Review

Weichen Xu*, Binbin Zhang, Yu Deng, Zhengquan Wang, Quantong Jiang, Lihui Yang and Jie Zhang*

Corrosion of rail tracks and their protection

<https://doi.org/10.1515/correv-2020-0069>

Received July 14, 2020; accepted October 19, 2020;

published online December 24, 2020

Abstract: Rapid development of railway industry makes safety increasingly important. Wear, contact-impact, fatigue and corrosion are important factors initiating rail track degradation from the beginning, while corrosion attracts far less attention than other issues. Direct corrosion cost due to railway corrosion in China was 18.88 billion RMB, so corrosion definitely deserves more attention. This work has reviewed studies focussing exclusively on rail corrosion, including corrosion forms, protection and detection technologies. General corrosion on large rail surface is not limiting, while crevice corrosion between rail and liner, resulting in thinning of rail foot, is regarded significant but overlooked. Moreover, reciprocating micro-motion between rail foot and liner mechanically assists the ongoing of crevice corrosion. However, it was mentioned in very few reports and not investigated extensively. Coating and surface modification may be applied for mitigation of rail track corrosion. The weakness of coating is poor mechanical

properties, while surface modification, including thermal spraying and laser cladding, may be a better way. Development of novel steel is another effective method, but loss of mechanical properties becomes obstacles for practical applications. Ultrasonic and infrared have been applied for detection, while more advanced technologies are promising. Suggestions are made on specific research topics in this field.

Keywords: corrosion; protection; rail track.

1 Introduction

Railway industry has developed rapidly all over the world. Until 2018, total mileage of high-speed rail transits in China has exceeded 25,000 km, followed by Spain, Germany, Japan and France. It has become a most efficient approach for transportation including both passengers and freight in these countries. However, rapid development of railway industry is making the rail surface damage become increasingly severe (Cannon et al. 2003; Panda et al. 2008a; Zhong et al. 2011), and operation safety and service life issues are of great importance. With the increase of train speed, car loading and also traffic volume, requirements on durability and reliability of railways are also increasingly stringent.

1.1 Rail steels

There are many types of steels applied as rail track with “I shaped” cross section, mainly Mn containing carbon steels (standard rail) and low alloy steels (high strength rail) with Mn, Cr, V, Mo, Ti, Nb and Re. Table 1 summarised chemical compositions of several typical heavy rail steels (for high speed trains, inter-city railway, subway, etc.) according to different standards, and it can be seen that the chemical compositions are similar (Zhi et al. 2019). Rail steels are applied to withstand enormous pressure of wheels and guide wheels of railcars to move, so high strength and hardness, high resistance to friction wear and corrosion, and reasonable toughness are most significantly desired characteristics. The requirements of desired

***Corresponding authors: Weichen Xu and Jie Zhang,** Key Laboratory of Marine Environmental Corrosion and Bio-fouling, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, People's Republic of China; Open Studio for Marine Corrosion and Protection, Pilot National Laboratory for Marine Science and Technology, Qingdao 266237, People's Republic of China; and Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao 266071, People's Republic of China, E-mail: w.xu@qdio.ac.cn (W. Xu), zhangjie@qdio.ac.cn (J. Zhang). <https://orcid.org/0000-0002-0934-2328> (W. Xu)

Binbin Zhang, Zhengquan Wang, Quantong Jiang and Lihui Yang, Key Laboratory of Marine Environmental Corrosion and Bio-fouling, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, People's Republic of China; Open Studio for Marine Corrosion and Protection, Pilot National Laboratory for Marine Science and Technology, Qingdao 266237, People's Republic of China; and Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao 266071, People's Republic of China

Yu Deng, Open Studio for Marine Corrosion and Protection, Pilot National Laboratory for Marine Science and Technology, Qingdao 266237, People's Republic of China; and School of Shipping and Naval Architecture, Chongqing Jiaotong University, Chongqing 400074, People's Republic of China

properties in different countries are not exactly the same but similar. For example, the tensile strength is generally above 800 MPa for standard rails and 1200 MPa for high strength rails, the elongation is generally above 4% for standard rails and 10% for high strength rails, and the hardness (HB) is about 400 for high strength rails (Wang et al. 2016a).

1.2 Basic structure of fixed rail track

A fastening system is necessary to fix rail on the sleeper, and there are various types of fastening systems suitable for different tracks (e.g. ballasted/ballastless tracks, different track weight) and sleepers (e.g. shoulder/shoulderless, bolt/boltless), providing different clamping force normally in the range of kN. The clamping force is applied directly on rail foot mainly provided by clip fastening, elastic slice or elastic strip. The first two types are mostly out of use, and elastic strip is widely applied for modern railways. Figure 1 shows a typical fastening system with type II elastic strip (TB/T 3065-2002, China). A fastening system basically includes elastic strip, screw spike, gauge block and under-rail cushion. The gauge block is used to maintain track gauge and avoid lateral displacement of rail track, acting as a liner between elastic strip and rail foot. It is preferentially an insulator due to the electrification of modern railways and to avoid galvanic corrosion between metallic components.

1.3 Deterioration of rail track

The design lifetime of railways is sometimes stated to be 100 years (life-cycle), but the lifetime of a certain rail track is generally no more than 30 years based on proper

Figure 1: Fastening system with type II elastic strip.

inspection, maintenance and replacement. It is decided by specific service condition and there is no certain standard lifetime. Based on daily inspection and maintenance, the period for overhaul or major replacement is often in about 10–20 years if there is no accident or reported quality problems, but for specific sections of railway the period for replacement may be largely shortened, e.g. at bend/curve section where wear is serious, or at coastal or humid area where corrosion issues may be severe (even in several months), and short period regular maintenance should be applied for these specific conditions, e.g. weekly application of anti-rust oil and daily inspection.

The deterioration of rail track has already attracted attention, including wear, contact-impact, fatigue (often cited as RCF, i.e. rolling contact fatigue), corrosion, cracking and fracture (Hernandez et al. 2007; Hernandez-Valle et al. 2013; Liu et al. 2019; Ren et al. 2013; Safa et al. 2015; Shariff et al. 2013; Shurpali et al. 2012; Yazici and Yilmaz 2018; Yu and Feng 2013; Zhao et al. 2015). Among these research topics, wear, contact-impact, fatigue and corrosion are regarded as main factors initiating degradation of rail materials from the very beginning, while cracking and fracture can be regarded as the noticeable results of failure. They exert adverse influence under

Table 1: Chemical composition of several typical heavy rail steels according to different standards.

Standards	Designation of steels	Chemical composition (wt %)										
		C	Si	Mn	P	S	Cr	Al	V	H	O	N
ISO 5003-2016	HR260A	0.62–0.80	0.15–0.58	0.70–1.20	<0.025	<0.025	<0.15	<0.004	<0.030	<2e-4	<0.002	<0.009
	HR280	0.71–0.80	0.50–0.80	0.70–1.05	<0.025	<0.025	<0.15	<0.004	0.04–0.12			
BS EN 13674-2011	R260	0.62–0.80	0.15–0.58	0.70–1.20	<0.025	<0.025	<0.15	<0.004	<0.03	<2.5e-4	<0.002	<0.009
TB/T 3276-2011	U71MnG	0.65–0.75	0.15–0.58	0.70–1.20	<0.025	<0.025	<0.15	<0.004	<0.03	<2e-4	<0.002	<0.008
	U75VG	0.71–0.80	0.50–0.70	0.75–1.05	<0.025	<0.025	<0.15	<0.004	0.04–0.08			
TB/T 2344-2012	U71Mn	0.65–0.76	0.15–0.58	0.70–1.20	<0.030	<0.025	<0.15	<0.010	<0.030	<2e-4	<0.003	<0.009
	U75V	0.71–0.80	0.50–0.80	0.75–1.05	<0.030	<0.025	<0.15	<0.010	0.04–0.12			
JIS E1101-2001	60 kg/m	0.63–0.75	0.15–0.30	0.70–1.10	<0.030	<0.025	–	–	–	–	–	–

different service conditions. For example, there are differences on deterioration of rails for freight trains and passenger trains. The priority is load capacity for freight trains while it is speed for passenger trains (especially high speed trains above 200 km/h). Freight trains usually apply primary suspension systems (poor damping efficacy) and also lack of effective shock absorber on the axles, leading to serious contact-impact on the top surface and wear on the side of rails. Passenger trains often exert remarkable lateral pressure on the side of rails at curve section, so the radius of curve for tracks of passenger trains is generally bigger. Also, salt deposition and contaminants from atmosphere largely affect corrosion of rail tracks for both freight and passenger trains, while there are some specific service condition for either, for example, rail track for freight trains may be covered by thick braise (coal dust) which affects corrosion behaviours of steels, and wastewater and discharge from lavatories are sometimes a concern for corrosion of rail track for passenger trains. In addition, the track lines for high speed passenger trains usually pass through more tunnels with high humidity and poor ventilation. Therefore the environment along the lines is different. The service conditions are not the same, leading to different deterioration on rails for freight and passenger trains. However, these differences are difficult to be quantitatively characterised, and sometimes a same section of rail track is shared by freight and passenger trains (regular speed).

Different parts of rail also suffer different forms of deterioration. On the top surface of rail, corrosion is not a serious issue since it is mainly general corrosion, but RCF (rolling contact fatigue) and wear are serious, sometimes leading to rail corrugation and cracking. For the side, if we divide it into upside and downside, the degradation of upside is also mainly ascribed to wear, especially at bend sections, normally visible and sometimes massive. For the downside of rails, wear is not crucial since it is out of the contact area between rails and wheels, but corrosion is a significant issue near rail foot and rail base mainly ascribed to crevice corrosion and stray current corrosion. However, extra thickness for corrosion allowance is generally not considered for rail track, and the sizes of rail head, waist and base are designed to meet requirements of load and speed of the trains.

1.4 Current studies on rail track corrosion

Extensive, various and systematic studies on wear, contact-impact, fatigue of rail track materials have been carried out, most of which did not consider the effect of

humidity (wet environment) (Franklin et al. 2005; He et al. 2017; Hernandez et al. 2007; Kowalski and Cygnar 2019; Lewis et al. 2017; Lyu et al. 2015; Shariff et al. 2010; Qi et al. 2017; W. Wang et al. 2014b; Wang et al. 2016a, b; Yazici and Yilmaz 2018; Zhong et al. 2011), while corrosion is left as a relatively less concerned issue in the literature. However, the adverse effect of corrosion is no less severe than the others for rail track materials. The service environment of rail track is complicated since railways are widely applied all over the world. Conditions including sunlight, relative humidity, temperature and atmosphere largely affect corrosion. Besides, salt deposition is a significant factor initiating corrosion. In addition, the change of temperature on rail surface lags behind the temperature of air, and condensation of water from air and evaporation would result in wet/dry cycles, which also favours corrosion. Corrosion itself would not induce remarkable mass loss of rail track and is generally hidden and difficult to be detected in time. This might be one of the main reasons that corrosion issue of rail has not yet attracted enough attention and become a major concern. However, small loss of rail materials (e.g. probably no more than $6.5 \text{ kg km}^{-1}\cdot\text{year}^{-1}$ for North American transit systems (Hernandez et al. 2009)) may induce substantial change on material performance or even act as “stress concentrator” for an initiation of cracking (Hernandez et al. 2009). NACE International carried out an “*International Measures of Prevention, Application, and Economics of Corrosion Technologies Study*” (IMPACT) and reported corrosion cost of rail transport sectors of several countries including India (496 million USD in the year 2011–2012), United States (500 million USD in the year 1998), Japan (18.4 billion Yen in the year 1997) (Koch et al. 2013). The cost of rail track corrosion was not singled out in this study, but it has been suggested that corrosion of rail tracks and railcars are the two main areas of this sector. A corrosion cost study in China has been carried out recently regarding five main industrial fields including transportation (Hou et al. 2017). It has been reported that the direct cost due to corrosion of only railways (railcars not included) in the year 2014 was 18.88 billion RMB (Hou et al. 2017). According to international conventions of corrosion cost study, corrosion cost of a certain sector includes direct cost of corrosion mitigation measures, material substitution and maintenance due to corrosion, and also indirect cost of casualties and environmental damage caused by accidents due to corrosion. A cost of 18.88 billion RMB in China reported above is only direct cost, while the overall cost can be estimated to be doubled or even more (Uhlig 1950). Direct cost is the cost directly induced by corrosion, including change of corroded components, track maintenance due to

corrosion, application of corrosion protection technologies (coatings, corrosion resistant materials, insulating materials) etc. Indirect cost is the cost that can be partially ascribed to corrosion, including decrease of income by temporary suspension of service or schedule change due to corrosion, casualties in accidents ascribed to corrosion, environmental pollutions, etc.

Corrosion is one of the main reasons for the short service lifetime of rail components (Shi and He 2011). Since these materials are exposed in the open air, wet environment can provide sufficient conditions for the initiation of corrosion, which is even more severe at coastal zones or salt lake areas. Corrosion can induce severe surface delamination, and serious rustiness has been observed on rails within months in Sichuan and Chongqing (high humidity with acid rain) of China (Hou 2019). Actually, very high maintenance standards [e.g. raising steel grades by 2–3 levels (steel grades represent different mechanical properties including strength and hardness and different sizes including railhead width and rail base thickness; for example, P75 and P60 rails are both stronger and thicker than P50 rail, and for a rail section on which the properties of P50 rail are sufficient, P60, P75 or even higher grade rail is used to ensure optimal performance), largely reducing replacement period] have to be implemented to guarantee safety in many countries, resulting in excessive and unnecessary cost (Hou 2019).

Until now, studies on rail track corrosion are still very limited and unsystematic. In this work, previous studies focussing exclusively on corrosion and protection of rail track has been reviewed for the first time. The purpose of this work is not limited to discussing the previous research findings, more importantly, it should help

emphasise the significance of corrosion research, attract more attention in this field and help carry out further work in those areas more needed. We have also provided suggestions on specific research topics that are more crucial in this field.

2 The forms of corrosion failure on rail tracks

Corrosion failures of rail tracks are basically near rail base and rail foot. Corrosion at rail base and rail foot would lead to thinning of foot section and instability of rail, inducing a potential risk of displacement, introduction of large stress or even rail failure. Figure 2 shows examples of corrosion failure on rail tracks. It is very clear that corrosion of the lower part of rail are more severe, especially at rail base and foot. Figure 2a shows serious corrosion loss at rail base mostly induced by stray current. Figure 2b and Figure 2c show corrosion induced by salt precipitation probably initiated from localized corrosion and coalesced to induce remarkable metal loss and even rust debris falling off. Figure 2d typically shows that the base and foot has been seriously corroded while the circumstance of the upper part is much better. Figure 2e shows seriously corroded rail foot with thick rust layer. Corrosion failure of rail has not been reported to directly induce severe accidents like derailment, but it is believed that any engineering failure is resulted from more than one factors and corrosion is a significant precursor. A high standard for detection and maintenance is always required, and corrosion keeps inducing safety concerns and high costs.

Figure 2: (a) A section of rail provided by Port Authority Trans-Hudson, New Jersey; (b) a section of rail around clip provided by TTC (Toronto Transit Commission) subway, Canada; (c) an example of rail corrosion in high humidity operated by TTC, Canada; (d) a section of rail provided by TTC, Canada; (e) seriously corroded rail foot section made of C–Mn steels. Figures (a–d) are from National Academies of Sciences, Engineering, and Medicine 2007, reproduced with permission from The National Academies Press, license ID 1071355-1; Figure (e) is from Balasubramaniam et al. 2011, reproduced with permission from Current Science Association).

3 Corrosion forms and characteristics

3.1 General corrosion

Same to the general classification of corrosion, corrosion forms of rail tracks can also be divided into general corrosion and localised corrosion. General corrosion normally takes place on large surfaces of rails, while the initiation may be in the form of pitting corrosion. Since pitting corrosion resistance of rail steels (for both Mn containing carbon steels and low alloy steels stated in Section 1) is poor due to the lack of stable and resistant passive film, pits usually initiate easily and coalesce quickly on the large surface instead of growing deep, thus presenting as general corrosion when observed. This is not crucial, since general corrosion would normally induce loss of materials on large surface without serious local attack which can lead to the failure of the rail. Although corrosion products may promote deterioration of rail materials in certain circumstances, e.g. akaganeite formed underground in high chloride concentration (Isozaki et al. 2016), under more general conditions corrosion product may exert protective effect on rail surface, and corrosion rate is then lowered. Therefore, it is very common that rust can be observed on rail surface several months after use, and proper maintenance and inspection can ensure safe operation. General corrosion can be largely ascribed to salt deposition and atmospheric corrosion, especially in areas with high temperature, high relative humidity or high salinity (easily inducing the initiation of pitting and the following coalescence). In addition, researchers also proposed the effect of discharge from toilets of passenger trains, which mainly induce microbiologically influenced corrosion (MIC) (Balasubramaniam et al. 2011; Maruthamuthu et al. 2011), and the role of certain types of bacteria has been intensively characterised, demonstrating the alteration of corrosion products and acceleration of corrosion rate due to microbes (Maruthamuthu et al. 2011). The adverse effect of general corrosion can be well controlled by proper inspection and maintenance, and the application of corrosion prevention technologies which will be discussed in Section 4.

3.2 Localised corrosion

Although pitting corrosion can easily take place on rail surfaces, it does not tend to grow deeper but is more likely to coalesce, forming wide and shallow corrosion morphologies, and deep pits on rails have not been reported.

While crevice corrosion has been reported to be a typical form of localised corrosion. Panda et al. (2008a) has clearly reported the crevice corrosion at rail foot section, with liner covering above acting as a crevice former. A liner is often applied between elastic clip and rail foot, which ensures stable clamping force to fix rail and avoid lateral and longitudinal movement. Due to electrification of modern railways, insulating materials like polyamides are often used, which is referred as gauge block insulator. A typical fastening system is already shown in Figure 1, and a crevice is formed between the insulator and rail foot section. Therefore, accumulation of corrosive media including chloride ions and maybe microbes can easily take place, initiating crevice corrosion as shown in Figure 3 (Panda et al. 2008a). Authors of the current work also observed this phenomenon during rail maintenance period after elastic strip being removed (Figure 4). Rail foot possesses the thinnest cross-section while it is the only part to be contacted with and to be fixed by fastening system (elastic strip provides the clamping force), so severe crevice corrosion will lead to thinning of rail foot, which is essentially dangerous (Balasubramaniam et al. 2011). In addition, there is also crevice between rail base and cushion, where crevice corrosion may also occur. Figure 5a describes the relative location of elastic strip, gauge block and rail foot, and Figure 5b emphasises roughness on the contact surface between gauge block and rail foot, between gauge block and elastic strip and also between rail base and cushion, where electrolyte film can be formed and crevice corrosion is feasible. However, this issue has not yet attracted enough attention.

Figure 3: Crevice corrosion at rail foot (circled). The removed elastic strip and mild steel liner are marked as A and B, respectively. Figure from Panda 2008a, reproduced with permission from Elsevier, license number 4932771126633).

Figure 4: Crevice corrosion patterns on rail foot sections after removal of elastic strip from a section of rail in eastern coastal area of China.

Figure 5: (a) Schematic diagram showing relative location of the cross sections of elastic strip, gauge block, rail foot and cushion; (b) schematic diagram emphasising roughness of the contact surface between gauge block and rail foot, between gauge block and elastic strip and between rail base and cushion.

More seriously, rail foot section is subjected to vibration of very small amplitude when trains move over rail tracks, and an amplitude of 100 μm has been used by Panda et al. (2009a). Due to large clamping force provided by fastening clip, the micro-motion between rail foot and liner (see fastening system geometry in Figure 1) would induce damage of passive film or removing of corrosion products, leading to fresh surface directly being exposed in corrosive in-crevice electrolyte. This can be regarded as a combination of crevice corrosion and fretting wear, which can also be described as mechanically assisted crevice corrosion, firstly proposed by Gilbert (Gilbert et al. 1993) for corrosion of modular hip-prosthesis human implant components. During walking, reciprocating micro-motion would occur on the interface between femoral head and

neck, and with the existence of mechanical load, passive film will be damaged, while the crevice geometry would be maintained due to the very small amplitude of the motion. This is characterised by “large size of contact area” and “much smaller size of displacement distance”, so the surrounding body fluid cannot easily enter in to dilute the developing aggressive crevice solutions. A synergistic effect of crevice corrosion and fretting wear would deteriorate interface remarkably and induce serious and continual corrosion. The reciprocating micro-motion between femoral head and neck are just like that between rail foot and liner, for which the area of the contact area is in the range of $\sim 10^1 \text{ cm}^2$ while the amplitude of the motion is only in the range of μm -mm, so this special type of corrosion is inevitable. Load, amplitude and frequency of the vibration are significant parameters for the study of this kind of crevice corrosion. Scars on rail foot are also observed in Figure 3 and Figure 4, which are ascribed to the reciprocating micro-motion between rail foot and liner. The scar area was a small anode, if the surrounding metal surface could act as a large cathode, severe localised corrosion would potentially occur. However, there is no systematic research on this issue, except that only Panda et al. (2008a) very briefly raised this problem.

Moreover, a typical characteristic is still overlooked in the literature. Since the wet environment initiating crevice corrosion of rail foot is largely due to the collection of moisture from atmosphere, and the conductive electrolyte for corrosion would only exist as a thin solution film, so the cathodic area is typically limited and variable. This is another complicating factor affecting crevice corrosion behaviours of rail foot. Crevice corrosion under this circumstance is often controlled by cathodic current, so this is a very important issue to be considered. Bocher and Scully (2015) recently reported their work investigating the effect of cathodic area on crevice corrosion, although not regarding rail steels, their work can be used as an important reference for typical crevice corrosion research of rail foot.

Besides crevice corrosion, stress corrosion cracking is also important. Cyclic stress imposed on rail track steels has been intensively studied (Kang and Gao 2002; Kang et al. 2002), but there is a lack of concentration regarding corrosion issue. Corrosion at a local site has been suggested to be one of important precursors for stress cracking and also secondary cracks afterwards (Al Juboori et al. 2019), while a recent study reported that stress induced corrosion can significantly affect strain of steels during loading process (Sun et al. 2018), therefore stress and corrosion are mutually influenced, which initiates cracks and largely deteriorates durability of rail steels.

Generally, previous research has shown that stress cracking are commonly initiated from the development of localised corrosion (Hill and Lillard 2006; Zhu et al. 2013). Localised corrosion coupled with mechanical displacement/vibration under the fastening system has not been reported to initiate cracking in the literature, but this should be largely ascribed to the lack of focus on this corrosion issue.

3.3 Other forms of corrosion

3.3.1 Stray current corrosion

Electrification is increasingly important with the rapid development of modern railways. Since perfect insulator does not exist and complete insulation between rails and ground/track bed is not possible, current tends to break circuit through a less resistant path and normally leaks from rails through track bed into underground metallic structures like buried pipelines, then leaks out again and returns to traction substations. The leakage of stray current increases with tractive current and the distance between traction substations, and it is also favoured by increase of rail track resistance in longitudinal direction or decrease of resistance between rail base and track bed. The voltage difference between different materials would be largely increased by stray current, including AC (signal current) (Mariscotti and Pozzobon 2005) and DC (return current) (Chen et al. 2006), resulting in corrosion. Stray AC current would not be a major concern for corrosion of rail itself (Hernandez et al. 2009), instead, research on stray AC current corrosion has been focused on other surrounding metallic structures, e.g. buried pipelines (Hosokawa et al. 2004) and viaducts (Hong et al. 2017). As to stray DC current, generally applied for subway and urban railway system, much of the research has also been focused on the corrosion of other surrounding metallic structure (Kale et al. 1999; Xu and Li 2015), but it has been found to accelerate corrosion of rail base in the presence of humidity and deposited salt, while corrosion was less important in the absence of DC current (Hernandez et al. 2009). Generally, the position where current leaks out is anodically corroded, and the position where current flows into is cathodically protected. DC stray current leaks from rail base where anodic dissolution takes place and corrosion products tend to accumulate near rail base inducing serious corrosion and even noticeable metal loss or cracking. In addition, rebar in the concrete of ballastless track bed, although may be cathodically protected, may suffer damage initiated by hydrogen evolution if the

cathodic potential is largely reduced, potentially inducing a risk of cracking and strength reduction, and this is another threaten for the safety of railways. It has been estimated that current leak of 1 A can induce iron loss of 20 pounds per year, and that is a loss of 7.5 tons per year for current of 750 A if left uncontrolled (National Academies of Sciences, Engineering, and Medicine 2007). The serious corrosion on rail base shown in Figure 2a is mainly ascribed to stray current corrosion because rail base is at the position for current leakage.

Stray current leaks can be effectively inhibited mainly through two ways, proper insulations between rails and ground, and environmental resistance reduction. The gauge block insulator between rail foot and fastening system, and the under-railed cushion beneath rail base, are significant to effectively suppress current leaks into the ground. Also, electrical continuity of track is important because large resistance (especially at rail joint) favours current flow through other paths, which can be effectively controlled by proper welding. In terms of resistance control of the surrounding environment, humidity control is crucial especially when coupled with high salinity, so a water re-direction design may be necessary for both above ground and underground to keep environment dry (around ballast or slabs). Stray current corrosion of rail itself, and also surrounding structures, can be partially mitigated by proper design and control system (Berman and Williams 2017; Hernandez et al. 2009), but is still inevitable at present.

3.3.2 Corrosion of ballasted/ballastless tracks

Although traditional ballasted track is cost effective and easy for construction, its reliability, stability and durability are not as good as ballastless track, and requires more maintenance. In terms of corrosion issue, the movement on both lateral and longitude directions would be larger for ballasted track, implying that the micro-motion promoting crevice corrosion would be favoured, and stress is also increased inducing a risk of cracking. Crushed stones may be splashed to damage rail and wheels, and abrasion is exacerbated if stones are left on rail surface. In addition, fine particles of the stones may block drainage of ballast bed, increasing risk of corrosion. As to ballastless track, corrosion problems stated above can be inhibited to a large extent, however, deterioration of concrete is the weak point for durability and has to be considered carefully, including rebar corrosion, carbonization, acidic erosion, freeze-thaw cycles, alkali aggregate reaction and mechanical abrasion. Corrosion is regarded as one of the most important factors for concrete of ballastless track,

easily initiated near pre-splitting crack on slab (Q. Wang et al. 2014a). Corrosion of concrete is mostly affected by chloride permeation, poor drainage and stray current, inducing risk of expansion cracking.

3.3.3 Galvanic corrosion

A few other forms of corrosion have also been discussed in the literature. For example, galvanic corrosion behaviour has been discussed for rail materials when contacted with stainless steel structure in a train station (Xian et al. 2007), but this kind of corrosion can be largely prevented by proper design.

4 Corrosion protection technologies

Since rail corrosion is common and closely related to stable operation, protection technologies must be applied to lower safety risk and also maintenance cost. The most applied are coatings and advanced corrosion-resistant materials, which are discussed in detail as follows.

4.1 Coating technologies

4.1.1 Coatings (paintings)

Coating is one of the most significant technology for corrosion protection of railway industry, the attempt of which can be dated back to 1933 on German railways (Lindermayer 1933). In consideration of the complicated service environment of rail materials, coatings must simultaneously possess characteristics of both high corrosion resistance and high abrasion resistance, also with long-term durability (resistance to weather conditions). Harsh conditions to accelerate corrosion process, including wet/dry and freeze/thaw cycles, UV radiation and salt spray, are suggested to be applied for reliability evaluation of anti-corrosion coatings (Sorensen et al. 2009; Wang et al. 2017). Very importantly, operating conditions of rail require excellent mechanical property of coatings to resist not only corrosion, but also abrasion. Wear resistance must be considered since wear would largely deteriorate coating system. Recently, an anti-graffiti coating system has been developed, with multiple layer including corrosion resistant primer, putty, repair/primer filler, basecoat and graffiti resistant clear coat, showing good properties of adhesion, hardness and elasticity (Radek et al. 2018),

however, its application on rail surface has not been field-tested. The improvement on corrosion resistance was found to be obvious in a later report (Pasiczynski et al. 2018), but long term evaluation on the maintenance of corrosion resistance was missing, and the durability of the coating was unclear. Wang et al. (2017) developed multifunctional water-based inorganic coating systems for rail track, mainly aiming at the properties of low solar absorption (thus rail temperature was effectively reduced), long-term durability and corrosion resistance. It is reported that this coating can be applied on active rail tracks with a proper scheduling (field observation of two months was carried out for long-term durability test, and salt spray test was carried out for corrosion resistance evaluation), however, the very important tribological performance were not considered, and traffic volumes of the track under field observation was not known, so the abrasion resistance of this coating was actually unclear. In addition, Kowalski and Cygnar (2019) has developed “CrN + CrO_x” and “TiSiN/TiAlN” PVD coatings to mitigate the fretting wear aiming at joint structures of rail vehicle wheel sets. Low friction coefficient, high resistance to corrosion (demonstrated by the elimination of micro-pits and brownish rust) and abrasion have been characterised. However, this coating may only resist local wear of specific mechanical parts like the joint structures, and the attempt to apply it to full-scale rail surface was not demonstrated. Therefore, based on the current literature, coating (painting) technologies are able to satisfy the requirement of corrosion resistance, but the wear resistance is currently the weak point for practical application. Actually, poor mechanical properties have always been obstacles for its application in many fields, and treatment such as coatings inevitably increases cost, making it less competitive.

4.1.2 Surface modification technologies

Surface modification technologies, including thermal spraying and laser cladding, can promote material performances, increase service lifetime and also save economic loss for rail industries (Meng et al. 2019). Thermal spraying coatings are abrasion-resistant with low friction (Bartuli et al. 2007; Ciulli 2009; Steffens et al. 1995), among which ceramic-based abrasive coatings (including alumina, titania, zirconia, chromia, yttria and the mixtures (Rainforth 2004)) are the most applied, as so called “tribo-coatings”. Plasma nitriding surface treatment was also suggested for mechanical components of rail industry aiming at enhancing abrasion and corrosion resistance, and also surface hardness (Franklin et al. 2006; Lailatul and Maleque 2017). However, the most intensively studied coating

technology for rail materials is laser cladding, which induces little deformation and small heat-affected zone for rail materials, and also allows efficient formation of metallurgical bonding with the substrate (Meng et al. 2019). Laser cladding coatings with various elements (including Fe (He et al. 2017; Lewis et al. 2015; Wang et al. 2016b), Co (Lewis et al. 2015; Wang et al. 2016c), Ni (Lewis et al. 2015) and La_2O_3 (Wang et al. 2016b)) have been found to largely improve wear resistance and prevent fatigue/cracks of rail surface (Franklin et al. 2005; Hiensch et al. 2005; Lewis et al. 2015; W. Wang et al. 2014b; Wang et al. 2016b, c). However, as a surface treatment technology for rail materials, the resultant martensite transformation in heat affected zone (HAZ) would negatively affect mechanical properties, leading to embrittlement (Clare et al. 2012), decrease of strength/toughness (Delgado et al. 2017) and tendency of fatigue (Lewis et al. 2017). A novel method, laser-induction hybrid cladding (LIHC) technology has been applied on rail steel surface recently, which not only effectively reduced the size of HAZ and increased fracture toughness, but also can be applied in rail hardfacing and repair, being regarded as an important improvement for traditional laser cladding assisted by oxy torch preheating (Meng et al. 2019). As to corrosion issue, laser cladding coating technology is well acknowledged to be effective for the improvement of corrosion resistance of rail surface (He et al. 2017), nonetheless, this performance has not been evaluated systematically for rail materials. As stated above, previous research work has been focused on wear resistance and mechanical properties, which is just the weak point of coatings. However, there is a lack of attention on the evaluation and characterisation of corrosion resistance property of rail surface modification technologies. These technologies make up the weak point of coatings to some extent, which have to introduce an extraneous skin outside rail surface. However, the cost of this surface modification technologies for real application has not been clarified yet, and it can be speculated that, without reasonable control of cost, this technology still cannot be widely applied.

4.2 Development of novel rail track steels

Traditional rail materials contain high carbon (~ 0.7 wt%) and manganese (~ 1.2 wt%) with pearlitic and/or ferrite structures (Cannon et al. 2003; Panda et al. 2009a), and rail materials with fully pearlitic structure have been regarded as “premium rails” for good mechanical properties, but without corrosion issue being considered (Hernandez et al. 2007). High carbon content actually induces more cementite exerting adverse effect on corrosion resistance

(Chen et al. 2005), therefore Kumar et al. (2019) has designed a novel high-strength, carbide free and fine bainitic structured steels for application of railway crossing, but the change on corrosion resistance property was not evaluated. Panda et al. (2008a, b) paid special attention on the adverse effect of corrosion on rail materials and developed several novel steel by microalloying Cu, Cr, Ni and Si, which are known to be able to improve corrosion resistance or induce passivation of steels by promoting formation of protective corrosion products (Asami and Kikuchi 2003; Itagaki et al. 2004; Kimura et al. 2005). It has been found that rust composition highly depended on different microalloying elements, and novel rail steels exhibited compact thus more protective rust films. Similar effect for corrosion products has also been found on a newly developed U76CrRE rail steel (Wang et al. 2013) and novel Cu–Mo rail steel (Panda et al. 2009c). Corrosion of novel U68CuCr steel has also been compared with traditional U75V steel, indicating a better corrosion resistance with alloyed Cu and Cr, likely to be ascribed to change on microstructure instead of variation of corrosion products (Ren et al. 2013). It has also been reported that Cu, Ni, Cr and Mo microalloying can reduce the degree of hydrogen embrittlement to some extent compared to traditional C–Mn rail steels (Moon et al. 2010). However, hydrogen embrittlement has only been studied in labs till now and there is no reported failure of rails directly induced by hydrogen embrittlement. The amount of hydrogen in rail track steels is a significant index and strictly controlled when fabricated, normally below 3 ppm (Moon et al. 2010).

As is stated in Section 3.2, Panda et al. (2009a) proposed the small amplitude oscillatory vibration between rail foot and rail fixture (fastening system), so fretting corrosion resistance of novel steels microalloyed with Cu, Cr, Ni and Si have been investigated, and it was found that newly added elements were prone to result in a lower friction coefficient and reduce surface damage, moreover, a protective “tribo-electro-chemical layer” could be maintained under fretting conditions.

Among these novel steels, microalloyed Cr–Cu–Ni steels showed superior performance, including both easy passivity and high resistance to fretting corrosion (Panda et al. 2008a, 2009a). Also importantly, without Mo addition, the cost of this Cr–Cu–Ni novel rail steel can be reasonably controlled, which has already been manufactured and applied on Indian railways (Balasubramaniam et al. 2011). In addition to corrosion resistance evaluation, mechanical properties of novel rail steels have also been characterized (Panda et al. 2009b). The mechanical behaviours were generally not changed by the microalloying elements, except that the strength was lowered by Ni and

Si. This is a typically difficult area in material research when the improvement of corrosion resistance often does not agree with the improvement of mechanical property. Under such circumstances, corrosion resistance usually cannot be prioritised or put in the front of the design list, however, corrosion may become the “short slab” inducing the shortening of service lifetime. Therefore, it has been suggested that “synergistic effect” of microalloying elements on the improvement of corrosion resistance should be determined, without deteriorating mechanical properties (Balasubramaniam et al. 2011), and this should be the key point for research on novel rail steels in the future, instead of simply considering corrosion resistance.

Some other technologies like sacrificial anode method (attach zinc to steel surface using adhesive tape) has also been applied (Isozaki et al. 2016), but have not been widely applied under other more general circumstances, so it would not be discussed in this work.

5 Corrosion detection

In-situ detection of rail in service is important, preferentially nondestructive and contactless. High powered laser positioned above rail surface producing ultrasonic waves, combined on the same side with an air-coupled transducer receiving ultrasonic signals, can detect flaws within and under rails on an entire rail section. The detection efficiency can be largely raised if the device is equipped on a detection vehicle. Ultrasonic detection on rail base corrosion is difficult but important, and special design is required to probe rail base properly. Infrared inspection is also applied for rail detection, which is able to locate defect according to different thermal characteristics (National Academies of Sciences, Engineering, and Medicine 2007). Since localised corrosion is always undetectable by sight at early stages, ultrasonic defect detection has been used to detect unobservable surface breaking and internal defects, and also used to assess corrosion of rail foot (Cannon et al. 2003). It has to be emphasised that, the development and proper application of detection technology are equally significant as research on localised corrosion. An attempt to use guided wave propagation to detect corrosion at the flat bottom of rail base has been reported, with a laser generator placed at the top surface of the rail foot section, and artificially made holes on the bottom surface (to simulate pitting corrosion) can be successfully detected, while further practical application in field has not been reported (Cerniglia et al. 2012).

There are some other nondestructive flaw detection technologies that have been applied for other scenarios, including radiographic inspection, Eddy current inspection, electromagnetic acoustic transducer, ground penetrating radar, etc. These techniques have application prospect for rail corrosion/flaw detection, but there are still difficulties on implementation (National Academies of Sciences, Engineering, and Medicine 2007).

6 Corrosion assessment

The assessment standards for rail replacement are not exactly the same in different countries. In China for instance, corrosion damage is regarded as unacceptable and rail replacement must be performed when the damage can be categorised as “major” (in comparison to “minor”). To save maintenance cost, rail replacement is often performed when the damage is very close to “major”. For rail track designed for train speed higher than 120 km/h, it is regarded as “major” damage if thickness of rail base is less than 8 mm or rail waist is less than 14 mm; while for lower than 120 km/h, it is regarded as “major” damage if thickness of rail base is less than 5 mm or rail waist is less than 8 mm. In addition, it is regarded as “major” damage once crack is detected regardless of its size and position. It is also suggested that immediate replacement is required when 1/8 to 1/4 in. (ca. 3.2–6.4 mm) of rail base is lost for railways in the USA (National Academies of Sciences, Engineering, and Medicine 2007). Thickness measurement is all after proper rust removal. Since thickness of rail base is normally in the range of 10–14 mm, these standards in China and the USA roughly agree with each other.

7 Summary and recommendation

The literature focussing on corrosion of rail tracks, including corrosion forms, corrosion protection and detection technologies, have been reviewed.

General corrosion would not be a crucial issue on large rail surface, but crevice corrosion between rail and liner has a risk for thinning of rail foot. Reciprocating micro-motion between rail foot and liner would mechanically assist the initiation and continuation of crevice corrosion, while this has only been briefly proposed by very few researchers without enough further work. We suggest that crevice corrosion under both static and micro-dynamic conditions should be focused on, otherwise this corrosion problem would keep being a potential threaten for service lifetime and safe operation of rail tracks. Besides, DC stray

current corrosion is also a significant issue for the deterioration of rail track, especially for rail base and rebar in concrete slab.

Coating (painting) can effectively increase corrosion resistance of rail track, but currently has a weak point of poor mechanical properties, especially for the intense interactions between rail surface and wheels. Surface modification technologies including thermal spraying and laser cladding, should be able to overcome the weakness and simultaneously maintain a proper corrosion resisting layer, but the actual cost remain unclear. Another effective way is developing novel rail steel, but inevitable loss of mechanical properties with improving corrosion resistance sometimes becomes obstacles for further practical applications. We suggest that synergistic effect of corrosion resistance and mechanical property should be the research focus, instead of simply concentrating on corrosion.

Development on corrosion detection technologies is equally significant as corrosion research on rail track, especially *in-situ* nondestructive and contactless technologies. Ultrasonic detection and infrared inspection have been practically used, while many advanced flaw detection technologies used in other scenarios are also promising for rail track inspection.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was funded by National Natural Science Foundation of China (grant no. 51501180 and 51708541), Natural Science Foundation of Shandong Province, China (grant no. ZR2019QEM011) and National Natural Science Foundation of China for Exploring Key Scientific Instrument (grant no. 41827805).

Conflict of interest statement: The authors declare no conflicts of interest regarding this paper.

References

- Al-Juboori, A., Zhu, H., Wexler, D., Li, H., Lu, C., McCusker, A., McLeod, J., Pannila, S., and Barnes, J. (2019). Evolution of rail surface degradation in the tunnel: the role of water on squat growth under service conditions. *Eng. Fract. Mech.* 209: 32–47.
- Asami, K. and Kikuchi, M. (2003). In-depth distribution of rusts on a plain carbon steel and weathering steels exposed to coastal-industrial atmosphere for 17 years. *Corrosion Sci.* 45: 2671–2688.
- Balasubramaniam, R., Panda, B., Dwivedi, G., Moon, A., Mahapatra, S., Manuwal, A., Bhattacharyya, A., Srikanth, K., and Rath, R. (2011). Alloy development of corrosion-resistant rail steel. *Curr. Sci.* 100: 52–57.
- Bartuli, C., Valente, T., Casadei, F., and Tului, M. (2007). Advanced thermal spray coatings for tribological applications. *Proc. Inst. Mech. Eng. Pt L-J. Mater-Design. Appl.* 221: 175–185.
- Berman, M. and Williams, Q. (2017). *Proceedings of ASME 2017 joint rail conference, April 4 2017: corrosion control of modern light rail transit (LRT) systems*. American Society of Mechanical Engineers, New York.
- Bocher, F. and Scully, J. (2015). Stifling of crevice corrosion and repassivation: cathode area versus controlled potential decreases assessed with a coupled multi-electrode array. *Corrosion* 71: 1049–1063.
- Cannon, D., Edel, K., Grassie, S., and Sawley, K. (2003). Rail defects: an overview. *Fatig. Fract. Eng. Mater. Struct.* 26: 865–886.
- Cerniglia, D., Pantano, A., and Vento, M. (2012). Guided wave propagation in a plate edge and application to NDI of rail base. *J. Nondestr. Eval.* 31: 245–252.
- Chen, S., Hsu, S., Tseng, C., Yan, K., Chou, H., and Too, T. (2006). Analysis of rail potential and stray current for Taipei metro. *IEEE Trans. Veh. Technol.* 55: 67–75.
- Chen, Y., Tzeng, H., Wei, L., Wang, L., Oung, J., and Shih, H. (2005). Corrosion resistance and mechanical properties of low-alloy steels under atmospheric conditions. *Corrosion Sci.* 47: 1001–1021.
- Ciulli, E. (2009). Tribology research trends in Italy. *Proc. Inst. Mech. Eng. Part J-J. Eng. Tribol.* 223: 1091–1113.
- Clare, A., Oyelola, O., Folkles, J., and Farayibi, P. (2012). Laser cladding for railway repair and preventative maintenance. *J. Laser Appl.* 24: 10.
- Delgado, F., Acosta, R., Nieto, F., Alcántara, S., and Sauce, V. (2017). A failure analysis 115RE rail type, due to a compression load state in areas where it was placed exothermic welding copper cable for attaching electrical continuity. *Eng. Fail. Anal.* 79: 130–139.
- Franklin, F., Weeda, G., Kapoor, A., and Hiensch, E. (2005). Rolling contact fatigue and wear behaviour of the infrastar two-material rail. *Wear* 258: 1048–1054.
- Franklin, M., Huang, S., Chandra, T., and Tieu, K. (2006). Microstructural features of plasma nitrided molybdenum alloy steel. In: Chandra, T., Tsuzaki, K., Militzer, M., and Ravindran, C. (Eds.). *Thermec 2006, Pts 1–5*, Vol. 539–543. Trans Tech Publications Ltd., Durnten-Zurich 2007, pp. 1282–1287.
- Gilbert, J., Buckley, C., and Jacobs, J. (1993). *In-vivo* corrosion of modular hip-prosthesis components in mixed and similar metal combinations – the effect of crevice, stress, motion, and alloy coupling. *J. Biomed. Mater. Res.* 27: 1533–1544.
- He, H., Zhang, T., Ma, M., and Liu, W. (2017). Microstructure and wear resistance of laser cladding particulate reinforced Fe-based composite coating on railway steel. *J. Laser Appl.* 29: 5.
- Hernandez, F., Demas, N., Davis, D., Polycarpou, A., and Maal, L. (2007). Mechanical properties and wear performance of premium rail steels. *Wear* 263: 766–772.
- Hernandez, F., Plascencia, G., and Koch, K. (2009). Rail base corrosion problem for North American transit systems. *Eng. Fail. Anal.* 16: 281–294.
- Hernandez-Valle, F., Edwards, R., Clough, A., Rosli, M., and Dutton, B. (2013). Laser generation and detection for surface wave interaction with different defect geometries. In: Thompson, D.O. and Chimenti, D.E. (Eds.). *Review of progress in quantitative nondestructive evaluation*, Vols. 32a and 32b, Vol. 1511. Amer. Inst. Physics, Melville, pp. 324–329.
- Hiensch, M., Larsson, P.-O., Nilsson, O., Levy, D., Kapoor, A., Franklin, F., Nielsen, J., Ringsberg, J., and Josefson, B. (2005). Two-material rail development: field test results regarding rolling contact fatigue and squeal noise behaviour. *Wear* 258: 964–972.

- Hill, M. and Lillard, R. (2006). Methods for accessing pitting damage in carbon steel exposed to alkaline chloride waste environments. *Corrosion* 62: 801–810.
- Hong, Y., Li, Z., Qiao, G., and Ou, J. (2017). Numerical simulation and experimental investigation of the stray current corrosion of viaducts in the high-speed rail transit system. *Construct. Build. Mater.* 157: 416–423.
- Hosokawa, Y., Kajiya, F., and Fukuoka, T. (2004). Alternating current corrosion risk arising from alternating current-powered rail transit systems on cathodically protected buried steel pipelines and its measures. *Corrosion* 60: 408–413.
- Hou, B. (2019). *The cost of corrosion in China*. Springer, Singapore.
- Hou, B., Li, X., Ma, X., Du, C., Zhang, D., Zheng, M., Xu, W., Lu, D., and Ma, F. (2017). The cost of corrosion in China. *npj Mat. Degrad.* 1: 4.
- Isozaki, H., Oosawa, J., Kawano, Y., Hirasawa, R., Kubota, S., and Konishi, S. (2016). Measures against electrolytic rail corrosion in Tokyo metro subway tunnels. In: Alpatov, S., Prentkovskis, O., Sterling, R.L., and Kaliampakos, D. (Eds.). *15th international scientific conference underground urbanisation as a prerequisite for sustainable development*, Vol. 165. Elsevier Science Bv, Amsterdam, pp. 583–592.
- Itagaki, M., Nozue, R., Watanabe, K., Katayama, H., and Noda, K. (2004). Electrochemical impedance of thin rust film of low-alloy steels. *Corrosion Sci.* 46: 1301–1310.
- Kale, E., Sanders, M., and Sidoriak, W. (1999). *Proceedings of ASME 1999: corrosion control for the Dallas area rapid transit system*, Vol. 16. Amer. Soc. Mechanical Engineers, New York.
- Kang, G. and Gao, Q. (2002). Uniaxial and non-proportionally multiaxial ratcheting of U71Mn rail steel: experiments and simulations. *Mech. Mater.* 34: 809–820.
- Kang, G., Gao, Q., and Yang, X. (2002). Experimental study on the cyclic deformation and plastic flow of U71Mn rail steel. *Int. J. Mech. Sci.* 44: 1647–1663.
- Kimura, M., Kihira, H., Ohta, N., Hashimoto, M., and Senuma, T. (2005). Control of Fe(O,OH)(6) nano-network structures of rust for high atmospheric-corrosion resistance. *Corrosion Sci.* 47: 2499–2509.
- Koch, G., Varney, J., Thompson, N., Moghissi, O., Gould, M., and Payer, J. (2013). *International measures of prevention, application, and economics of corrosion technologies study*. Technical Report, NACE International.
- Kowalski, S. and Cygnar, M. (2019). The application of TiSiN/TiAlN coatings in the mitigation of fretting wear in push fit joints. *Wear* 426: 725–734.
- Kumar, A., Makineni, S., Dutta, A., Goulas, C., Steenberg, M., Petrov, R., and Sietsma, J. (2019). Design of high-strength and damage-resistant carbide-free fine bainitic steels for railway crossing applications. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* 759: 210–223.
- Lailatul, H., and Maleque, M. (2017). *Proceedings of 3rd international conference on mechanical, automotive and aerospace engineering, 2016: hardfacing of duplex stainless steel using melting and diffusion processes*, Vol. 184. Iop Publishing Ltd., Bristol.
- Lewis, S., Lewis, R., and Fletcher, D. (2015). Assessment of laser cladding as an option for repairing/enhancing rails. *Wear* 330–331: 581–591.
- Lewis, S., Lewis, R., Goodwin, P., Fretwell-Smith, S., Fletcher, D., Murray, K., and Jaiswal, J. (2017). Full-scale testing of laser clad railway track; case study – testing for wear, bend fatigue and insulated block joint lipping integrity. *Wear* 376–377: 1930–1937.
- Lindermayer, O. (1933). Operation and successes of the German national rail in the area of the protection against corrosion by coating. *Z. Ver. Dtsch. Ing.* 77: 385–392.
- Liu, J., Zhou, Q., Zhang, Y., Liu, F., Tian, C., Li, C., Zhi, X., Li, C., and Shi, T. (2019). The formation of martensite during the propagation of fatigue cracks in pearlitic rail steel. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* 747: 199–205.
- Lyu, Y., Zhu, Y., and Olofsson, U. (2015). Wear between wheel and rail: a pin-on-disc study of environmental conditions and iron oxides. *Wear* 328: 277–285.
- Mariscotti, A. and Pozzobon, P. (2005). Experimental results on low rail-to-rail conductance values. *IEEE Trans. Veh. Technol.* 54: 1219–1222.
- Maruthamuthu, S., Nagendran, T., Anandkumar, B., Karthikeyan, M., Palaniswamy, N., and Narayanan, G. (2011). Microbiologically influenced corrosion on rails. *Curr. Sci.* 100: 870–880.
- Meng, L., Zhao, W., Hou, K., Kou, D., Yuan, Z., Zhang, X., Xu, J., Hu, Q., Wang, D., and Zeng, X. (2019). A comparison of microstructure and mechanical properties of laser cladding and laser-induction hybrid cladding coatings on full-scale rail. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* 748: 1–15.
- Moon, A., Balasubramaniam, R., and Panda, B. (2010). Hydrogen embrittlement of microalloyed rail steels. *Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process.* 527: 3259–3263.
- National Academies of Sciences, Engineering, and Medicine (2007). *Rail base corrosion detection and prevention*. The National Academies Press, Washington, DC.
- Panda, B., Balasubramaniam, R., and Dwivedi, G. (2008a). On the corrosion behaviour of novel high carbon rail steels in simulated cyclic wet-dry salt fog conditions. *Corrosion Sci.* 50: 1684–1692.
- Panda, B., Balasubramaniam, R., Dwivedi, G., and Mahapatra, S. (2008b). Corrosion of novel rail steels in 3.5 % NaCl solution. *Trans. Indian Inst. Met.* 61: 177–181.
- Panda, B., Balasubramaniam, R., Mahapatra, S., and Dwivedi, G. (2009a). Fretting and fretting corrosion behavior of novel micro alloyed rail steels. *Wear* 267: 1702–1708.
- Panda, B., Balasubramaniam, R., and Moon, A. (2009b). Microstructure and mechanical properties of novel rail steels. *Mater. Sci. Technol.* 25: 1375–1382.
- Panda, B., Balasubramaniam, R., Vajpei, A., Srikanth, S., and Bhattacharyya, A. (2009c). Characterisation of rust on microalloyed rail steel exposed to coastal location in India. *Corrosion Eng. Sci. Technol.* 44: 275–279.
- Pasieczynski, L., Radek, N., Klonica, M., Kaminski, J., and Swiderski, J. (2018). Properties of BO100-AGR clearcoat anti-graffiti coating systems used in the railway industry. In: Szczotok, A., Pietraszek, J., and Radek, N. (Eds.). *Terotechnology, 2017*, Vol. 5. Materials Research Forum LLC, Millersville, pp. 225–230.
- Qi, H., Xu, Q., Zhao, Y., Guo, T., and Ren, D. (2017). Study on realization method of automatic repair wear rail by laser cladding. *J. Mech. Eng.* 53: 160–165.
- Radek, N., Pasieczynski, L., Makrenek, M., and Dudek, A. (2018). Mechanical properties of anti-graffiti coating systems used in the railway industry. In: Szczotok, A., Pietraszek, J., and Radek, N. (Eds.). *Terotechnology, 2017*, Vol. 5. Materials Research Forum LLC, Millersville, pp. 243–247.
- Rainforth, W. (2004). The wear behaviour of oxide ceramics – a review. *J. Mater. Sci.* 39: 6705–6721.

- Ren, A., Zhou, H., Zhu, M., and Yuan, Z. (2013). *Comparative study on the cyclic corrosion test of rail steel U68CuCr and U75V. Sustainable development of natural resources, Pts 1–3*, Vol. 616–618. Trans Tech Publications Ltd., Durnten-Zurich, pp. 1059.
- Safa, M., Sabet, A., Ghahremani, K., Haas, C., and Walbridge, S. (2015). Rail corrosion forensics using 3D imaging and finite element analysis. *Int. J. Rail. Transp.* 3: 164–178.
- Shariff, S., Pal, T., Padmanabham, G., and Joshi, S. (2013). Influence of chemical composition and prior microstructure on diode laser hardening of railroad steels. *Surf. Coating. Technol.* 228: 14–26.
- Shariff, S., Pal, T., Padmanabham, G., and Joshi, S. (2010). Sliding wear behaviour of laser surface modified pearlitic rail steel. *Surf. Eng.* 26: 199–208.
- Shi, R. and He, Y. (2011). The investigation and analysis of the use of rail fastening in Shanghai. In: Li, L.J. (Ed.). *Advances in structures, Pts 1–5*, Vol. 163–167. Stafa-Trans Tech Publications Ltd., Zurich, pp. 2641–2646.
- Shurpali, A., Van Dam, E., Edwards, J., Lange, D., and Barkan, C. (2012). *Proceedings of ASME 2012: laboratory investigation of the abrasive wear mechanism of concrete crosstie rail seat deterioration (rsd)*. Amer. Soc. Mechanical Engineers, New York.
- Sorensen, P., Kiil, S., Dam-Johansen, K., and Weinell, C. (2009). Anticorrosive coatings: a review. *J. Coating Technol. Res.* 6: 135–176.
- Steffens, H., Haumann, D., Gramlich, M., Wilden, J., Wewel, M., Hohle, M., and Nestler, M. (1995). *Low friction coatings for lubricant free use in rail points*. Asm International, Materials Park.
- Sun, Y., Li, H., Wang, C., and Shao, G. (2018). Plastic strain accumulation behaviour of AH32 steel in a cyclic stress-corrosion environment. *J. Constr. Steel Res.* 145: 1–9.
- Uhlig, H. (1950). The cost of corrosion to the United States. *Corrosion* 6: 29–33.
- Wang, X., Song, B., Li, Y., An, S., Jun, P., and Fu, G. (2013). Corrosion behaviors of U75V, U76CrRE heavy rail steel in simulated industrial atmosphere. In: Galkowski, K., and Kim, Y.H. (Eds.), *Advances in mechatronics and control engineering li, Pts 1–3*, 433. Trans Tech Publications Ltd., Durnten-Zurich, pp. 2031–2037.
- Wang, Q., Wei, J., and Dong, R. (2014a). Durability life prediction of CRTSII ballastless track slab for the local corrosion-induced cracking. *Concrete* 12: 134–138.
- Wang, W., Hu, J., Guo, J., Liu, Q., and Zhu, M. (2014b). Effect of laser cladding on wear and damage behaviors of heavy-haul wheel/rail materials. *Wear* 311: 130–136.
- Wang, X., An, S., and Cao, Z. (2016a). Advances in corrosion resistance for heavy rail steel. *J. IMU. Sci. Technol.* 35: 205–208.
- Wang, W., Fu, Z., Cao, X., Guo, J., Liu, Q., and Zhu, M. (2016b). The role of lanthanum oxide on wear and contact fatigue damage resistance of laser cladding Fe-based alloy coating under oil lubrication condition. *Tribol. Int.* 94: 470–478.
- Wang, W., Fu, Z., Guo, J., Zhang, Y., Liu, Q., and Zhu, M. (2016c). Investigation on wear resistance and fatigue damage of laser cladding coating on wheel and rail materials under the oil lubrication condition. *Tribol. Trans.* 59: 810–817.
- Wang, H., Salemi, M., and Balaguru, R. (2017). *Proceedings of ASME 2017: multifunctional coating system for rail track applications*. Amer. Soc. Mechanical Engineers, New York.
- Xian, N., Liu, D., and Tan, H. (2007). Research on galvanic corrosion behavior of the U71Mn rail steel and stainless steel in the simulated rain environment. *J. Mat. Prot.* 40: 63–66.
- Xu, S. and Li, W. (2015). Research on stray current corrosion evaluation of buried metallic pipeline in an urban rail transit system. *Int. J. Electrochem. Sci.* 10: 5950–5960.
- Yazici, O. and Yilmaz, S. (2018). Investigation of effect of various processing temperatures on abrasive wear behaviour of high power diode laser treated R260 grade rail steels. *Tribol. Int.* 119: 222–229.
- Yu, X. and Feng, L. (2013). Analysis on fractured gas pressure welded joint of rail U71Mn. *Hot Work. Technol.* 42: 215.
- Zhao, X., Fan, Y., Liu, Y., Wang, H., and Dong, P. (2015). Evaluation of fatigue fracture mechanism in a flash butt welding joint of a U75V type steel for railroad applications. *Eng. Fail. Anal.* 55: 26–38.
- Zhong, W., Hu, J., Shen, P., Wang, C., and Liu, Q. (2011). Experimental investigation between rolling contact fatigue and wear of high-speed and heavy-haul railway and selection of rail material. *Wear* 271: 2485–2493.
- Zhi, H., Li, H., and Zhang, H. (2019). Comparative analysis and research on railway rail standards at home and abroad. *Sci. Technol. Vision* 32: 1–6.
- Zhu, M., Lu, J., Xi, Y., Zhang, J., and Chen, Z. (2013). Analysis of heat treatment quality of a spring clip with failure. In: Li, S., Li, W., and Li, J. (Eds.). *Advanced Materials and Processes lii, Pts 1 and 2*, Vol. 395–396. Trans Tech Publications Ltd., Stafa-Zurich, pp. 887–890.