the rails' gauge corner. These defects cause severe economic and safety issues. In-use maintenance is based on corrective and preventive approaches, which are neither cost-effective nor reliable. The development of new predictive methods and the improvement of the existing corrective and preventive approaches offer a solution to this issue. In this investigation, an HC-infected rail sample was examined with non-destructive Dye Penetration Testing, Eddy-current Testing, and Visual Microscopic Testing after the sectioning of the sample. In the future, an extensive HC database can be created from the results of the developed evaluation process, which may serve as the base validation tool for newly developed predictive maintenance methods.

Keywords Railway · Maintenance · Rail failure · Rolling contact fatigue · Head checks

T. Máté (✉) · P. T. Zwierczyk
Department of Machine and Product Design, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest, Hungary
e-mail: mate.tamas@gt3.bme.hu

Introduction

Railway transportation is one of the most important, most widely used, and most economical way of passenger and goods carriage both on short and long hauls. The operation's efficiency is based on the contact condition between the rolling metal elements – rails and wheels–, which fundamentally have low friction values in normal circumstances. However, when the wheelset faces significant slip (e.g., in curves, at railroad switches, during acceleration, or intensive braking), this small amount of friction contributes enough to be the reason for various failures with time. Despite the development of rail and wheel materials, the most significant problems are the defects based on RCF (Rolling Contact Fatigue) [1–5], such as the HC (Head Check) cracks at the rail gauge corner. Such cracks occur due to the continuous plastic deformation of the contact surfaces caused by the unfavorably high contact loading and friction heat generation problems in sections where high sliding occurs. The industry's constant growth brings the need for higher speeds and axle loads in railroad service, which, even with enhanced lubrication management and inspection, accelerates failure mechanisms and requires more frequent and purposeful maintenance of the track [6].

Railway maintenance consists of three essentially different approaches [7]:

- Corrective maintenance: is performed after the occurrence of the failure.
- Preventive maintenance: requires frequent inspection of the railway asset to take preventive actions before failure.
- Predictive maintenance: determines the behavior of the damage mechanisms for the in-service equipment to

predict when it is necessary to take action against failure.

Rail system maintenance rules used in practice are mainly based on the first two approaches. They do not have a properly defined scientific background, which could create significant uncertainty in operation and could cause negative economic and safety issues. Furthermore, there is a substantial need to improve the existing processes and develop new predictive maintenance rules to increase railway asset reliability and service efficiency.

The key to these numerical predictive models is validation. In this investigation, a test and evaluation process was implemented to gather decent data on present HC defects, which will serve as a validation tool for future predictive models.

Preventive and Predictive Rail Maintenance

The preventive maintenance of rails is based on determining the depth of the defect measured from the surface. This means that it is necessary to act beyond a certain crack depth before it becomes dangerous. Besides replacing the rail section, the other option would be treating the surface area affected by cracks. One of the questions that induced the investigation is whether it is necessary to remove the cracks entirely, or it is satisfactory to grind the surface back to a state of insignificant defective depth. The appearance of HC cracks is inevitable in the current operating conditions and due to the applied hardened or naturally hard rail materials [8, 9].

The preventive maintenance idea is to develop a numerical crack propagation model to estimate the lifetime of different track sections with various known load conditions. Consequently, it would reduce the overall operation costs by reducing the number of required inspections, and all in all improving maintenance planning.

To create such a universal predictive method, a well-built database is needed of the HC cracks' propagation behavior in various load and lubrication conditions. This may provide a solid and reliable validation input source to the numerical method.

Test Process of the Rail Section

The experimental phase of the investigation aimed at developing a test process to obtain an overall view of the HC cracks in the available rail section. Another objective is to develop a comparison-based evaluation procedure to analyze several rail sections with various loading records to establish a database.

The examination started with non-destructive DPT (Dye Penetrant Testing) and ECT (Eddy-Current Testing) [10] and was followed by VMT (Visual Microscopic Testing) after the sectioning of the rail sample. The investigated rail section had been a part of a railroad switch.

Dye Penetrant Testing of the Rail Sample

The DPT gave a great view of the surface cracks' external dimensions, orientation, and quantity. Several small cracks were identified: both the significant and the almost invisible HC cracks were revealed. However, only the bigger cracks were considered during the evaluation, because smaller ones would not be useful for validation purposes. The result of the DPT is shown in Fig. 1. The surface contours of cracks are highlighted in color. Yellow indicates the medium-length HC cracks, and blue marks longer, coherent HC-like cracks. The damage covers the entire length of the sample.

Due to the slightly different loading of the railroad switch, the HC cracks are oriented at a smaller relative angle along the rail gauge corner. Some of them are even grown together. The deeper cracks can be roughly identified from the amount of recovered penetration fluid on the surface. This allows for a good comparison with the ECT and VMT measurements.

Eddy-Current Testing of the Rail Section

The ECT technique is an excellent method to have a quick rough view of the inner dimensions of the cracks. The method contains a significant assumption in the case of HC crack evaluation. The ECT can only determine the crack length in the rail section of the Eddy-current sensor, but the HC cracks are categorized by the vertical crack depth, which equals the distance of the crack tip from the surface. The aggravating factor in the evaluation is that the HC cracks tend to change direction at 3–5 mm depth, from the initial $\sim$ 10–30° (1st phase) to a severe propagation angle of $\sim$ 50–60° (2nd phase) [11]. The measured crack length must be converted to vertical crack depth by an assumed propagation angle to calculate a close approximation. According to the available inspection standard [11], the average propagation angle in use is 25° (Fig. 2), assuming both crack stages.

While the vertical crack depth in the 1st phase is overestimated, in the 2nd phase, it is underestimated by the ECT. The evaluation is based on the practical experience of the measured assumed crack and the actual crack path. These meet at 2.7 mm depth below the rail surface; therefore, if any measurements exceed this value, immediate action must be taken to avoid critical propagation, which can cause fracture of the rail or derailment in the
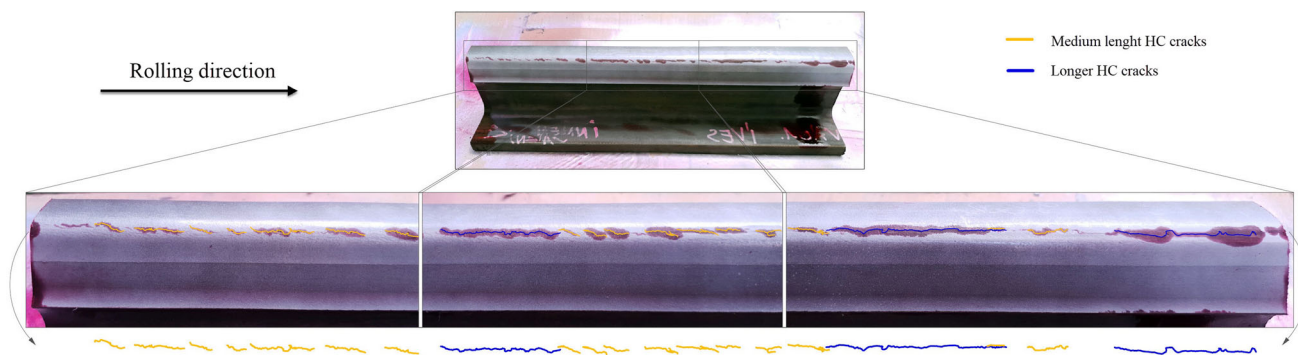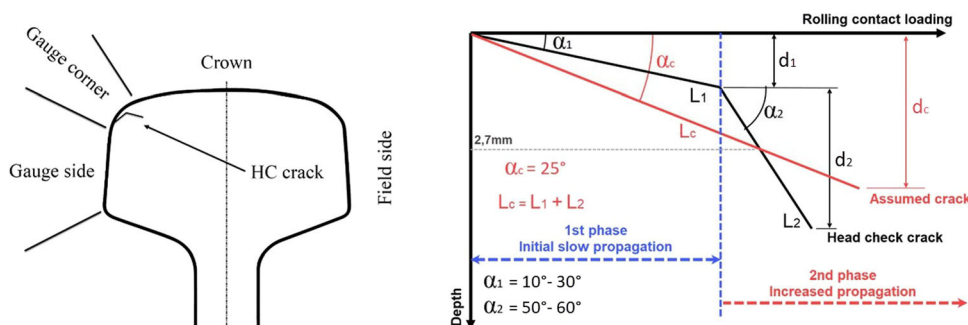
1900

J Fail. Anal. and Preven. (2022) 22:1898–1904

Fig. 1 The DPT highlighted the cracks along the rail gauge corner

Fig. 2 The concept of the agreed 25° (α_c) propagation angle, based on [11]

worst case. The test rig and the test arrangement with the Eddy Current sensor positions can be seen in Fig. 3. The ECT equipment had four sensors set at a specific angle, oriented from the railhead towards the rail gauge corner, and only the third and fourth channels provided appropriate data about the cracks. Consequently, these channels were evaluated. The test results are given in Fig. 4. According to the ECT inspection, there are no 2nd phase HC cracks in the rail section, but some significantly deeper cracks appear at the ends.

Visual Microscopic Testing of the Rail Section

To have a more accurate insight and to be able to reveal the absolute depths and inner crack geometries, a 75 mm long sample of the rail was sectioned (Fig. 5).

Sixteen slices had been made with an average thickness of 3.65 mm and material removal of roughly 0.9 mm between the pieces. The cutting was performed with an industrial saw machine; the rough surface had to be ground and polished to clear the cracks for microscopic inspection. After the preparation, a new DPT was performed on the reassembled group of slices (Fig. 6.) to see crack formation on the surface after the material removal.

Afterward, each side of the slices was examined through VMT, and the data recording was performed from the

railhead towards the rail gauge corner. Three main values were recorded about the cracks (Fig. 7): the vertical crack depth (1), the crack length on the cut surface (2), and the angle of the crack propagation (3). The inspection and measurements show that the upper cracks are usually the deepest and longest ones in the section. None of the cracks turned significantly upwards or downwards, but some changed directions slightly (Fig. 8).

Moreover, some slices have signs of minor pitting around the crack's initiation point. This material loss can be explained by the initial small propagation angle of these cracks and the enhanced mechanical load on the railroad switch (Fig. 9). The cracks with maximum vertical depth along the sectioning can be seen in Fig. 10. The propagation angle varies from 8 to 40°, which means that the assumption of 25° in the case of the ECT can lead to incorrect results in extreme cases.

Results

The performed tests revealed much information about the cracks themselves and the capabilities and boundaries of the processes.

All three tests are informative individually, but a coupled analysis is far more explanatory. A comparison of the

Fig. 3 The test rig and the sensor position setup (evaluated channels: channel 3–position 3, channel 4–position 1)
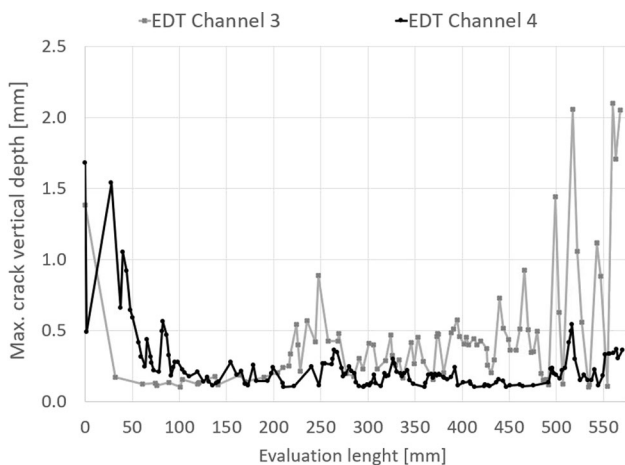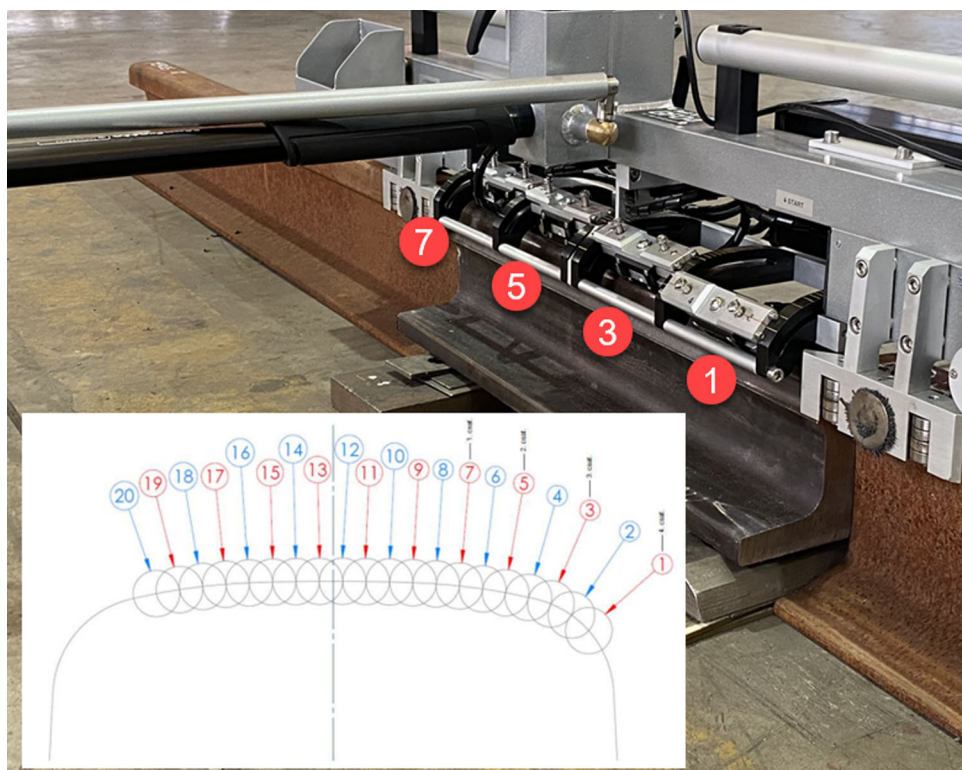

Fig. 4 Evaluation of the ECT, gray–channel 3, black–channel 4

Fig. 5 The part of the rail which was sectioned

three test results can be seen in Fig. 11. The DPT and the VMT results show strong similarities, while the ECT is further from them. However, concerning the whole length of the rail sample, similarities between the ECT and DPT could be observed as well (Figs. 1, 2, 3, and 4). The accuracy of the ECT depends on various circumstances at a time (e.g., the sensor angle, the crack orientation, the crack propagation angle, etc.). This reason is why it is most widely used to determine defect ratios as a statistical result in a given length of the track.

By coupling the visual data of the DPT from the rail surface and VMT data directly from the inner, crack-infected part of the rail, the visualization of the HC cracks can be created. The three-dimensional representation of the HC cracks in the sectioned sample is illustrated in Fig. 12.

1902

J Fail. Anal. and Preven. (2022) 22:1898–1904

Fig. 6 DPT on the reassembled pointed slices–highlighted crack paths
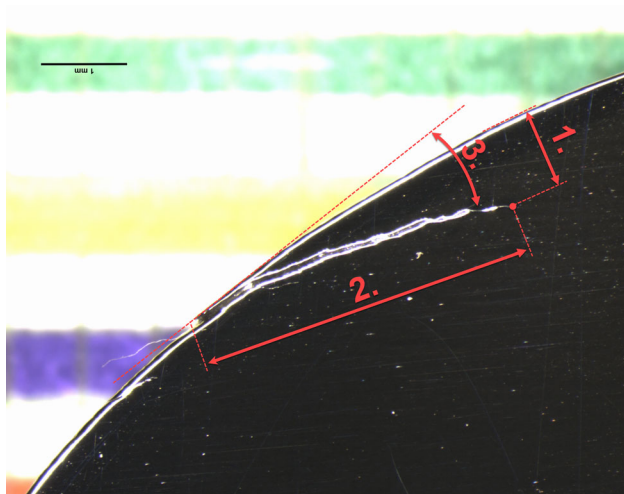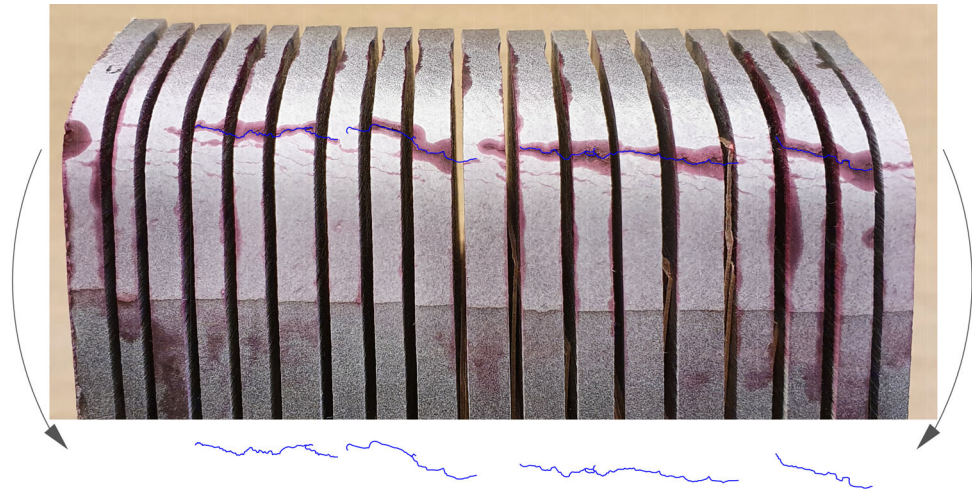
Fig. 7 A HC crack in a slice of the rail inspected with the VMT, 1–vertical crack depth, 2–crack depth on the cut surface, 3–crack propagation angle

Conclusions

In the present investigation, three phases of non-destructive and destructive tests were performed on an HC crack-infected rail sample. The objective was to evaluate the cracks and to develop a test process that could be used for effective mass testing on more samples in the future.

The tests gave a detailed view of the HC cracks in the rail material. By performing the DPT and the VMT, the cracks' actual shape and orientation could be determined. If this data is coupled with the ECT result, the connection between the actual crack details and the statistical data could be distinguished. By establishing an extensive crack database with all the measured samples' load history and ECT history, a powerful tool would be available to improve the actual preventive maintenance methods by supporting future ECT measurements. Moreover, a highly reliable validation tool could be accessible for the
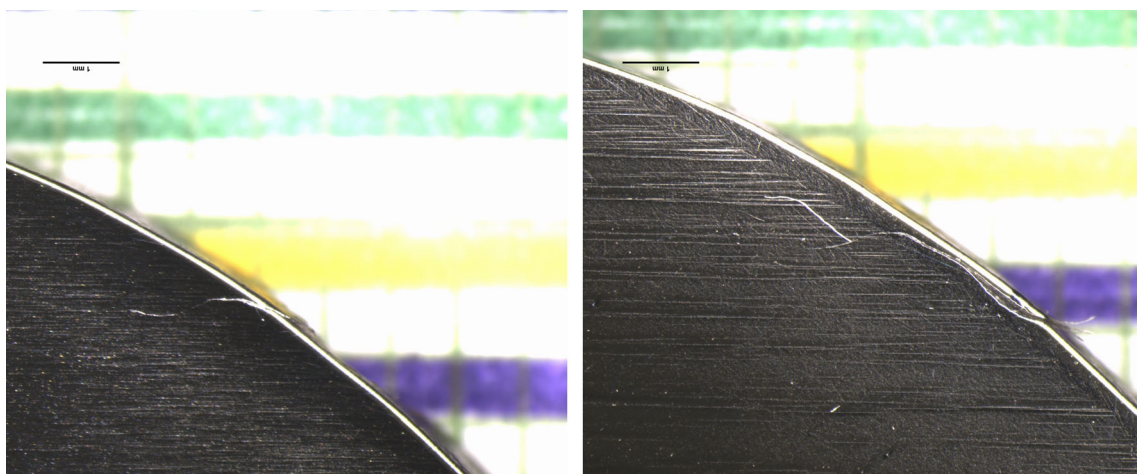
Fig. 8 Slight direction changes in the propagation of the cracks
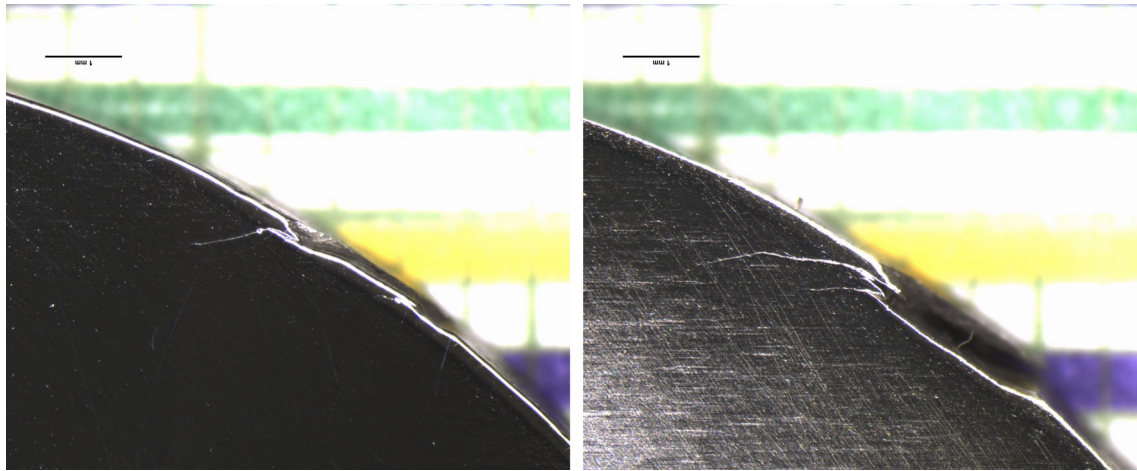
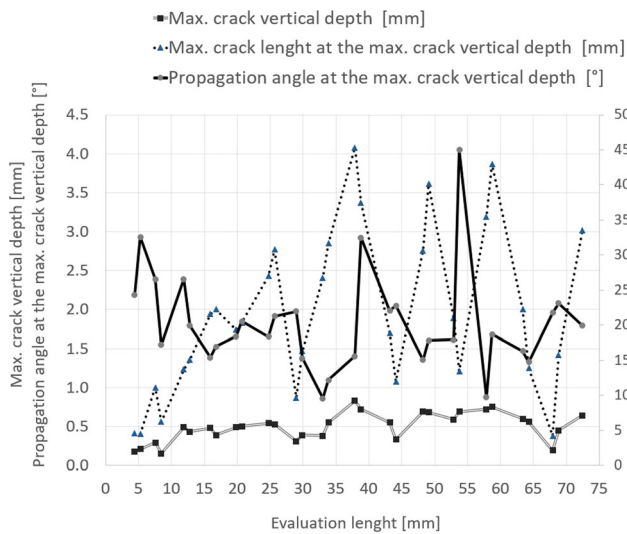**Fig. 9** Minor pitting around the initiation points of the cracks

Fig. 10 Evaluation of the VMT, details of the cracks with max. Vertical depth

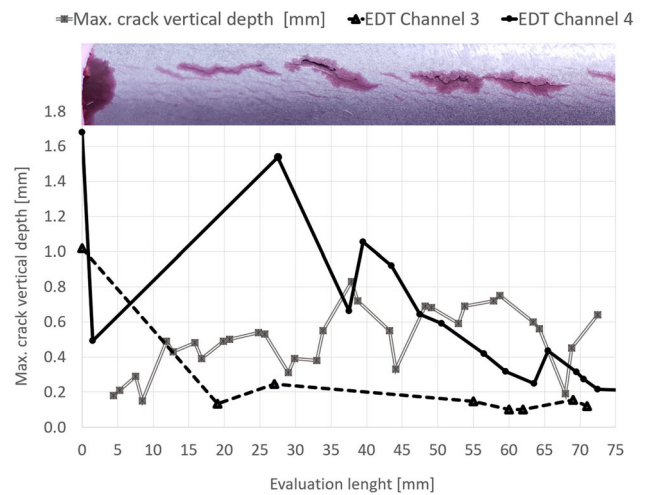**Fig. 11** Evaluation of the DPT, the ECT (ch.3, ch.4), and the VMT results on the sectioned part of the rail section

numerical crack propagation models, which are meant to be used to develop predictive maintenance methods.

Further possible improvements to the process include:

– EDM (Electric Discharge Machining) needs to perform the sectioning of the rail sample to have an acceptable surface quality for the VMT at first glance. The cutting of the railhead is more than enough locally, where the cracks are located, to accelerate the sectioning.

– A well-controlled test environment and application process are needed to achieve more accurate, comparable results with the DPT.

– Development of a controlled DPT station to achieve more reproducible results.

– With a well-controlled DPT process, the crack depths could be estimated roughly by the amount of liquid leaked back to the surface.

– Employment of a special setup of the Eddy-current mobile test equipment on railroad switches where the crack location and orientation are different from the regular head checks.

– Development of a simple software-based VMT crack evaluation and a parametric 3D model to represent the HC cracks more effectively.
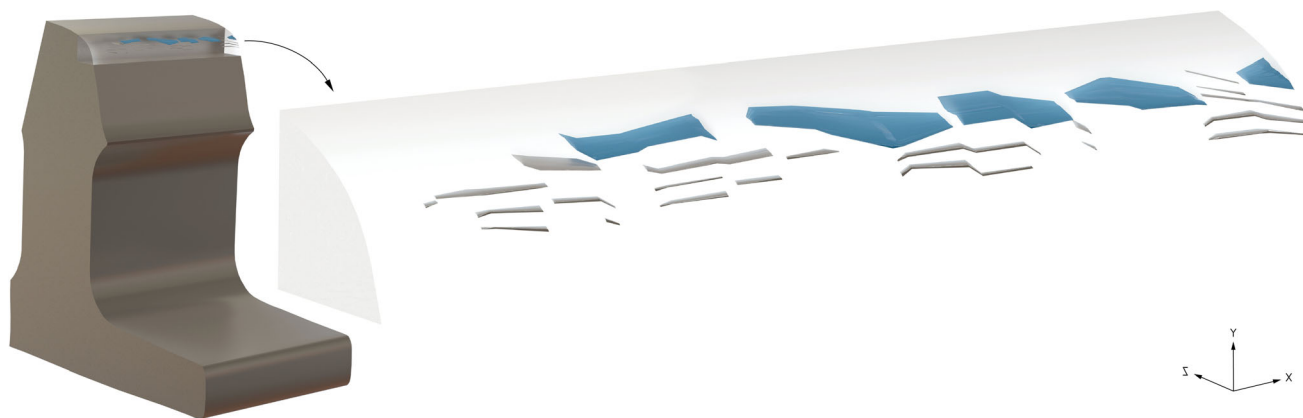
1904

J Fail. Anal. and Preven. (2022) 22:1898–1904

Fig. 12 Representation of the DPT and VMT inspection data, visualization of HC (blue), and other more minor (gray) cracks which was found in the sample (Color figure online)

References

1. E. E. Magel, 'Rolling contact fatigue: a comprehensive review', U.S. Department of Transportation. Federal Railroad Administration, 2011. doi: https://doi.org/10.4224/23000318.

2. A. Ekberg, E. Kabo, Fatigue of railway wheels and rails under rolling contact and thermal loading—an overview. Wear. **258**(7), 1288–1300 (2005). https://doi.org/10.1016/j.wear.2004.03.039

3. M. Steenbergen, Rolling contact fatigue: Spalling versus transverse fracture of rails. Wear. **380–381**, 96–105 (2017). https://doi.org/10.1016/j.wear.2017.03.003

4. M. Steenbergen, Rolling contact fatigue in relation to rail grinding. Wear. **356–357**, 110–121 (2016). https://doi.org/10.1016/j.wear.2016.03.015

5. A. Ekberg, B. Åkesson, E. Kabo, Wheel/rail rolling contact fatigue–Probe, predict, prevent. Wear. **314**(1), 2–12 (2014). https://doi.org/10.1016/j.wear.2013.12.004

6. R. Lundén, B. Paulsson, Introduction to wheel–rail interface research, in *Wheel–Rail Interface Handbook*. (Elsevier, 2009), p. 3–33

7. B. Dhillon, *Engineering Maintenance: A Modern Approach*. (CRC Press LLC, USA, 2002)

8. H. Muster, H. Schmedders, K. Wick, H. Pradier, Rail rolling contact fatigue. The performance of naturally hard and head-hardened rails in track. Wear. **191**(1), 54–64 (1996). https://doi.org/10.1016/0043-1648(95)06702-7

9. J.-W. Seo, H.-K. Jun, S.-J. Kwon, D.-H. Lee, Rolling contact fatigue and wear of two different rail steels under rolling–sliding contact. Int. J. Fatigue. **83**, 184–194 (2016). https://doi.org/10.1016/j.ijfatigue.2015.10.012

10. H.-M. Thomas, A. Dey, R. Heyder, Eddy current test method for early detection of rolling contact fatigue (RCF) in rails. Insight—Non-Destr. Test. Cond. Monit. **52**(7), 361–365 (2010). https://doi.org/10.1784/insi.2010.52.7.361

11. 788/2017/MAV–MÁV Zrt., 'D.10. Utasítás–Vasúti sínek diagnosztikája'. MÁV Zrt. Pályalétesítményi Főosztály, 2017.