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Rolling contact fatigue, wear and broken rail derailments

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A R T I C L E I N F O

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A B S T R A C T

Rolling contact fatigue (RCF) and wear are inevitable in the wheel/rail system, but resulting failures and derailments need not also be inevitable. Understanding why and under which conditions broken rails and derailments are likely to occur will focus research, inspection and maintenance efforts to minimize their probability. RCF leads to many broken rails, and rails with severe RCF damage are difficult to inspect. Yet wear reduces the extent of crack growth and hence can be beneficial in some cases. On the other hand, wear changes wheel and rail profiles, may expose virgin material to contact stresses, and reduces the section strength, which may lead to higher stress from bending and torsion. These influences are explored together with case studies of operational derailments. Based on this information and the current state of the art – both theoretical and practical – a number of issues are raised which need to be addressed through further developments in understanding and mitigating strategies to reduce the risk of failures from RCF and wear.

1. Introduction

Despite the increasing use of improved rail steels and maintenance practices, rails still fail and the costs of rail and wheel maintenance, inspection and replacement due to wear and rolling contact fatigue (RCF) are well acknowledged (e.g. Ref. [1]). But wear and RCF also contribute to broken rails. These are quite common in many railways and in North America roughly one in every 300[1] results in a derailment. While many rails break at welds, a large number fail at transverse defects, which for the purposes of this paper, are defined as [2];

> *A type of fatigue that has developed in a plane transverse to the cross-sectional area of the rail head. Development can be normal or in multiple stages prior to failure. The transverse defect is only identified by the nondestructive inspection process, unless the defect has progressed to the rail running surface and has cracked out.*

In either case, clean (straight) breaks are usually not a problem – the gap that arises can often be spanned by the passing wheels, particularly if the overall track condition is good. Broken rail derailments are most likely to result when a length of rail is affected by several transverse defects, such that one breaks and subsequent impact loading causes other nearby locations to fracture and a longer loss of running surface occurs. One of the most well-known examples of this was the Hatfield incident in the United Kingdom (UK) in October 2000 [3], when a high speed passenger train derailed as a result of multiple rail breaks from RCF damage, resulting in the loss of four lives and injuries to a further 70 individuals.

Some recent examples of derailments caused by RCF include:

i. Ellicott City, Maryland, USA: August 20, 2012.
A train derailed immediately in advance of a bridge, with two trespassers on the bridge being killed. The rail fractured at the point of derailment due to a transverse defect that initiated at gauge corner head checks. Several other fractures followed over a 5 m length, breaking the rail into several fragments. The largest defect found was relatively small – 24% of the head area. Less than 1.5 million gross tons (MGT) of traffic passed between ultrasonic inspection and failure.
ii. Columbus, Ohio USA: July 11, 2012.
A train travelling through a 9.1 degree curve at 27 mph derailed when the rail fractured under the train. There was a release of hazardous goods and fire. The probable cause of the accident was a broken rail that exhibited evidence of rolling contact fatigue. Fifteen transverse defects were found amongst the 35 pieces of rail recovered from the derailment site, ranging in size

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[1] US Class 1 railroads, average of 2011–2013, inclusive.

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from 5–70% head area. In all but one case head checking and flaking was also noted. The rail was well worn.

iii. Bates, South Australia, June 10, 2007.
A freight train derailment near Bates in South Australia caused significant damage to the track and rolling stock. Of 10 wagons that separated from the train, four overturned. The investigation found that a broken rail, emanating from a transverse rail defect, had probably caused the derailment [4].

iv. Gainford, Alberta, Canada, October 19, 2013.
Thirteen cars containing crude oil and liquefied petroleum gas (LPG) derail as the high rail of this 550 m radius curve breaks into several pieces. Two cars containing LPG were breached and ignited. About 185 m of track was destroyed, 106 homes evacuated, 1 home damaged. The high rail was near its wear limits, showed heavy surface fatigue and was later found to have many transverse defects [5].

v. Storsund–Koler, Sweden: May 11, 2013. A freight train derails and causes massive damage and traffic disruptions. The indicated cause was rail breaks setting out from longitudinal cracking of the rail, which had been in operation since 1978 [6].

Transverse crack growth and subsequent broken rails can result from a combination of several factors, including track geometry [e.g. Section 4.3 of Ref. [7]], environment (especially cold weather) [8], and the characteristics of the rail material such as residual stress levels [9]. The complex interaction of these (and other) factors is one reason that despite the abundance of rolling contact fatigue cracks in a system, relatively few lead to a broken rail, and fortunately only very few of these lead to a derailment.

2. ICRI focus

An International Collaborative Research Initiative (ICRI) specifically focused on RCF and wear of rails and wheels started a project in 2014 to look at rail safety related issues. One effort was to perform an international review of transverse defects to see if there were commonalities. This work, coordinated by Chalmers University [10], compared operational experiences of cracked and broken rails from China, Russia, South Africa, Sweden, UK and United States. They found some consistency in the depth at which a surface crack turns downwards into a transverse propagation. Still, that depth of 5 mm had considerable scatter that is no doubt affected by the type of steel, profile, friction conditions, etc. This compilation of experiences has uncovered several areas where knowledge is insufficient, including the initiation and early growth of surface cracks, the influence of various (operational, material, structural, etc.) factors on the propensity for transverse propagation, and the causes and mechanism of final fracture including the propensity for secondary rail breaks. One aspect which is, however, expected to be common is that conditions which result in the development of RCF damage over extended lengths of rails (for example, the high rails in curved track) are more likely to develop multiple transverse defects and hence pose a greater risk of secondary rail breaks and resulting derailments.

3. RCF and wear

RCF is direct contributor to broken rails through two primary mechanisms:

- RCF defects are the root cause in many broken rail derailments. An evaluation of freight derailments in the European Union, USA and Russia ranked it as one of the top eight causes [11], with statistics in the USA suggesting that RCF is the cause of roughly 10% of *all* derailments [12] (the number would be greater if weld failures due to RCF were added).
- Surface cracking can seriously compromise the effectiveness of automated internal flaw detection systems. This could result in the inability to test some portion or all of the rail head, or to give false signal indications.

Wear is not by itself a primary cause of broken rail derailments, but can be a contributor in several ways, including:

- Heavy head and side wear alter the cross section and the global and local head bending behaviour, particularly under high axle loads [13].
- Heavy wear in heat treated rail grades can expose rail material with lower strength than that of the outer hardened region, especially in older steels. This increases the sensitivity to RCF damage. When combined with the effects of increasing head loss on bending stresses, the risk of transverse defects is further increased [14,15].
- Periodic wear (corrugation) may induce significantly increased dynamic loads that increase the risk of (subsurface initiated) RCF failures [16]. For rails, this is perhaps most clearly evidenced by the link between corrugation and the formation of squats [17] and squat type defects.
- Wear will alter rail and wheel profiles, which alters wheel/rail contact conditions and hence may increase the rate at which RCF initiates and also the subsequent (shallow) crack growth in rails.

In contrast, wear can also reduce the apparent crack growth rate and may be beneficial [18]. In some cases wear may alter the profile thus moving the contact patch away from the highly stressed region and reducing the crack growth rate. If this happens, the crack growth rate can decrease substantially [19]. A similar outcome is achievable by using rail grinding to alter rail profiles to facilitate less severe wheel/rail contact conditions in the vicinity of pre-existing RCF defects [20].

However, to decrease the detrimental influence of rail breaks as operational conditions get ever more severe, further improvements in knowledge, predictive abilities and implementation will be needed.

4. RCF as a direct cause of broken rails

Rails may break from various initial defects, including from cracks that form at the rail base, bolt holes, wheel burns, etc. Breaks may also develop from cracks that propagate from internal flaws resulting from the manufacturing process (e.g. hydrogen defects and non-metallic inclusions). References [2,21] provide summaries of typical defect types associated with broken rails. Here we focus on transverse defects.

We further tighten our focus to include only those transverse defects that are initiated by RCF such as squats, head checking and gauge corner collapse.

Squats develop from surface initiated cracks in the crown of the rail that propagate at a gentle slope to the rail surface. When they reach a depth of 3–5 mm they can deviate into the railhead and initiate a break. Squats have not lately been a large cause of broken rails, largely because the depression in the railhead associated with squats (also called "dark spot" [22]) is readily visible and since not all squat-type defects show a tendency to transverse deviation [23]. For example, in a review of squats on four European railroads in the late 1990s, in only one case were squats found to be within the top four causes of broken rails [24]. But squats are a large economic concern in Europe, Asia and Australia, for example,

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representing nearly 50% of defects and responsible for 20% of rail removals at one Japanese railway [25]. Regular grinding to preventively remove a thin layer of damaged material from the rail surface has proven effective in preventing rail squats [26] and squat type defects.

Head checking is the result of progressive plastic flow of near surface material as a result of high contact stress and large tractions. This is well described in many publications, including [27]. The result is a regular series of cracks, usually located towards the gauge corner of the high rail and crown or field side of low rail (see Fig. 1).

Gauge corner collapse refers to yield of the rail gauge corner under heavy concentrated loading near the rail edge. This is depicted in Fig. 2 and analyzed in [28].

In all cases, as the fatigue cracks propagate further below the running surface of the rail they are increasingly influenced by bending stresses. With wear of the rail head, these bending stresses may increase. Deep RCF cracks are affected by these longitudinal stresses which promote a transition from Mode II/Mode III growth behaviour to Mode I behaviour [18]. Subsequent transverse crack growth may eventually cause a rail break.

Whereas the squat and RCF cracking are externally visible, the transverse crack growing within the rail head, whether originated

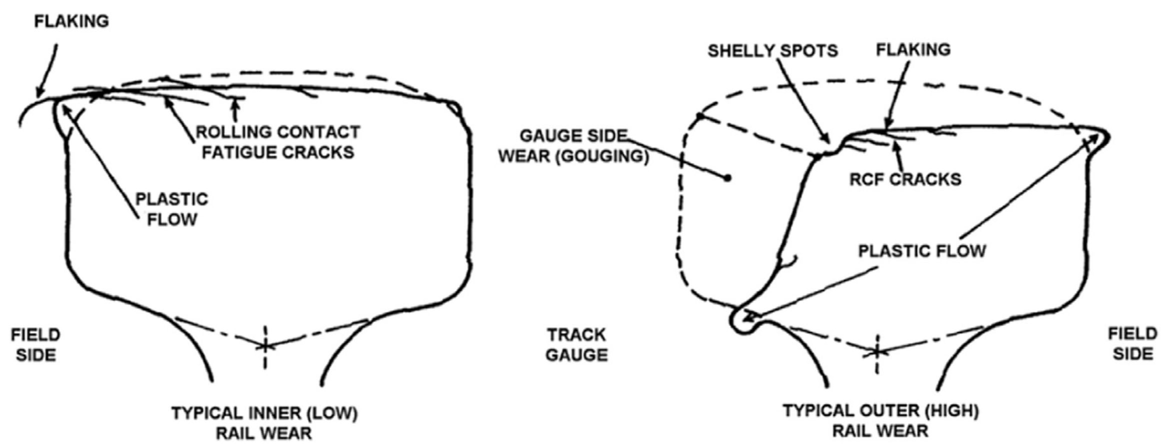

Fig. 1. Common wear and checking conditions on curved rails.

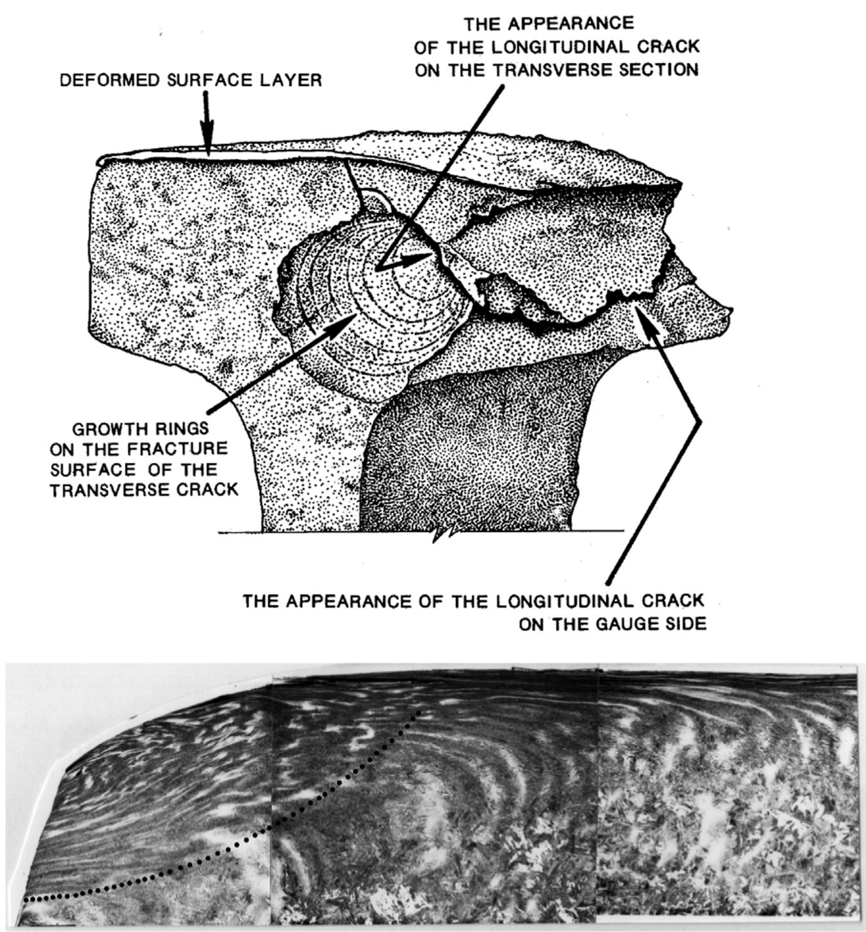

Fig. 2. The mechanism of gauge corner collapse.

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by surface or subsurface failure, is much more insidious since it hides beneath the surface of the rail giving little or no outward indication of its existence. In the same review of four European agencies [24], three of the four agencies list transverse defects as the leading cause of broken rails, accounting for roughly 40% of failures in each case.

Since the Hatfield incident in 2000, awareness of broken rails from rolling contact fatigue has significantly increased in Europe and extensive re-railing improvements to track geometry and regular rail grinding have eased broken rail concerns. But the transverse defect remains a threat, especially on heavy haul railways, as the derailment examples at the start of the paper illustrate. Transverse defects from rolling contact fatigue can be initiated in several ways:

1. Excessive loading near the rail gauge corner overstresses and can cause yield along an arc of collapse. The resulting deep seated shell when combined with an internal flaw may initiate a transverse crack (see Fig. 3). Initiators have historically been non-metallic inclusions [29], which are now much less common due to improvements in steel-making technology. But even in the absence of inclusions, and in well-lubricated conditions, gauge corner collapse can occur.

2. Surface initiated RCF cracks [30] that grow into the rail head under repeated loading may eventually turn transverse in response to a combination of contact loading, bending, thermal and residual stresses (see Fig. 4).

3. Transverse defect can also form by mechanisms that are not strictly RCF. For example, the “reverse TD” has recently emerged in North America as a cause of broken rails, derailment and rail replacement. It develops from a “cold-rolled” plastic lip that develops at the bottom of the gauge face (see Fig. 5A) and appears to be initiated by fracture of the plastic lip and

Fig. 3. Transverse defect initiated by a deep seated shell from gauge corner collapse.

Fig. 4. Transverse defect developed from gauge corner cracking.

A

B

C

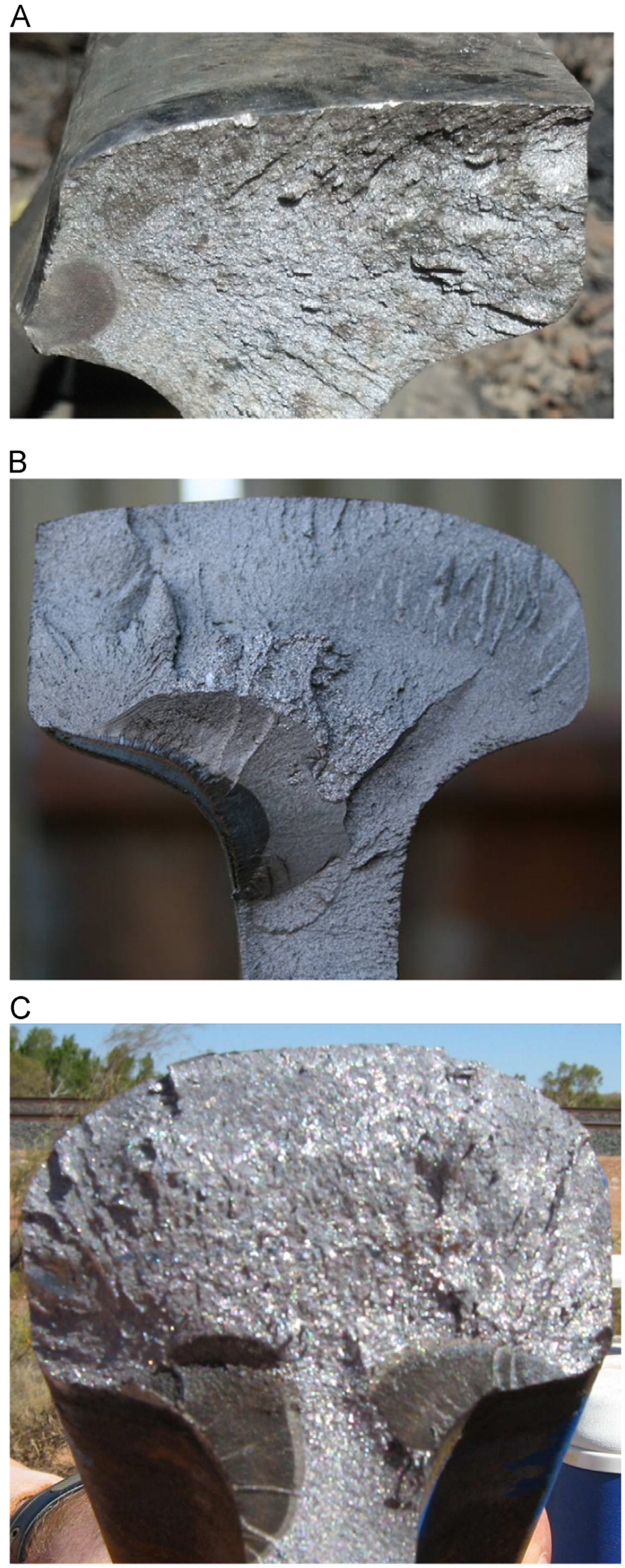

Fig. 5. Examples of transverse defect forms that are not directly the result of RCF.

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subsequent propagation under a yet to be fully understood stress regime. An analysis of the growth behavior of these defects has indicated that loss of rail head height has a major effect on growth rates [31]. However these types of defects have also been found recently in new rail with little head wear and only modest total gauge face wear. Another mechanism for transverse defects is very large tensile spikes that can develop at stress raisers in the underhead radius and cause cracks to initiate and grow from underneath the head. Defects of this type are not expected to develop in plain rail sections, since under normal circumstances there are no stress raisers present in this region. However fatigue defects can develop in both flash butt and aluminothermic welds. In the former, the stress concentrators can take the form of flow lips from the shearing or trimming process; in aluminothermic welds, initiation occurs at cold laps or defects at the edge of the weld collar [32]. In both cases the presence of elevated residual stresses from the welding process contributes to the initiation and propagation of fatigue cracks, while head wear increases the bending stresses that propagate the transverse crack. There may also be additive localized tensile stresses where the rail head bends at the web, the magnitude of which can vary with the wheel/rail contact conditions [33]. Examples in flash butt and aluminothermic welds are included in Fig. 5B and C, respectively.

The transverse defect from gauge corner collapse appears frequently on heavy freight railroads [10], with European passenger mixed/freight lines experiencing more failures from gauge corner cracking. Statistics from one North American freight railroad showed that between 2010 and 2015, the broken rails due to transverse defects were less than 4% on the low rail, about 30% on the high leg, and 65% in tangent track. Transverse defects that occasionally occur on tangent track most often resemble those of Figs. 3 and 4 on high rails, exhibiting a gauge side initiation point and hence being caused by gauge corner loading and/or extensive gauge face plastic flow. Consequently, the tangent defects are most common in the proximity of switches or areas of tight track gauge or track warp errors. The root causes are high gauge corner contact stresses and saturated creepage, possibly supplemented by metallurgical issues. The high creepages are understood to result from sudden changes in the position of the wheel/rail contact that produce rapid changes in rolling radius and large frictional traction [34].

Derailments at broken rails from transverse defects generally require at least two nearby defects such that one break leads to battering at nearby locations, additional fractures and then lengths of rail, sometimes metres in length, are lost. Often large clusters of defects infect a rail. Explanations for clustering include:

- Track geometry errors that cause most or all passing wheelsets to exert high dynamic forces at the same point on track, overstressing the rail.
- Insufficient rail grinding. This may occur, for example, around obstructions such as switches and crossings, where mainline production grinders must raise stones to avoid destroying either the track component or the grinding stones. These areas of track, often about 15 m to either side of the feature, incur statistically greater failure rates due to the combination of poor track geometry and more severe RCF. This topic is a current subject of study in North America.
- A length of old or poor metallurgy rail, sometimes 12 m or less in length that is found amongst otherwise "normal" quality parent rail. Being softer or having greater numbers of inclusions, its rates of plastic flow, wear, or fatigue are greater than adjacent rail. But these short lengths, such as an older plug rail, are not practical to treat in isolation, for example through grinding, without over-grinding adjacent rail. Such rail should be identified and planned for accelerated removal.
- Clusters of defects can infect whole curves if, for example, there is consistently poor metallurgy, lubrication, track geometry, and profiles. The current reverse TD has been found in large numbers through a single curve.

Considering clusters at a smaller scale, theoretical analyses indicate that crack tip shielding occurs, which reduces the stress intensity factor at the crack tip as the number of cracks in a cluster increases [35]. This effect is initially beneficial. However, as crack growth progresses one crack typically becomes dominant and grows ahead of the other cracks. The beneficial shielding effect is then lost.

5. RCF and the reliability of rail flaw detection

The ability of ultrasonic equipment to effectively detect flaws like transverse defects is complicated by surface anomalies and heavy wear. Poor surface condition adds noise to the collected ultrasonic and induction signals that can mask defects [36]. Furthermore, shelling, plastic flow "slivers" and head checking interfere with the entry and exit of acoustic energy, especially when they are directly between the emitter and the internal defect [37].

Wear patterns on the rail change the way that the ultrasonic beam is reflected within the rail head. Extreme patterns deflect the incident beam in unpredictable ways, increasing the possibility of not intersecting a defect, especially one that is near the gauge face of the rail. Changes in the incident angle of the ultrasonic beam (for example, as a result of incorrect calibration or wear of the ultrasonic equipment) can cause mode conversion [38] where a surface wave is created that may give a return off the surface fatigue that is mistakenly read as transverse defect ("false positive").

In addition to the above factors, the probability of detecting a transverse defect below surface cracking is influenced by the growth behaviour and hence overall shape of the internal defect. For example, under wheel–rail conditions that develop considerable lateral bending of the rail head, transverse defects may also tend to propagate across the rail head (for example, as shown in Fig. 6A as compared with Fig. 6B). These defects are readily detected once they extend out from under the region of surface cracking.

Deviations in the plane of fatigue crack propagation can also influence the apparent size of the defects (i.e. relative to the vertical direction). Referring again to the examples shown in Figs. 3 and 4, the fatigue crack gradually changes direction over the first 10 mm below the running surface, and hence the angle between the incident beam and the crack plane varies.

Increased reliability of flaw detection can be achieved by:

- Refining the ultrasonic sensor configuration to improve detection in the presence of poor surface condition. One approach is to fire the incident beam at an area on the rail that has both more consistent geometry and is less likely to have heavy fatigue (e.g. more towards the rail crown rather than the gauge corner), at angles more likely to intercept an internal flaw [37]. While this approach makes it possible to test under the region affected by surface cracking, the change in orientation of the ultrasonic signal (relative to the travel direction) often necessitates a reduced testing speed.
- Exploring other technologies such as longitudinal guided waves that propagate along the rail length and can run underneath any shallow surface defects [39]. While this approach has been

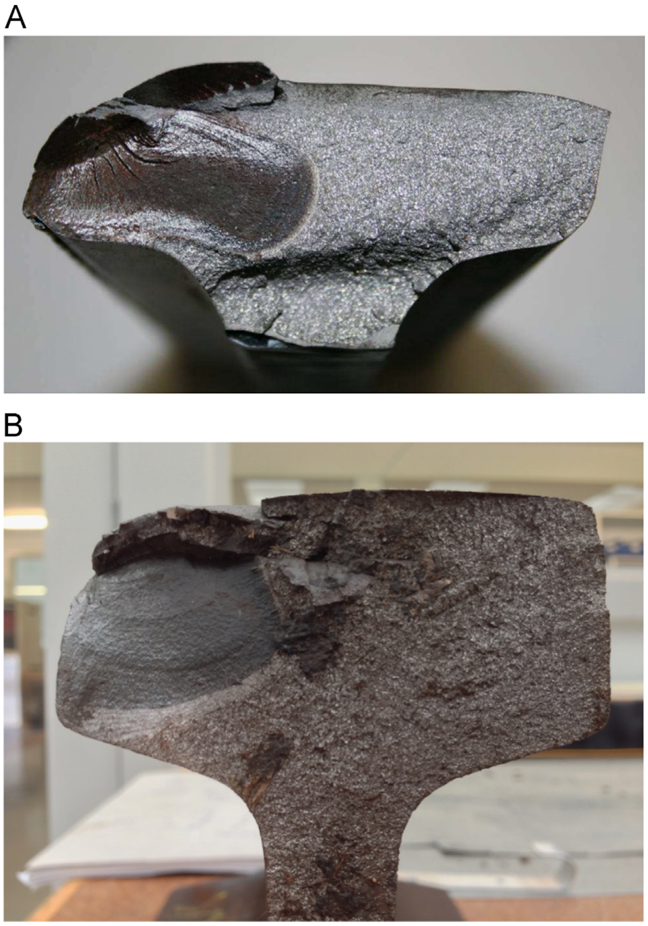

Fig. 6. Two transverse defects – the first having a crack plane much more angled from vertical.

proposed for detection of fatigue cracks in the rail foot, the presence of surface cracking on the running surface may result in "false positives" as discussed previously in the context of surface waves.

- Minimizing the presence of heavy RCF. There have been numerous publications on this subject that discuss the role of profiles that lower stress and improve steering, RCF resistant rail steels, friction management, improved track geometry and rail grinding.

While heavy surface fatigue is known to pose a problem for ultrasonic rail flaw detection, leading in some cases to "no-tests", no studies exist that establish the RCF severity at which this happens.

6. Influence of wear on vertical dynamic loads and RCF

Wear may have a significant influence on the dynamic vertical wheel/rail interaction (the related influence on lateral dynamics is discussed in Section 7). This interaction is very obvious in cases of corrugated rails and/or out-of-round (OOR) railway wheels.

Corrugated rails are especially important factors with respect to RCF at fairly high-speed operations with speeds from 200 km/h and above. The periodic excitation caused by short-pitch corrugation under such circumstances will result in repeated high dynamic forces (typically up to some 30% above dynamic forces in a non-corrugated state [16]). In particular the excitation will occur for frequency ranges between some 200 to 1000 Hz [40]. This is a complicating factor since standard measurements and simulations usually do not capture such high frequency loads. Consequently the phenomenon has a tendency to come as an unwanted surprise when operations at higher speeds commence. In particular the high (peak) vertical force magnitudes due to corrugation will increase the risk of subsurface initiated rolling contact fatigue [16]. This phenomenon, which also requires the presence of material defects, may in wheels be manifested in the detachment of a large piece of the wheel tread. For rails the consequence of subsurface initiated RCF may be a transverse fracture or squat/stud initiation, as discussed above.

The influence of wear-induced OOR wheels is most clearly manifested in the extreme case of a wheel flat, which will induce very high impact forces. The higher contact stresses will naturally have an adverse effect on the wheel. However, in most cases of larger wheel flats, the bearings and other equipment tend to fail before the wheels. For more moderate OOR, the case may be different as load magnitudes are lower, but usually influence over a longer time [41]. The higher forces from OOR wheels will naturally also increase the deterioration of rails. However, since severe OOR wheels are generally rare, the effect on rail crack growth is moderate. In contrast, wheels with severe OOR will have a significant effect on the risk of complete rail fracture in the presence of existing large defects in the rail [42] and especially under conditions of large tensile stresses during cold weather [8].

7. Influence of wear on lateral dynamic loads and RCF

Worn profiles will influence steering capabilities of operating vehicles. This is apparent in the case of hollow worn wheels, where there may be a loss of conicity that decreases wheelset steering in curves. Higher lateral forces and poor contact geometries arise as the vehicle is forced to negotiate the curve in spite of the reduced steering, see e.g. [43]. The end result is typically severe RCF on the wheel tread and increased RCF impact on the rail. In the same manner, poor rail geometry may result in similar poor steering through curves.

A related phenomenon occurs if wheel wear or improper truing practices has resulted in diameter differences between wheels on the same axle. The result is often seen as severe flange wear on one wheel and heavy RCF damage on the opposite wheel [44,45]. The same can occur with bogie alignment issues [46]. Further, RCF damage on the rail and switches and crossings also tends to increase [44].

8. Effect of wear on wheel/rail contact geometry and rcf formation

The influence of wear on the contact geometry can be beneficial in that mismatched wheel and rail profiles can adapt towards each other, a process referred to as "wear in". The increased conformality between the surfaces increases the contact patch size, which reduces contact stress magnitudes and consequently the propensity for RCF formation. Unfortunately that same conformality can be a cause of rail corrugation [47], hunting and higher wear of the gauge corner and gauge face of rail [48].

In contrast, wear that tends to decrease the size of the contact patch will increase the propensity for subsequent crack formation and wear. The picture is complicated by the fact that wear patterns on a piece of rail will evolve as a response to the spectrum of traversing wheel profiles (each with their own set of contact forces). Consequently, although the worn profile may cause low RCF and wear for the majority of passing wheels, it may induce very

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high RCF and wear on some wheels that poorly match the worn rail.

Similarly, the worn wheel profile develops as a response to traversed rail profiles, which may result in very high RCF or wear on some less compatible rail sections.

9. Heavy wear can expose vulnerable steel

In older heat-treated rail steels, the off-line head hardening process results in a shallower depth of hardening compared to premium rail steels manufactured using an in-line hardening process. In the former, the depth of the hardened region can be roughly 20–25 mm in depth, below which there is a softer heat-affected zone (HAZ), as shown in Fig. 7. When used in rail systems which allow relatively high rail wear limits [9], this can result in the lower hardness region being subjected to higher contact stress levels.

The lower hardness region is much more vulnerable to sub-surface plastic flow, gauge corner collapse and to transverse defect initiation (e.g. Fig. 8).

10. Heavy wear promotes higher internal stresses

Wear of the rail head reduces the cross sectional area of the rail head, and hence leads to increased bending stresses throughout the rail section. But more specifically, increasing head wear leads to higher stresses in the rail head resulting from the local bending response of the rail head on the web [30]. The magnitude of these stresses is particularly sensitive to offset vertical loads and tangential forces in the lateral direction. The effect of these conditions on the distribution of bending stresses within the head of the rail has been quantified [33]. An example is shown in Fig. 9 for the case of a 20 mm offset of the vertical load from the rail centre.

11. Competition between wear and crack formation

As cracks initiate and grow into the rail, it is possible for wear to truncate them as fast as or faster than they develop. If the wear rate exceeds the crack growth rate into the material, cracks are progressively removed and the deterioration will be dominated by wear. To capture this phenomenon in numerical predictions a damage function can be introduced [49]. Alternatively, separate wear and RCF evaluations can be carried out [50] to establish which mechanism that dominates the overall response. The practical implications of the wear/RCF competition on rail and wheel maintenance have been explored in [51] using the concept of a magic, or optimal, wear rate.

Fig. 8. Transverse defect that initiated from RCF at the gauge corner of heavily-worn, off-line treated head hardened rail.

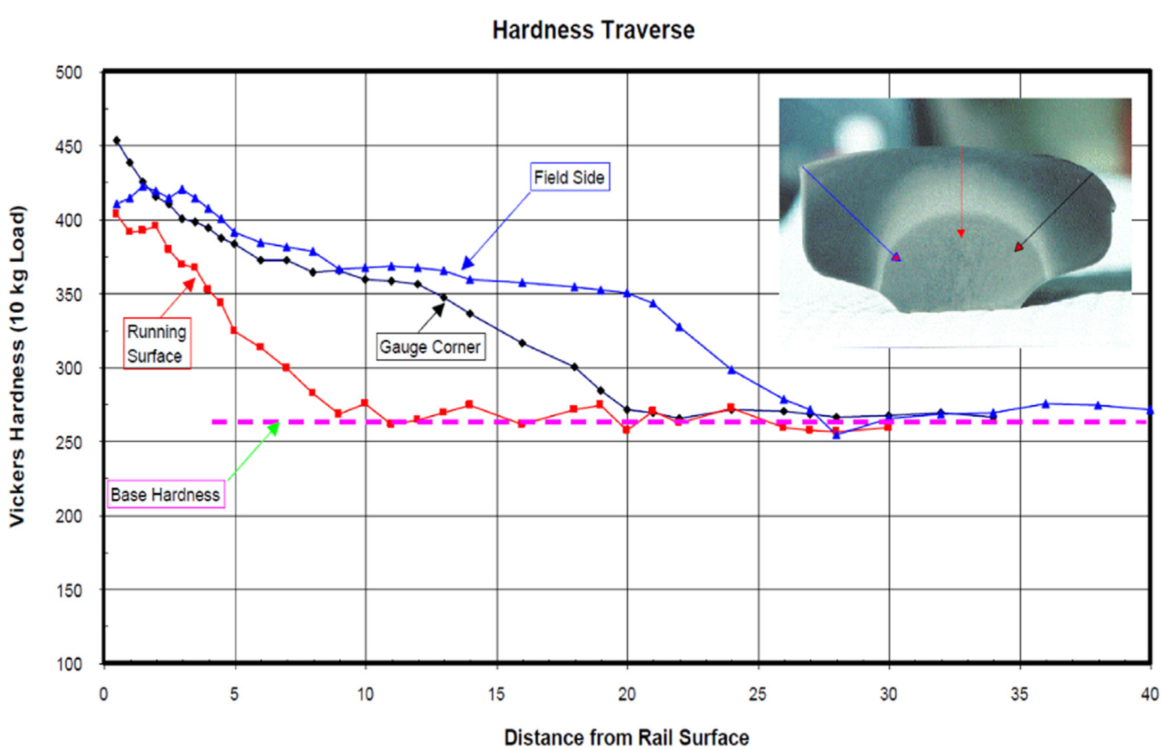

Fig. 7. Rail hardness may be significantly lower in the lower part of the rail head, especially in older head-hardened rail steels manufactured using an off-line hardening process.

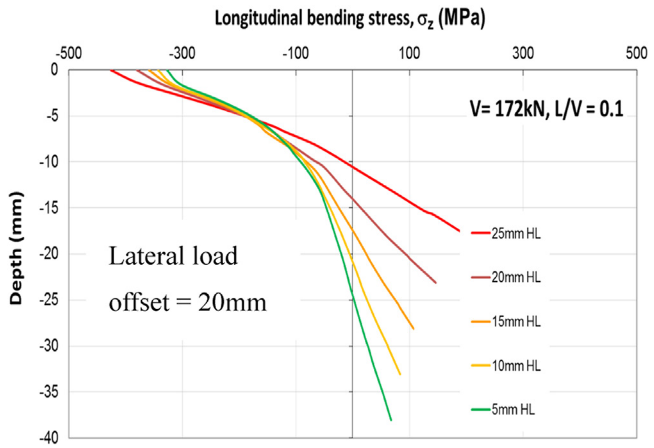

Fig. 9. Beneath the wheel load, a longitudinal bending stress develops in the rail head that increases with head wear and offset of the load from the rail head center [33].

The environment, particularly the presence of water, lubricants and friction modifiers, can have a large impact on the relative rates of wear and RCF. Disc-on-disc testing has clearly demonstrated a dramatic increase in RCF due to water at the contact interface [52]. Lubricants have a similarly profound effect on wear [53] with reductions in wear rates under proper lubrication being greater than 10 fold. But lubricants also serve as an accelerant to surface breaking cracks by reducing the crack face friction [54]. Friction modifiers have shown to significantly reduce rates of wear and crack initiation [55] but the water or oil base of these products raises questions regarding potential increases in RCF under certain conditions.

12. Influence of maintenance

Maintenance will have a very decisive role in preventing adverse – and in particular safety related – effects of wear and RCF. This relates to the entire maintenance chain including its quality and scheduling. In general, poor maintenance will lead to higher load magnitudes that will result in both higher wear and faster crack formation and growth (see [50] for an explanation of this apparent paradox). Poor quality in maintenance and inspection may cause cracks and severely worn profiles to be undetected. In addition, poorly organized maintenance may lead to a situation where cracks are not mitigated before they reach a critical size that will cause fracture. This critical crack size will in turn be shorter if load levels are high due to poor or insufficient maintenance of tracks and vehicles.

The magnitude and nature of the contribution of maintenance to accidents will vary widely. It is thus very important that failure investigations consider the specific maintenance practices and how (the lack of) these practices may have affected the failure.

13. Concluding remarks

While much is understood about surface fatigue and its impact on defects, broken rails and safety, there remains much to learn. Some questions, all related to, but some not explicitly mentioned in this paper, that need answering include the following:

1. Is it possible to quantify a severity of surface fatigue cracking at which the effectiveness of ultrasonic detection is seriously compromised?
2. What are the crack driving forces when there are multiple cracks in close proximity, and when/why does a dominant crack form?
3. What are the conditions under which a long, but otherwise dormant crack deviates deep into the rail and precipitates a break?
4. Which is more dangerous: widely spaced cracks or densely spaced cracks?
5. While the mechanism of fluid entrapment and subsequent crack face lubrication and hydraulic crack propagation appears to be sound theory, is there any way – experimentally or otherwise – to distinguish the contribution of these two phenomena in an operating railway, and to establish the volume of water or lubricant in an operational crack and thereby model and quantify its effect?
6. What happens with cracks that are not fully removed during a rail grinding cycle? Are these residual cracks benign or are they more or less dangerous than new cracks?

References

[1] V. Reddy, et al., Modelling and analysis of rail maintenance costs, Int. J. Prod. Econ. 105 (2007) 475–482.
[2] Track Inspector Rail Defect Reference Manual Federal Railroad Administration, Washington, DC. ⟨http://www.fra.dot.gov/Elib/Document/2130⟩, August 2011.
[3] Office of the Rail Regulator, Train Derailment At Hatfield: A Final Report By The Independent Investigation Board, July 2006, UK.
[4] Australian Transport Safety Bureau Investigation Report, Rail Occurrence Investigation No. 2007/004 Derailment of Train 6MP9 – Bates, SA, 10 June 2007.
[5] Transportation Safety Board of Canada, Railway investigation report R13E0142, Feb. 2016 (see ⟨http://www.tsb.gc.ca/eng/rapports-reports/rail/2013/r13e0142/r13e0142.asp⟩).
[6] Trafikverket, Olycka – Urspårning tåg 4371 Storsund - Koler 2013-05-11 (in Swedish), Report TRV 2013/65118, 2013.
[7] K. Sawley and R. Reiff, Rail Failure Assessment for the Office of the Rail Regulator, TTCI Report # P00-070, October 2000.
[8] Y. Liu, C. Ladubec, E. Magel, J. Preston-Thomas, Cold weather train speed optimization based on stress-strength approach, Proc. 9th Int. Heavy Haul Conf., Shanghai, China, 2009.
[9] R.K. Steele, M.W. Joerms, D. Utrata, G.F. Carpenter, Catastrophic web cracking of railroad rail, in: Residual Stress in Rails, Effects on Rail Integrity and Railroad Economics, O Orringer, J Orkisz and Z Swiderski (Eds), Kluwer Academic Publishers, Vol 1, pp. 1–19, 1992.
[10] A. Ekberg and E. Kabo (Eds), Surface fatigue initiated transverse defects and broken rails – an International Review, Research report 2014:05, Department of Applied Mechanics/CHARMEC, Chalmers University of Technology, Gothenburg, Sweden 2014.
[11] D-RAIL, D1.1–Summary report and database of derailments incidents, 71+3 pp, 2012, ⟨http://d-rail-project.eu⟩.
[12] E. Magel, Rolling contact fatigue – a comprehensive review, DOT/FRA/ORD-11/24, November 2011.
[13] P.J. Mutton, D. Welsby and E. Alvarez, Wear and rolling contact fatigue behaviour of heat-treated eutectoid and hypereutectoid rail steels under high axle load conditions. Proc. 8th Int. Conf. on Contact Mechanics and Wear of Rail/Wheel Systems, 2009.
[14] L. Wessels, S. Oswald, D. Welsby and P. Mutton, Managing the transition from rail wear to rolling contact fatigue in a heavy haul environment, Proc. Int. Heavy Haul Conf., Perth, Australia, 2015.
[15] S.A. Ranjha, K. Ding, P.J. Mutton, A. Kapoor, Finite element modelling of the rail gauge corner and underhead radius stresses under heavy axle load conditions, IMechE J. Rail Rapid Transit 226 (3) (2012) 318–330.
[16] A. Ekberg, E. Kabo, J.C.O. Nielsen, R. Lundén, Subsurface initiated rolling contact fatigue of railway wheels as generated by rail corrugation, Int. J. Solids Struct. 44 (2007).
[17] Z. Li, Squats on railway rails, in: R. Lewis, U. Olofsson (Eds.), Wheel-rail interface handbook, Woodhead Publishing, Cambridge (UK), 2009, pp. 409–436.
[18] A. Kapoor, F. Schmid, D.I. Fletcher, Managing the critical wheel/rail interface, Railway Gazette Int. Jan. (2002) 25–28.
[19] D.I. Fletcher, A. Kapoor, A rapid method of stress intensity factor calculation for semi-elliptical surface breaking cracks under three -dimensional contact loading, IMechE J. Rail Rapid Transit 220 (3) (2006) 219–234.
[20] R. deVries, P. Sroba and E. Magel, Preventive Grinding moves into the 21st Century on Canadian Pacific Railway, Proc. AREMA Annual Conf., Chicago, USA Sep. 2001.
[21] UIC Code 712CR, Rail defects, 4th edition, 107 pp, 2002.
[22] M. Kaneta, K. Matsuda, K. Murakami, H. Nishikawa, A possible mechanism for rail dark spot defects, J. Tribol. 120 (2) (1998) 304–309.

[23] S.L. Grassie, Squats and squat-type defects in rails: the understanding to date, IMechE J. Rail Rapid Transit 226 (2012) 235–242.
[24] K. Sawley and R. Reiff, An assessment of Railtrack's methods for managing broken and defective rails, Report # P-00-070, October 2000.
[25] K. Masanobu and K. Kataoka, Research and development for the improvement of reliability of rails, JR East technical review #9.
[26] M. Ishida, M. Akami, K. Kashiwaya, A. Kapoor, The current status of theory and practice on rail integrity in Japanese railways – rolling contact fatigue and corrugations, Fatigue Fract. Eng. Mater. Struct. 26 (10) (2002).
[27] D.I. Fletcher, F.J. Franklin, A. Kapoor, Rail surface fatigue and wear, in: R. Lewis, U. Olofsson (Eds.), Wheelrail interface handbook, Woodhead Publishing Ltd, Cambridge (UK), 2009, pp. 280–310.
[28] M.T. Hanson, L.M. Kerr, A simplified analysis for an elastic quarter space, Q. J. Mech. Appl. Math. 43 (4) (1990) 561–587.
[29] G. F. Carpenter, R. K. Steele and M. J. Markase, Effects of inclusion content on fatigue performance of rail steels, Proc. Int. Symp. on Rail Steels - Developments Manufacturing and Performance, Montreal, Canada, 49-56, 1992.
[30] A. Kapoor, A re-evaluation of the life to rupture of ductile metals by cyclic plastic strain, Fatigue Fract. Engng. Mater. Struct. 17 (2) (1994) 221–219.
[31] D.Y. Jeong, Y.H. Tang, O. Orringer and A.B. Periman, Propagation analysis of transverse defects originating at the lower gage corner of rail, Volpe National Transportation System Center, Cambridge, Massachusetts, Report No. DOT/FRA/ORD-98/06., 1998.
[32] Main-Track Train Derailment: Railway Investigation Report-R06C0104 (July 2006). Canada, C. P. R., Freight Train CP 803-111, Mile 97.4, Canadian National Ashcroft Subdivision, Lytton, British Columbia.
[33] P.J. Mutton, P. Bartle, M. Tan and A. Kapoor, The effect of severe head wear on rolling contact fatigue in heavy haul operations, Proc. 8th Int. Conf. on Contact Mechanics and Wear of Rail/Wheel Systems, 2009.
[34] A. Doherty, S. Clark, R. Care, M. Dembowsky, Why rails crack, Ingenia 23 (2005) 23–28.
[35] D.I. Fletcher, P. Hyde, A. Kapoor, Growth of multiple rolling contact fatigue cracks driven by rail bending modelled using a boundary element technique, IMechE J. Rail Rapid Transit 218 (3) (2004) 243–253 (11).
[36] R. Clark, Rail flaw detection: overview and needs for future developments, NDTE International 37 (2004).
[37] M. Havira and J. Boyle, Detection of transverse defects under surface anomalies, Proc. of AREMA Annual Conf., Chicago 2009.
[38] Mode conversion in ultrasonic signal, ⟨www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/modeconversion.htm⟩ (accessed 23 May 2015).
[39] T.R. Hay, D.R. Hay, D. Plotkin, C.M. Lee and J.L. Rose, Rail defect detection under shelling, Proc. World Conf. on Railway Research, World Conf. on Railway Research, Montreal Canada, June 2006.
[40] J.C.O. Nielsen, A. Ekberg, R. Lundén, Influence of short-pitch wheel/rail corrugation on rolling contact fatigue of railway wheels, IMechE J. Rail Rapid Transit 219 (F3) (2005) 177–187.
[41] A. Johansson, J.C.O. Nielsen, Out-of-round railway wheels—wheel-rail contact forces and track response derived from field tests and numerical simulations, IMechE J. Rail Rapid Transit 217 (2) (2003) 135–146.
[42] J. Sandström, A. Ekberg, Predicting crack growth and risks of rail breaks due to wheel flat impacts in heavy haul operations, IMechE J. Rail Rapid Transit 223 (2) (2009) 153–161.
[43] K. Karttunen, E. Kabo, A. Ekberg, Numerical assessment of the influence of worn wheel tread geometry on rail and wheel deterioration, Wear 317 (1–2) (2014) 77–91.
[44] R.D. Fröhling, Analysis of asymmetric wheel profile wear and its consequences, Veh. Syst. Dyn. 44 (Supplement) (2006) 590–600.
[45] A. Gianni, A. Ghidini, T. Karlsson, Bainitic steel grade for solid wheels: metallurgical, mechanical, and in-service testing, IMechE J. Rail Rapid Transit 223 (2) (2009) 163–171.
[46] M.R. Lynch, P.J. Mutton, K.J. Epp, R.F. Donnelly, Improving wheelset performance under high axle loads, Proc. 13th Int. Wheelset Congress, 2001.
[47] J. Kalousek, K.L. Johnson, An investigation of short pitch wheel and rail corrugation on the Vancouver mass transit system, Proc. IMechE 206 (1992) 127–135.
[48] E. Magel, J. Kalousek, The application of contact mechanics to rail profile design and rail grinding, Wear 253 (2002) 308–316.
[49] M.C. Burstow, Whole life rail model application and development for RSSB – continued development of an RCF damage parameter, Rail Safety & Standards Board, Report AEATR-ES 2004–2880, Issue 2, 2004.
[50] K. Karttunen, E. Kabo, A. Ekberg, A numerical study of the influence of lateral geometry irregularities on mechanical deterioration of freight tracks, IMechE J. Rail Rapid Transit 226 (6) (2012) 575–586.
[51] E. Magel, J. Kalousek, P. Sroba, Chasing the magic wear rate, Civil-Comp Proceedings 104 (2014).
[52] W.R. Tyfour, J.H. Beynon, A. Kapoor, Deterioration of rolling contact fatigue life of pearlitic rail steel due to dry-wet rolling-sliding line contact, Wear 197 (1–2) (1996) 255–265.
[53] R.K. Steele and R.P. Reiff, Rail: Its behaviour and relationship to total system wear, Proc. 2nd Int. Heavy Haul Conf., Colorado Springs, September 1982.
[54] L.M. Keer, M.D. Bryant, A pitting model for rolling contact fatigue, ASME J. Lubr. Technol. 104 (1983).
[55] D.T. Eadie, D. Elvidge, K. Oldknow, R. Stock, P. Pointner, J. Kalousek, P. Klauser, The effects of top of rail friction modifier on wear and rolling contact fatigue: Full-scale rail–wheel test rig evaluation, analysis and modelling, Wear 265 (2008).

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