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A review on wear between railway wheels and rails under environmental conditions

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Abstract:

The wheel-rail contact is an open system contact, which is subjected to various environmental conditions, such as temperature, humidity, water, and even leaves. All these environmental factors influence wheel-rail wear. Classical wheel-rail wear was basically discussed under dry and clean conditions, particularly for engineering purposes. However, with the presence of environmental conditions, wear rate and wear mechanism change. The paper reviews recent contributions to wheel-rail wear with a special focus on the influence of environmental conditions. The main part includes basics of wheel-rail wear, experimental methodology, wear and rolling contact fatigue (RCF), and some measures to reduce wear.

Keywords: wheel-rail wear; environmental conditions; rolling contact fatigue; open system contact

1 Introduction

Railway transport is generally acknowledged for its low cost, energy efficiency, environmental friendliness, ride comfort, and high speeds (over short and medium distances) compared with other means of transportation. The wear between railway wheels and rails influences all of above mentioned factors, particularly the cost of maintaining safe and efficient operations. Over time, the rail needs to be ground and the wheels need to be turned to have a "matched" profile for improved running behavior and safety. If the wear or fatigue is severe, the rail sections or the wheels may be replaced or discarded before the expected lifetime. Around the year 2000, rail maintenance costs within the European Union

were estimated to total 300 million Euros annually [1]. In China, recent railway maintenance costs were over 10 billion CNY annually, due to rapid expansion of the railway network.

Wheel-rail wear is a complex wear system. First, the contact point is constantly changing due to vehicle dynamics. Second, the wheel-rail contact is a rolling/sliding contact. In addition to wear, rolling contact fatigue (RCF) is also very important. Both aspects influence each other and are sometimes coupled. Third, the wheel-rail contact system is an open system, which is affected by various contaminants (foreign substances) applied both intentionally and unintentionally to the wheel–rail interface [2,3]. These factors make the system different from other well-studied tribo-systems, such as roller bearings, ball bearings or gears, which are often operated in a closed environment. Here, environmental factors include temperature, humidity, iron oxides, leaves and water (rain) which differ from those intentionally applied on the wheel-rail interface, such as lubricants and friction modifiers.

This paper reviews the research performed on the wear between the wheels and rails with a specific focus on environmental factors. Section 2 presents basic information on wheel-rail wear including contact conditions and classical wheel-rail wear behaviors. Section 3 discusses the methodology of studying wheel-rail wear, which includes experimental methods. Sections 4 and 5 review the literature on wear and RCF of the wheel-rail contact respectively. Section 6 presents measures that can be used to reduce wear including lubricants and laser cladding. Finally, the concluding remarks summarize the reviewed articles and identify gaps to be addressed in future work.

2 Basics of wheel-rail wear

It is often assumed that only a small area (1 cm^2), where the wheel meets the rail, carries the axle load. However, the contact position continuously varies, resulting in a varying contact area and contact pressure due to different vehicle running conditions. There are different types of contacts, as shown in Fig. 1. The wheel tread-rail head contact usually occurs in a straight track where both contact pressure and sliding speed are lower than they are for the wheel flange - rail gauge contact which often appears in a curved track. Moreover, even for a single wheel, the profile changes due to wear lead to varied contact pressure and contact area, as shown in Fig. 2. Notably, the real situation can be more complex than mentioned here. Under such a high load, wheels and rails may deform plastically, particularly when a rough surface is taken into account [4–6]. The wheel and rail materials used worldwide are mostly carbon steels. The material composition may slightly differ depending on the country and the

transportation type (passenger or heavy-haul trains). In this paper, the material composition will not be discussed.
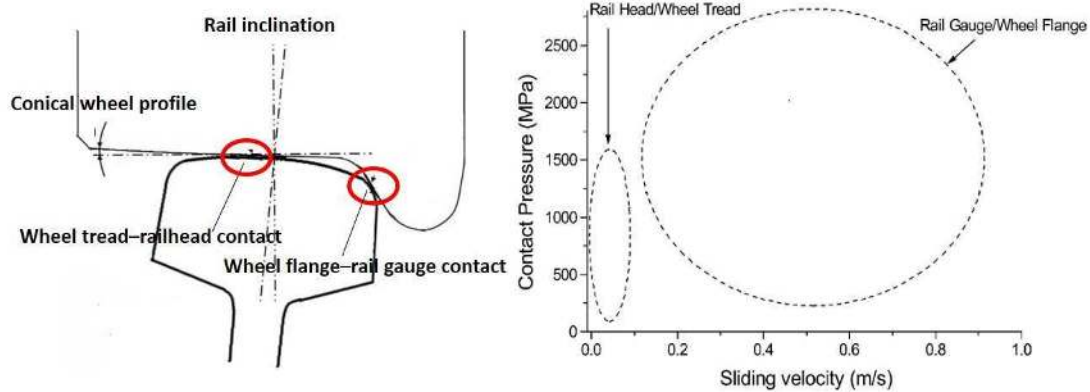

Figure 1. Contact positions and contact conditions in the wheel–rail contact (modified from[7,8])
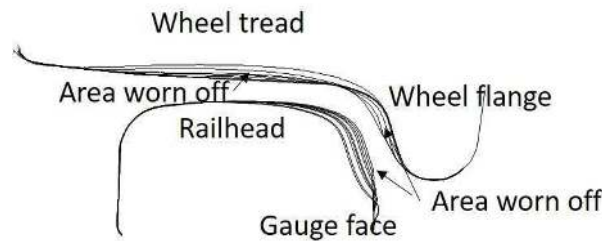

Figure 2. Profile change of the wheel and rail over a two year period from the Stockholm test case, (UIC60 standard rail profile and the wheel profile from X10 powered vehicles) [9] .

The adhesion force (also known as tractive force or braking force) is transmitted through the small contact patch due to the difference between the tangential velocity of the wheel and the body velocity (the translational wheel velocity), resulting in a rolling-sliding contact. The slip ratio is used to evaluate the difference to show the degree of sliding (only the longitudinal direction in a wheel tread-rail head contact is considered).

Therefore, the contact area can be divided into a stick zone and a slip zone, as shown schematically shown in Fig. 3 (this curve is also called a creep curve in a railway text). When there is no slip, the whole contact area sticks and no tangential force is transmitted, the motion is known as "free rolling". Slip occurs at the trailing edge and spreads forward through the contact area as the adhesion force increases. The slip region increases and the stick region decreases resulting in a rolling–sliding contact until pure sliding occurs. In that state, the adhesion force equals the friction force between the two bodies under pure sliding conditions [7]. It is noted that the above description has been simplified for the wheel-rail contact as a tribo-system. The real situation is more complicated, which has been
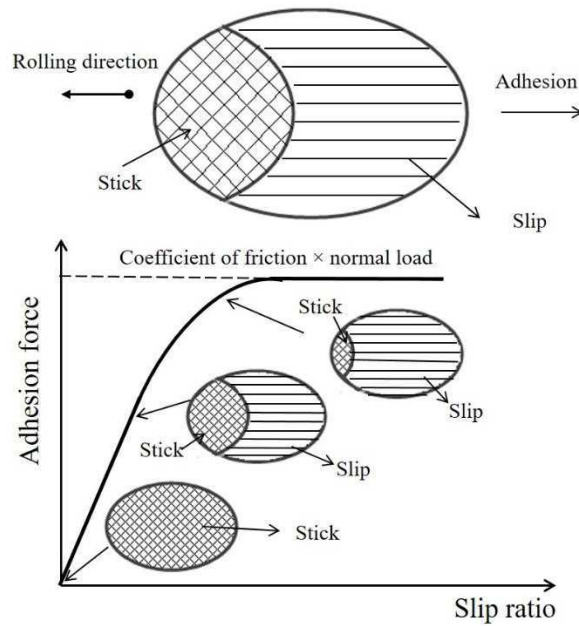
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considered in [10,11].

Fig. 3 A schematic showing the relationship between the adhesion force and the slip ratio.

Generally, wheel-rail wear is classified as being mild, severe, or catastrophic based on the observation that materials are subjected to a sudden jump in the wear rate. Fig. 4 shows wear maps obtained from twin-disk and pin-on-disc testing [8,12,13]. Each wear regime is related to the $T\gamma$ value, which is representative of the amount of energy dissipated in the contact. $T\gamma$ is directly proportional to factors such as sliding velocity and contact pressure. The wear between the rail gauge and the wheel flange is very severe thus lubricant is applied in curves where this contact is most prevalent. The interface between the railhead and the wheel tread cannot be lubricated since the adhesion force is transmitted by this interface and it is critical for braking. According to field measurements, lubrication greatly reduces rail wear in curves [9]. Depending on materials, curve radius, and lubrication system, the lubrication benefit factor ranges from 4 to 9 [1,14–16]. A high-positive friction modifier (HPF) is often applied in the wheel tread–rail head contact area to keep the friction coefficient between 0.25 and 0.4 [17]. For locomotives or any locations suffering from adhesion losses, a very-high-positive friction modifier (VHPF) or adhesion enhancer is used. The main composition of the VHPF is sand. One of the side effects of using such a friction modifier is that wear increases significantly. Arias-Cuevas et al. [18] compared four types of sand, differing in grain size and indicated that the particle size has a strong influence on wear that is dependent on the slip. Lewis and Dwyer-Joyce [19] discussed the mechanism of sanding entrainments. The rail was subjected to abrasive wear from crushed sand particles and the

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wheel material was subjected to surface cracking and material spallation, as shown in Fig. 5. Huang et al. [20] reported that wheel-rail surface damage increased with increased sand size and feed rate of sanding under wet conditions. Alumina particles, a replacement of sand, were found to cause less wear and damage [21,22].
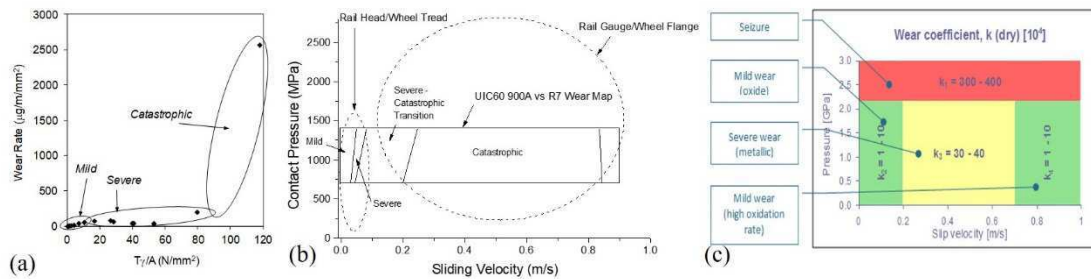
Fig. 4. Wear Maps for (a) R8T Wear Rates (against a 900A rail) from twin-disc testing [12]; (b) UIC60 900A rail steel wear map from pin-on-disc testing [8]; (c) a 900A rail (against an R7 wheel) by collecting data from twin-disc and pin-on-disc testing [13].
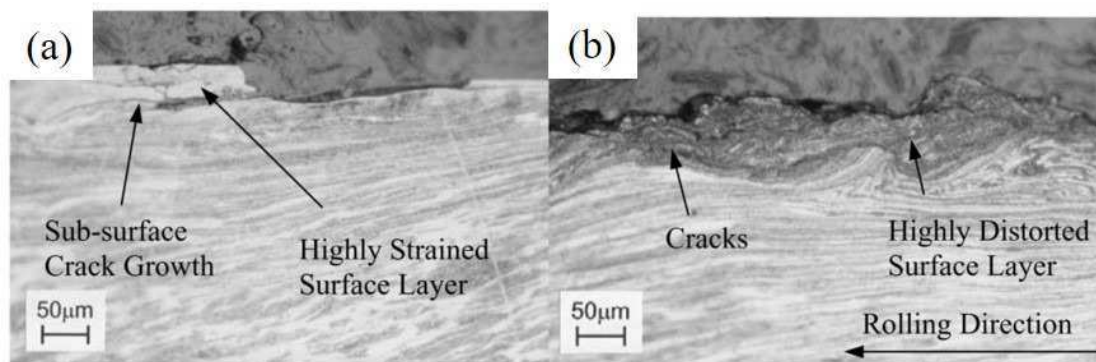
Fig. 5. Subsurface morphology of wheel test discs: (a) without sand and (b) with sand [19].

3 Experimental methodology of wheel-rail wear

There are a number of reasons why wheel and rail material wear tests may be carried out:

- to develop fundamental understanding of wheel and rail material wear mechanisms

- to benchmark performance of wheel and rail materials to help in the process of creating new materials or in assessing new technology such as laser cladding of rail

- to assess effects of products applied to reduce wear such as curve lubricants and Top-of-Rail Friction Modifiers (TOR-FMs)

- to help in developing wear models

- to generate wear coefficients for use in wear models implemented, for example, in wheel or rail profile evolution predictions

- to validate output from the predictive tools

In all of these the aim is to use test approaches that are as representative as possible of the actual wheel-rail interface, which presents a real challenge to tribologists. The open nature of the actual contact and the constantly varying contact conditions make it one of the most complex machine element interfaces.

This section looks at how tests can be carried out in order to illustrate the good practice needed to make the tests as relevant as possible. Issues arising from the methodologies that still need addressing are highlighted and modelling approaches where the data generated may be used.

3.1 Wear modelling

Wear models are typically implemented as part of multi-body dynamics (MBD) tools incorporating vehicle and track models to predict wheel or rail profile evolution [23,24]. A flow chart illustrating a possible scheme for such a tool can be found in Fig. 6 [25]. As can be seen, the MBD simulations provide global conditions in terms of slip, load and contact position. A local contact model is then used to break down the conditions within the contact. The wear model can then be used to work out the wear across the contact. Wear for all the contacts is then summed and profile change predicted and fed-back [26,27].
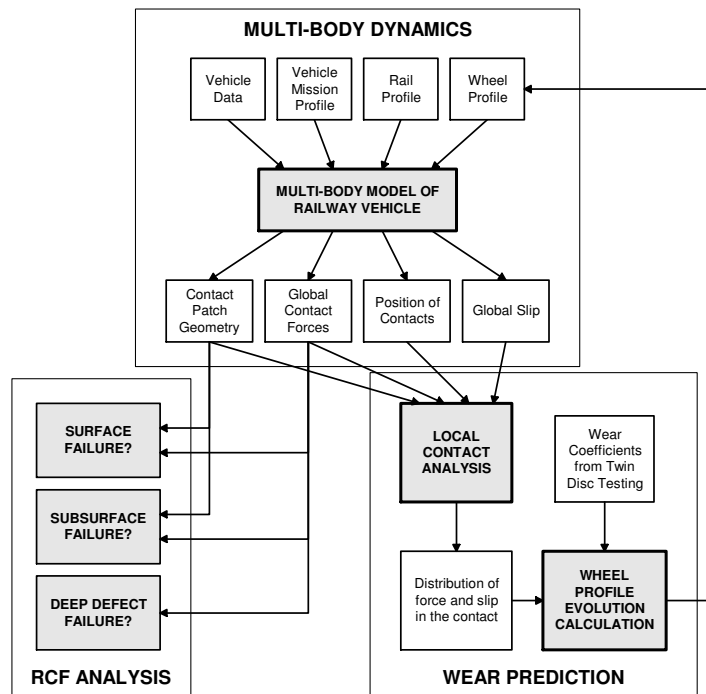

Figure 6.   Typical Process in MBD based Damage Prediction [25]

There are a number of different modelling methodologies that may be implemented. They can be split into semi-empirical approaches depending on wear coefficients (generated in wear tests) and physical

models. The two most commonly used semi-empirical approaches are based on Archard wear coefficients [28] and $T\gamma$ wear curves (where T is tractive force (normal force × traction coefficient) and γ is creep in the contact (relative velocity of wheel and rail divided by velocity of vehicle)), see Fig. 4. Physical models also exist, such as the brick model initially developed for the Whole Life Rail Model [29], which is able to predict wear based on material strain accumulation. This model is also able to integrate RCF predictions. Competition between wear and RCF in wheels and rails is a very important consideration. The aim is to find the "magic wear rate", which just prevents RCF from being the dominate failure mode [30]. Testing to isolate the two is very challenging though.

An important input to the MBD models is the friction behavior within the wheel-rail interface. One issue here is that friction should not be an input as it would actually result from the interface conditions, but the main problem is the lack of well-defined values for the wheel-rail interface, particularly for changing environmental conditions and when third body materials (natural or applied) are present. Errors in the friction coefficients used can lead to large inaccuracies in predicted interface forces which in turn are used as inputs to damages models [31]. This is a big gap that needs filling along with the lack of complete wear maps for third body materials. Some have been developed for grease and water [32,33], but there is a lot of work to be done in this area.

3.2 Different types of wear test

A number of test approaches exist for assessing wheel and rail material performance as shown in Table 1 and Figure 7. The most commonly used approaches are small-scale pin-on-disc tribometers [34–37] and twin-disc machines [12,38–41], largely due to their availability and because tests are relatively quick and cheap to carry out. Scaled test-rigs exist [42] and full-scale experiments are possible [25,43–46]. While much more difficult to carry out, trials have been carried out in the field, both on normal service lines [1,14,47] and dedicated test tracks [48].

Moving from small-scale tests to field trials gives increasing complexity, i.e. the contact and environment become more representative, but at the same time the level of control over tests conditions and ease of measurement reduce. Appropriate choices have to be made on the approach needed based on the time and budget available. A good strategy would be to use a combination of approaches. Using small-scale and full-scale allows, for example, parameterisation of a model to be carried out using small-scale data and then predictions for full-scale used as validation.
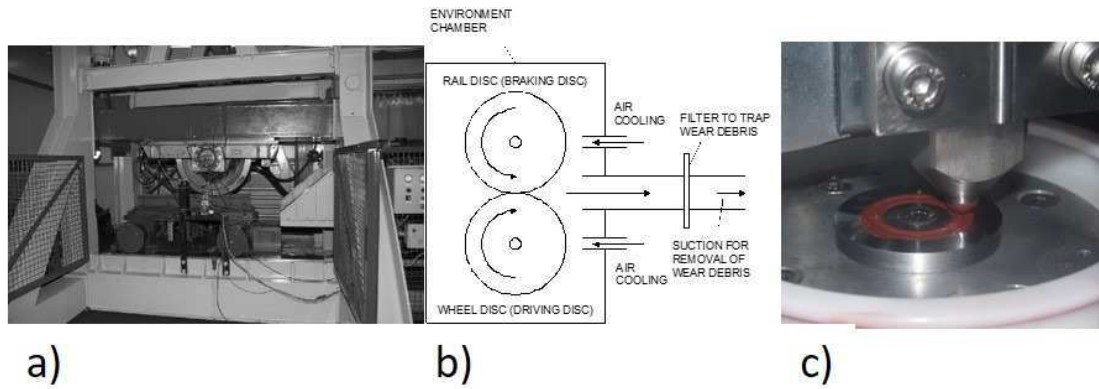
Figure 7.   Laboratory Based Test Methods: (a) Full-Scale [45]; (b) Twin-Disc Machine [12];

Pin-on-Disc [37].

Table 1.   Summary of Wear Test Methodologies

Test Approach	Advantages	Disadvantages
Pin-on-disc [34–37]	Quick and cheap to run; specimens can be cut from actual wheel and rail; good control over test parameters; easy to take measurements; easy to add 3rd body materials; environmental chambers can be added	Full-sliding (can assess limited scenarios such as sharp curves, although can be considered to simulate the "slip" part of a partially sliding contact); simplified contact geometry
Twin-disc [12,38–41]	Easy to run; specimens can be cut from actual wheel and rail good control over test parameters; easy to take measurements; easy to add 3rd body materials	Simplified contact geometry; Hard to achieve environmental conditions
Scaled wheel-rail [42]	Contact conditions more representative	Specimens expensive and hard to procure; measurements harder to take accurately
Full-scale laboratory [25,43–46]	Actual contact conditions; actual components usually	Tests expensive and time consuming; control over test conditions more limited; measurements hard to take accurately
Field [1,14,47,48]	Actual environmental and contact conditions	No control over contact conditions; hard to obtain data; no friction data

3.3 Good Practice in Carrying Out Small-Scale Tests

The vast majority of wear tests are carried out using small-scale approaches, such as pin-on-disc and

twin-disc. In order to try and minimise the issues these approaches create in terms of relating the data

to the full-scale and to ensure the best possible data is obtained, a "best practice" guide to testing was

developed [49]. Stock et al. [50] also has some good observations on the key differences between

laboratory and field testing that need be addressed.

From this key factors to pay attention to in carrying out a test are:

- use an adequate number of cycles – has steady state wear been achieved? (see [51] for some good observations on this topic)

- if possible create representative environmental conditions (easier on a pin-on-disc machine as some have this incorporated)

- cool specimens – when applying multiple cycles to the same contact surface the temperature rises above that in the field and material properties may change and/or third-body layers (oxides) become thicker

- manufacture specimens from actual wheel and rail and from the right place to get representative properties and finish to achieve the right roughness

- use representative contact conditions for the situation you are simulating, it is best to test across a range of conditions for generating data for models

- where third-body materials are being applied, scale the application to mimic field rates

Important data to collect is shown in Table 2.

Table 2.   Recommended Measurements for Wear Tests (adapted from Lewis et al. [49])

Pre-Test Measurements	
- Mass (after cleaning) - Roughness - Surface hardness	- Surface images - Sub-surface hardness (dummy disc) - Sub-surface images before deformation (dummy disc)
Measurements during Test	
- Friction - Load and slip - Room temperature and humidity - Wear (either using appropriate technology or by stopping test periodically)	- Contact temperature - Any unusual behaviour of test specimens i.e. change in noise (frequency, amplitude), visible change in wear debris, visible change of test specimen surface
Post Test Analysis	
- Disc mass - Surface images - Roughness - Surface hardness	- Sub-surface deformation - Sub-surface hardness gradient - Third-body layer thickness and composition - Wear debris characteristics

4 Wear characteristics in wheel-rail contact under environmental conditions

As already mentioned, wheel-rail contact is an open system contact. Thus wheel-rail wear is subjected to environmental conditions which may differentiate it from other well studied tribological systems. In

this section, the influence of some common environmental factors, e.g., water, humidity, temperature, leaves and iron oxides of the wheel rail wear is discussed.

4.1 influence of water, humidity and temperature

Rainfall is the most common form of water that appears on the rails. Water creates a natural lubricating layer between the wheel and the rail to reduce wear. Fig. 8 illustrates the influence of precipitation on the rail wear rates as measured from the field [9]. One may attribute the low wear rate to the reduction of friction due to water. As pointed out by Hardwick et al. [32], the actual wear rate under water lubricated conditions is much lower than simply reducing the coefficient of friction from 0.5 to 0.2 based on the Tγ/A approach. Some other factors can also influence the interface, such as humidity and temperature, which may not be as obvious as water. The effect of humidity was first recognized by the serious adhesion loss in the mornings, particularly for the first train. Work was performed using a pin-on-disc rig equipped with a climate chamber. It was found that humidity greatly influences wear [33], as shown in Fig. 9. Under medium and low contact pressure, the wear rates significantly reduces with increased humidity. The result indicated that the water induced tribo-layer is active under medium and low contact pressure which is consistent with the observation in the field that the wheel tread-rail head contact is sensitive to climate changes. A further study on the influence of humidity and temperature showed that adhesive wear is predominant under low humidity which becomes more significant with decreased temperature [36]. A wear transition from adhesive to oxidative can be found with increased humidity.
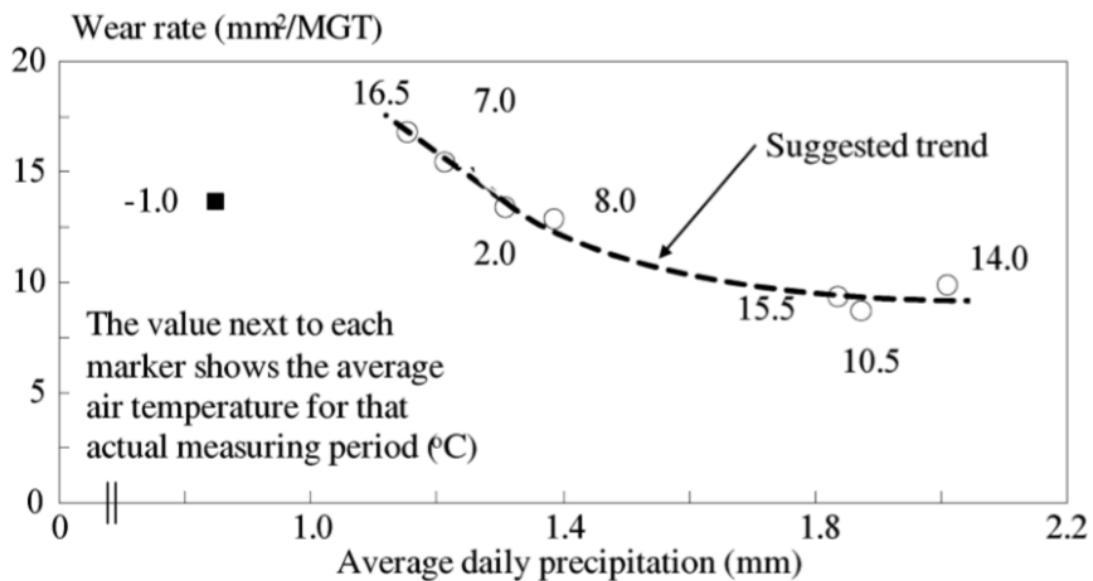
Fig. 8 Influence of average daily precipitation on the rail wear rates measured on a specific track site
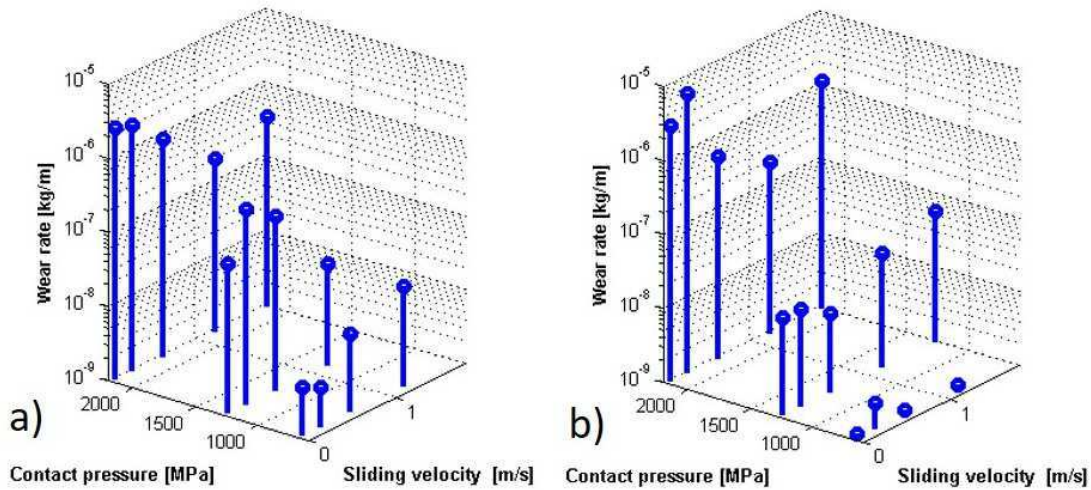
Fig. 9 Wear maps of wheel rail contact at a relative humidity of 30% (a) and 80% (b) [33]. Wear rate

calculation can be found in the Appendix.

In some geographical areas, wheel and rail wear under low temperatures are crucial since water transitions to snow or ice. Lyu et al. [52] and Olofsson and Lyu [53] studied the wheel rail wear focusing on low temperature, as shown in Fig. 10. When snow is present, snow particles are melting and forming a liquid-like layer under pressure, which facilitates oxidation. Thus the wear is reduced due to an oxide layer. In the absence of snow, the material brittleness is the dominating factor in the temperature range from 3°C to −15°C since cracks were formed leading to crushed wear debris which increased abrasion. When the temperature is extremely low (< −25°C), an ice layer was condensed, which absorbed a lot of energy in contacting. Therefore, the wear is very low. However, Ma et al. [54] reported that wear rates of rail material at low temperatures (-15°C, -30°C, and -40°C) are about double that at room temperature using a twin-disc rig. The results also showed that the wear mechanism is transformed from abrasive wear at room temperature to adhesive wear at low temperatures. Meanwhile, as the temperature decreases from 20°C to -40°C, the content of oxide in the debris decreases [55].
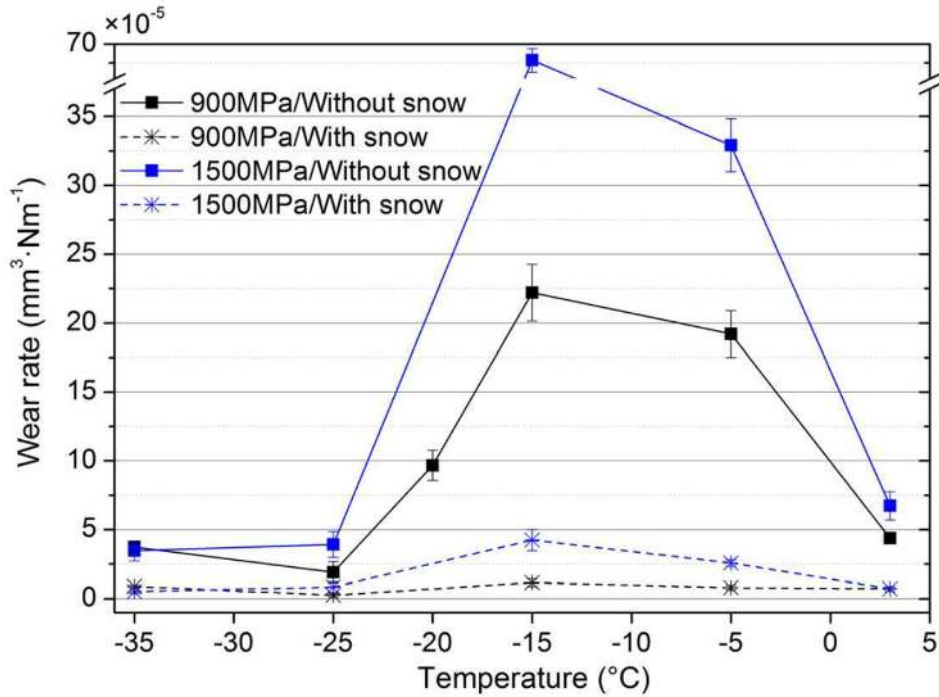
Fig. 9 Wear rates versus temperature at low temperatures [53]. Wear rate calculation can be found in the Appendix.

4.2 Influence of iron oxides and leaves

Iron oxides are constantly present on wheel and rail surfaces and are unavoidable while studying wheel rail wear. The types of iron oxides and their basic properties were summarized by Godfrey [56]. Factors that influence the extent of iron oxide formation and the types of iron oxide formed include applied loads [57,58], contact pressure, lubrication [59], presence of some minor elements [60] and atmospheric conditions [61]. However, the formation and removal of iron oxides on wheel and rail surfaces is affected by running wheels [62]. Suzumura et al. [63] studied the formation of iron oxides on rail surfaces in the field using in situ X-ray diffraction. The results are summarized in Table 3 which indicate that there are three types of rusts commonly present on the rail surface and the slip ratio greatly influences the removal of those rusts.

Table 3 Types of iron oxides detected on the tracks [64] (summarized from [63])

Running condition	Rust	Relative X-ray intensity (%)		
		Initial state	1 cycle	5 cycles
Rail top in tangent track; driving at 30 km/h and braking at 40 km/h.	α-FeOOH	3.7	4.5	4.2
	β-FeOOH	10.2	5.1	No peak
	γ-FeOOH	3.8	5.5	5.0
Rail top in tangent track; free rolling at	α-FeOOH	4.9	5.3	5.9

10 km/h.	β-FeOOH	8.4	8.5	7.1
	γ-FeOOH	7.5	9.7	9.1
Rail gauge of the high rail; driving at 10 km/h and braking at 15 km/h	α-FeOOH	6.7	4.2	2.3
	β-FeOOH	16.3	6.8	No peak
	γ-FeOOH	7.5	5.9	No peak

Beagley pioneered the laboratory tests that study the influence of iron oxides in the 1970s by mixing Fe_2O_3 with fluids [65,66]. Other researchers followed a similar procedure to study the influence of iron oxides on friction and wear [37,67,68]. However, iron oxides created by manual mixing are still unlike what is found in the field. Sone et al. [69] proposed a surface treatment for generating iron oxide surfaces similar to those obtained in the field. Zhu et al. [33,70–72] and Lyu et al. [36] followed the surface treatment procedure and conducted a series of laboratory tests using twin-disc and pin-on-disc rigs. The results indicated that three-body abrasion is the dominating wear mechanism. In general, a thin oxide layer containing a small amount manganese carbide can reduce wear under wet conditions due to a protective layer that is formed. A thick oxide layer which contains maghemite, lepidocrocite, and goethite significantly increases wear rates and surface roughness. A comprehensive review focusing on the iron oxides can be found in Zhu [64].

During autumn, leaves fall on the tracks and are swept onto the rails by the running trains. Those leaves are crushed by the wheels and form a tarnished layer that adheres to the rail surfaces and is hard to remove, as shown in Fig. 11. This layer causes low adhesion due to a chemical reaction [73,74] rather than wear related problems. However, some measures, such as sanding and applying traction gels to the rail head, could recover adhesion, but the increased wear will have to be considered [75–77].
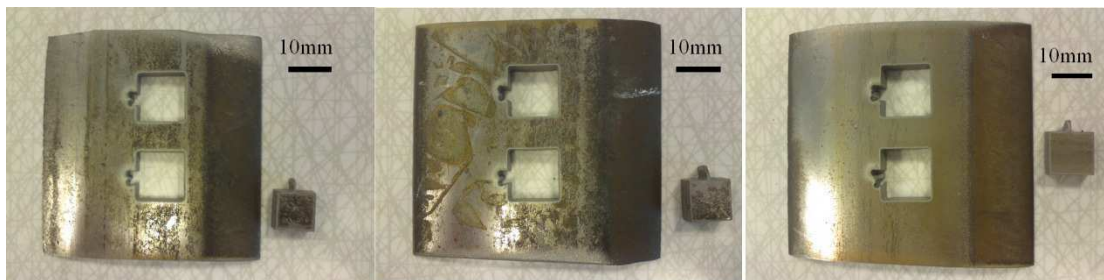

Fig. 11 Rail section samples: tarnished layer (left); leaf residue layer (middle); uncontaminated surface (right) [73].

The influence of the abovementioned environmental factors on the wheel-rail wear become even more complicated if other factors, such as sand, friction modifiers, and lubricants, are also taken into account.

Some important references mentioned in the section are summarized in Table 4.

Table 4 Summary of published papers on the influence of environmental conditions on wheel-rail wear

Reference	Experimental methods	Environmental factors	Effects
Nilsson [9]	Field measurements	Water	Increased daily precipitation reduces rail wear
Hardwick et al. [32]	Twin-disc	Water	Tγ/A wear results cannot apply to the water lubricated condition directly.
Zhu et al. [33] Lyu et al. [36]	Pin-on-disc	Humidity and temperature	In general, increased humidity reduces wear rate. The trend becomes more significant with decreased temperature.
Lyu et al. [52] Olofsson and Lyu [53]	Pin-on-disc	Low temperature	Presence of snow significantly reduces wear due to oxidation. Under extremely low temperature, the process of an ice layer condensing absorbs the contacting energy, leading to low wear.
Ma et al. [54]	Twin-disc	Low temperature	The wear rates of the rail material increase twice. The wear mechanism is adhesive wear.
Suzumura et al. [63]	Field measurements	Iron oxides	Iron oxides on rail surfaces were first measured in situ. The influence of running conditions on the iron oxides was studied.
Sone et al. [69]	Laboratory surface treatments	Iron oxides	They provided a procedure of surface treatments to generate iron oxides similar to those found in the field.
Zhu et al. [71,72] Lyu et al. [36]	Twin-disc and pin-on-disc	Iron oxides	Results indicated that three-body abrasion is a dominating wear mechanism. In general, a thin oxide layer can reduce wear under wet conditions due to a protective layer formed. A thick oxide layer increases wear rates and surface roughness.
Zhu et al. [73]	Field	Leaves	The mechanism of low adhesion caused by leaves is

Cann [74]	measurements and ball-on-disc		due to a chemical reaction between the leaves and the rail materials.

5 Rolling contact fatigue under environmental conditions

Rolling contact fatigue damage is a major form of wheel-rail damage. Statistics showed that RCF damage accounted for 41% of all tread damage [54]. The main failure phenomena of wheel-rail RCF includes spalling, squat, crack, corrugation, flange wear at the interface between the wheel and the rail and side wear and fracture on the rail. These destructive phenomena are related to many factors, such as the motion behavior of the wheel-rail, the friction coefficient, the conditional factors (such as surface damage [78], rolling directions [79], rough surface [80], and so on), the wheel-rail materials, the "congenital" defects left by processing and the structural form of rail vehicles. As was already mentioned, environmental factors also greatly affect the RCF.

5.1 Influence of ambient temperature and humidity

At high latitudes or in cold areas, the ambient temperature is as low as -40~-50°C in the winter. At low temperatures, the pearlite in the rail material becomes smaller and irregularly arranged [81,82] while the tensile strength and the yield strength of the material increases [81,83]. Under such conditions, the crack growth rate increased and the crack length became longer. This is caused by the brittleness of the material increasing with the uneven microstructure of the material in a low temperature environmental condition, while the mode of material damage is transformed from a shear-dominated (ductile) fracture mode to a cleavage dominated (brittle) fracture mode [81]. Ma et al. [54] reported that -15°C was close to the ductile-brittle transition temperature (DBTT) which caused severe RCF damage on the surface, as shown in Fig. 12. High ambient temperature does not significantly affect RCF as much as flash temperature does which can easily increase to several hundred degrees [84,85]. However, it is related to the running conditions which are beyond the topic of this paper.
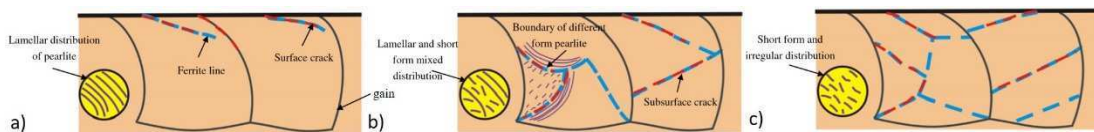

Fig. 12 The influence of ambient temperature on the fatigue crack growth [81] at: a) room temperature; b) -15°C; c) -30 and -40 °C.

The RCF life of the wheel and rail decreases with the increase of ambient humidity. In some practical railway lines, the RCF damage of the rail surface is more serious under high humidity and high sulfur conditions [86]. The humidity and temperature of the condition are closely related. In the laboratory, the ambient humidity decreases with the decrease of temperature [82]. However, there are few studies on the RCF of the wheel-rail under different humidity conditions.

5.2 Influence of water

In general, the damage of the wheel and rail surfaces is exacerbated by water at the wheel-rail interface, while the RCF life is also reduced. On one hand, the liquid accelerated the expansion of the fatigue crack on the surface of the material. On the other hand, the large amount of wear between the wheel and rail in the dry state was beneficial for removing the fatigue crack in the shallow surface of the material [87]. In earlier studies, cracks were believed to be generated only on the driven surface and expanded in the direction of the loading force [87]. In subsequent wheel-rail rolling tests, cracks were found on both surfaces of the two specimens. The experimental results showed that the RCF life of the driven wheel was higher than that of the driving wheel [88]. When the crack under wet conditions was closed under pressure, crack propagation was accelerated under the action of hydraulic pressure. Therefore, it was easier to find aggravation of the damage on the surface of the driven wheel under the wet condition [87]. Moreover, the water reduced the adhesion coefficient between the wheel and the rail and delayed the generation of surface cracks [89]. When the slip ratio was zero, it was difficult to observe the crack on the surface of specimens due to the low adhesion force [90]. The propagation of rail surface cracks was aggravated by the presence of water on the rail surface [84], as shown in Fig. 13. Therefore, excessive surface and subsurface cracks reduced the bearing capacity of the rail surface and increased the risk of squat damage on the rail surface [91]. Some studies have simulated the effect of water on crack propagation by establishing a three-dimensional model [92]. In addition, Cookson et al. [86] proposed that if the electrochemical effect of water in RCF crack growth was considered, the corrosion effect from impurities such as pH, oxygen, chlorine, sulfur, organic acids and the stray current caused by the track circuit should be taken into account.

Other environmental conditions, such as iron oxides and leaves, may aggravate the wheel-rail damage and reduce the RCF life by reducing the adhesion coefficient [93]. However, no detailed research can be found.

Some important references mentioned in the section are summarized in Table 5.
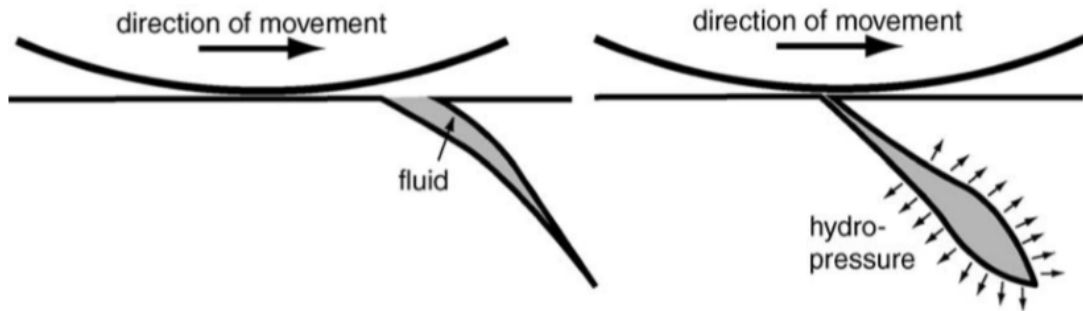
Fig. 13 Mechanism of crack propagation by the pressure of a trapped fluid [84].

Table 5 Summary of published papers on the influence of environmental conditions on RCF

References	Experimental methods	Environmental factors	Effects
Ma et al. [81]	Twin-disc	Low temperature	The propagation speed of the cracks and the length of RCF cracks increases.
Franklin et al. [94] Wang et al. [90]	Twin-disc	Water	Water exacerbates RCF damage. RCF damage exacerbates with the increase of slip under water lubricated conditions.
Bogdański and Lewicki [92]	Numerical simulation	Liquid	The model was used to estimate the 3D crack front loading enhancements due to the action of the "liquid entrapment mechanism".
Cookson and Mutton [86]	Literature review	Water and oxygen contamination	Water can lead to local corrosion and hydrogen uptake in the rail, further increasing the likelihood of cracking.

6 Some measures to mitigate wear

There are two ways to mitigate wheel-rail wear. One is to lubricate the interface and the other is to upgrade materials, both of which are discussed in the following. It is noted that the effect of lubricants will be discussed from wear and RCF problems seen from railway lines rather than discussing lubricants and lubricating theory.

6.1 Lubricant

As mentioned in Section 2, reliable lubrication of the gauge face of the high rail on moderate to tight curves has been shown to reduce wheel and rail wear by a considerable amount. Most modern rail operators with flat bottomed or ballasted tracks employ grease as a lubricating medium due to its tackiness and thus ability to adhere to the rail [95]. The grease is supplied from the side of the track by automatic distributors which are activated by passing vehicles. The standing grease is then collected by the passing wheel flange and carried through the corner. The reliability of modern trackside lubricators has meant that this method of lubricating has become common. However, a continuous, uninterrupted supply of lubrication is required for this method to remain effective. Research has shown that intermittent lubrication causes a drastic increase of the wear rate of the rail and wheel and if continuous lubrication is not achieved the long term wear rate can be higher than not lubricating at all [96]. A dramatic increase is seen in the wear rate with each subsequent test as shown in Fig. 14. What is more striking is the increase in wear of both the wheel and the rail after subsequent tests, which in most cases is higher than the un-lubricated reference. This suggests that it may be better to not lubricate certain curves if a 100% reliable lubrication system cannot be guaranteed.
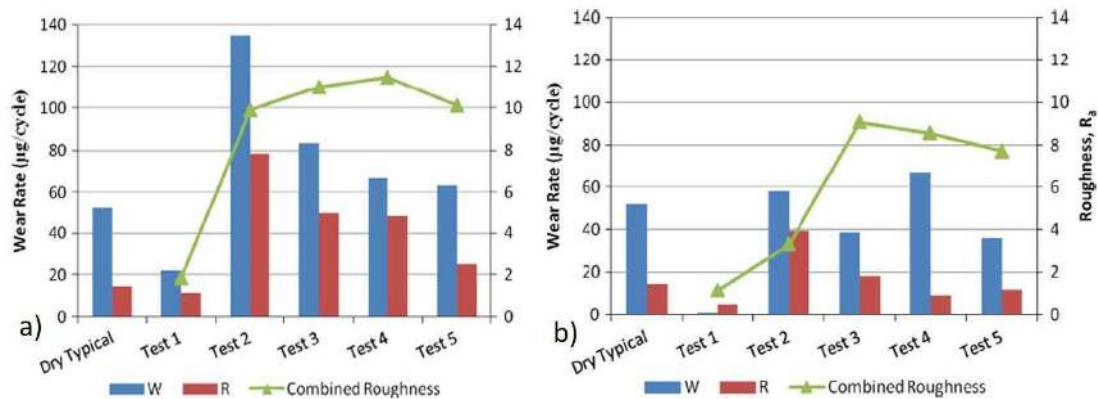
Fig. 14 Wear rate of wheel (W) and rail (R) discs after subsequent grease lubrication starvation tests (repeated on a single pair of discs 5 times) compared to typical un-lubricated (Dry) discs tested under the same conditions, a) and b) show two of the different brands of grease tested [96]. Wear rate calculation can be found in the Appendix.

Fletcher and Beynon [97] performed a series of twin-disc tests and found that intermittent application of grease accelerated RCF crack growth in the discs leading to rapid failure. Hardwick et. al. [32] performed a twin-disc test and found that un-interrupted lubrication prevents ratcheting from occurring and hence RCF cracks cannot form. However, if the supply of lubricant is stopped and the contact conditions allowed to return to dry/ un-lubricated then ratcheting will occur and cracks will form.

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Fletcher and Beynon [97] put forward a hypothesis that RCF cracks in the rail discs were being lubricated by entrapped grease which is causing an increase in the shear stress at the crack tip thus accelerating the crack growth. Wang et al. [98] found the presence of liquid could exacerbate the wear and RCF in the wheel and rail. Lubricants with high viscosity enhance hydraulic crack growth leading to many branch cracks.

Another phenomenon which has been highlighted by network operators and researchers is that the ability of trackside grease lubricators to effectively lubricate any particular curve is dependent on the types of vehicles traversing that curve whereby some vehicles will collect the standing grease but others will not [95,99].

A potential solution to this would be the adoption of solid lubricants which are applied from on board the vehicle. Research related to solid lubrication is rare but Chen et. al. [100] tested different lubricants including solid lubricants. It was found that solid friction modifier is the most effective type at reducing curving forces and corrugation.

Some important references mentioned in the section are summarized in Table 6.

Table 6 Summary table of published papers on effects of lubricants

Reference	Measures	Effects of lubricants
Temple et al. [95] Burtow and Temple [99]	Dynamic simulation, small-scale and full-scale testing	Grease pick-up mechanism is discussed and the installation of a trackside grease dispensing system needs to be tailored to the particular type of rolling stock being operated in order for optimal functioning.
Lewis et al. [96] Fletcher and Beynon [97] Hardwick et al. [32]	Twin-disc rig	Continuous lubrication is very important to reduce wear and damage. Intermittent application of grease accelerates RCF crack growth in the discs leading to rapid failure.
Chen et al. [100]	Twin-disc rolling contact machine	Solid friction modifier is the most effective type at reducing curving forces and corrugation.

6.2 Laser cladding

Compared to the lubricants which have been widely used in railway lines, laser cladding is a promising technology to reduce wheel-rail wear. Laser cladding is not a new technology, which is used for

enhancing the mechanical properties or repairing many engineering components [101,102]. Laser cladding is a hard facing technique which uses laser energy to melt the powders of atomized metal and metallurgically bond it to the surface of a substrate.

The application of laser cladding in rails started from a European frame research project INFRA-STAR [103–106]. This project investigated the application of a laser cladding process to rails for the purpose of preventing rolling contact fatigue (RCF) damage and to reduce squeal noise in curved tracks using both laboratory and field tests.
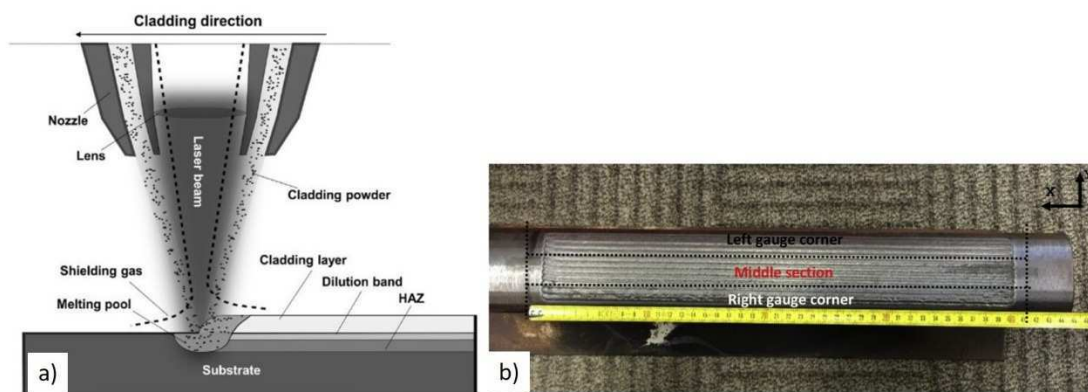

Fig. 14 a) Schematic of a typical laser cladding unit; b) a section of clad rail. [107]

Small scale rolling sliding tests have been performed by many researchers to study the influence of various cladding materials (mostly steel) on the wear and RCF resistance of rails [108–115]. Results indicated that clad rails generally have a higher wear and RCF resistance compared to unclad rails. However, some results may show variations depending on contact conditions and laser cladding quality. Lai et al. [107,116,117] performed a study from a material aspect by cladding several materials on the actual rail surface, as shown in Fig. 14. Different laser cladding processing parameters, including heat treatment and laser cladding direction are considered to identify the optimum laser cladding process for ideal microstructures which may result in high wear and RCF resistance.

Lewis et al. [118] carried out full-scale testing on laser clad one-meter rail track using a full-scale wheel-rail test rig. They measured wear of clad track and lipping resistance of insulated block joints. They found that the wear rate of the clad samples is between 78–89% lower than that of the reference and cladding either side of an insulated block joint greatly improved its lipping resistance. Hernández et al. [119] reported a full-scale field track test on laser cladded thermite welds using Facility for Accelerated Service Testing (FAST) at Transportation Technology Center, Inc. (TTCI), USA. Results indicated that claddings survived the test for up to 42 MGT in a full scale-heavy haul environment,

which is a 14 times improvement from previous work.

It has been shown that laser cladding rails with selected cladding materials and cladding processing parameters can improve its wear and RCF resistances. Limited data, other than microstructural analysis and the hardness measurements, is available on the mechanical properties of the claddings and the HAZs. Those properties are not only crucial for the strength and deforming behaviours of the clad rails but also important for numerically predicting the performance of the components under cyclic rolling contact [120,121]. Moreover, residual stress is one of the critical parameters concerning the fatigue behaviour of tribological components. Tensile residual stress near the surface will assist fatigue crack initiation and propagation while compressive residual stress will have the negative effect. Laser cladding could also be an effective technique to repair and maintain surface damaged wheels while the bonding interface between the cladding and bulk materials is very critical [122]. Practically, repairing wheels by laser cladding can be carried out in workshops, which might be more flexible and cost-effective than repairing rails.

Some important references mentioned in the section are summarized in Table 7.

Table 7 Summary of published papers on laser cladding in rail/wheel systems.

Reference	Cladding material	Experimental method	Effect of laser cladding
Hiensch et al. [104] Franklin et al. [106] Clare et al. [108,109] Lewis et al. [110,111] Fu et al. [112] Wang et al. [113] Guo et al. [114] Roy et al [115]	Duroc 222, Duroc 508 Co-Cr alloys, nickel alloy, Stellite 6, maraging steel, Hadfield steel, 316 stainless steels, Manganese Steel, martensitic stainless steel, TWIP Steel, NiCrBSi, Co-based alloy, Fe-based alloy, 410L stainless steel, SS420 stainless steel.	Scaled rolling-sliding test rig	In general, the wear and RCF resistance of the clad rail materials are increased. But it also depends on the cladding materials and cladding processing parameters. Many studies reported that Stellite 6 is a promising rail clad material.
Hiensch et at. [103]	Duroc 222 and Duroc 508 Co-Cr alloys	Field test on straight rail track	Increased wear and RCF resistance
Lewis et al. [118]	Martensitic stainless steel and Stellite 6	A full-scale laboratory test	Lower wear rate and increased lipping resistance. Stellite 6 is a suitable laser cladding material.
Hernández et al.	A undisclosed cladding	Full-scale track test	Claddings survive the test for

[119]	material selected based on its superior resistance to cracking during cooling	using Facility for Accelerated Service Testing (FAST) at TTCI, USA	up to 42 MGT in a full scale-heavy haul environment, which is a 14 times improvement from previous work. Proper heating and cooling prior and post laser cladding is one of the key factors for the improved field test.
Lai et al. [107,116,117]	410L stainless steel, SS420 stainless steel, Stellite 6 and Stellite 21	Microstructural characterization, shear punch test	Laser claddings have comparable or better mechanical properties than the un-cladded rail. Proper post-heat treatment can prevent the formation of brittle martensite in HAZ.

7 Concluding remarks and future trends

This paper presented a literature review on wheel-rail wear under environmental conditions. Some basic information on wheel and rail wear was presented, including contact conditions, typical wear characteristics, and forms of environmental exposures. Wheel rail contact is a typical tribological system with features that make the system unique and complicated. Experimental methodology was also discussed, which helps not only to understand the fundamentals of wheel-rail wear but also to develop measures in the field. The advantages and disadvantages of wear testing methodologies, including the pin-on-disc, twin-disc, scaled wheel-rail, full-scale laboratory and field, were compared in detail. Recommended measurements for wear tests were also presented. It is important to develop standards to measure wheel-rail wear and RCF to evaluate new materials and friction modifiers. Moreover, such standardized tests could narrow the gap between laboratory tests and reality. However, much work needs to be performed from both technical and application aspects.

The influence of environmental factors, such as temperature, humidity, water, and leaves on wheel-rail wear and RCF were presented. The environmental phenomena in the field have been recognized for a long time but only until recently have people from both academia and industry realized the importance of these phenomena and started to investigate their mechanisms and influence. As can be found in this review, most of the studies were performed to investigate a single factor on wear and RCF behavior. However, the environmental factors are combined in the field which makes their influences even harder

to understand. Compared with wear, the influence of humidity and iron oxides on RCF is not well studied. On the other hand, the interaction of wear and RCF is crucial. Wear can be used to remove cracks if it can be accurately controlled. Typically, RCF is more severe under lubricated conditions than under dry conditions. Therefore, there is a trade-off between reducing wear and removing RCF. Further studies taking both factors into account will be very useful to solve many problems.

Lubricants are widely used on railway lines to reduce wear while laser cladding is currently considered to be a promising technology to enhance wheel and rail materials. As already mentioned, laser cladding to repair wheels and enhance some rail sections will be more flexible and cost-effective than cladding the whole rail. From the application point of view, more field test research similar to those completed by Hernández et al. [119] will be the key step to convince the railway industry to apply the laser cladding technique to recover and enhance the wear and rolling contact fatigue resistance of the rails and the wheels.

Appendix

The wear rates presented in Figs. 4(a), 8, 9, 14 have inconsistent units due to different test rigs used and some practical reasons. The equations used to calculate wear rates are shown in the following table.

Table 8 Wear rate calculation in the articles

Wear rate unit	Wear rate calculation	Notes
mm^2/MGT in Fig. 4 (a)	Volumetric loss of the rail/applied load 1 million gross tons (MGT) = 10^9 kg.	MGT describes the total weight of rail vehicle which is commonly used in railway operations.
kg/m in Fig. 8	Mass loss of the sample/sliding distance	Used in pin-on-disc testing.
mm^3/N•m in Fig. 9	Volumetric loss of the sample/(sliding distance × applied load)	Used in pin-on-disc testing.
mm^3/cycle in Fig. 14	Volumetric loss of the sample/running cycles	Used in twin-disc testing

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