

Rolling contact fatigue and wear in rail steels: An overview

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Abstract. Rolling contact fatigue (RCF) and wear of rails are two critical failure generating problems of railway transport system worldwide. This paper presents an overview of investigations and state of the art knowledge on the mechanisms of RCF and wear studies revealed till date. Notably, majority of railway accidents are found to be promoted by RCF induced rail fracture and train derailments. The operational mechanism of wheel/rail contact introduces varied proportion of stick-slip formation from the involved rolling-sliding phenomenon. Sliding induced friction contributes many variety of defects of which wear is a prominent material separation process that in severity can also promote crack initiation. In view of the gravity of RCF and wear present study, as a first step, overviews their characterisation approaches. This understanding will help to formulate strategies in investigating the problems to evolve scientific and technological strategies for their mitigation.

1. Introduction

Rail failures on account of RCF and wear are marked phenomenon and a serious problem for the railways worldwide. RCF and wear greatly affect the rail life. Their prediction is, therefore, the need of the hour to frame an appropriate maintenance schedule. The demand of high-speed trains possesses a challenge for material engineers to supply with microstructural stability of the material of rail and wheel. Controlled rail steel wear is always desirable as it removes small surface cracks, thereby extending the fatigue life of the rail. RCF and wear have a competitive relationship [1]. The railway engineers are to find an optimal combination of them in order to arrest the propagation ability of a crack before attaining its critical size.

The onset of RCF crack and its propagation mechanisms are governed by the contact stress magnitude along with residual stresses evolved from asymmetric load-unload pattern giving rise to plastic strain accumulation. The source for contact stress involve rail/wheel profile geometry and axial load. The engine traction introduces surface shear stresses. Their combination with vehicle speeds and environmental conditions of operation imparts deleterious effects on material status at the contact patch zone. Because of very short contact duration and complete release of external loading with the traversal of a train, the accumulated plastic strain develops different failure signatures on the rail surface in the form of waviness, squat and material flowing to the rail head edges. The asymmetric loading pattern beyond yield capacity of the material in presence of surface shear produce rolling contact fatigue of rail head material penetrating up to a limited depth. These help in formation of fatigue crack on the rail surface recognised as rail head checks and gauge corner cracks. The wear mechanism involves presence of frictional load and separation of materials depending on hardness of the rail head layers. While, small surface cracks are removed by wear, involved large friction force arising from continuous sliding of wheel develops spalling like defects or white etching layer (WEL) like defects. But the wear separation mechanisms help in crack initiation from the boundary of WEL and normal rail material zone. Repeated rail-wheel rolling contact develops multi-



axial state of stress in the rail, that initiate cracks either on the surface or in the sub-surface level of the material. High tangential forces due to creepage at the contact patch also help in developing RCF failure. This has three stages: initiation of cracks followed by its propagation and finally, in the absence of proper maintenance, rail fracture occurs (figure 1). The first two stages can be controlled by rail grinding. Three phases of fatigue crack are shown in figure 2. In the first phase, a crack initiates from a point at the contact surface due to accumulation of plastic shear strain by continuous rolling-sliding action of wheel on rail. Second Phase shows steady propagation of crack. Finally, in third phase, branching of cracks occur: one propagates horizontally that later moves towards the rail surface. The other branch moves towards the depth of rail head.

Such cracks are the origin of surface defects: head-check, squat, spalling and sub-surface defects shelling, Tache Ovale. Rail wear, on the other hand, depends upon rail material grade, environmental conditions (humidity, temperature) and contaminants. Typical wear mechanisms are: adhesive, abrasive, corrosive, fatigue and oxidation [2].

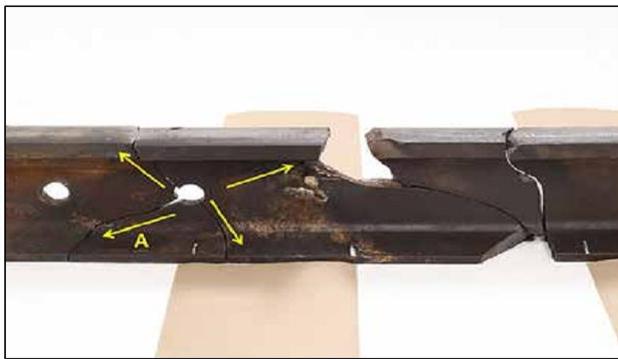


Figure 1. Rail Fracture [3]

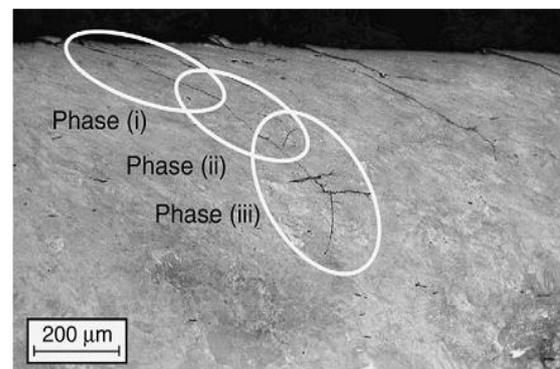


Figure 2. Different stages of RCF cracks [4]

An overview of some of the intriguing works of researchers in this domain is presented. The mechanism of RCF and wear formation along with their detrimental effects are discussed based on published experimental and numerical works. This discourse will help railway maintenance engineers to optimize their operating parameters for maintaining a balance between wear and RCF.

2. RCF in rails: Some past researches

RCF development in the rail is characterised by two phases: the first one begins with plastic flow of material followed by crack initiation at the event of ductility exhaustion. Rail material's damage behaviour can be well identified by shakedown limit [5] and Dang Van criterion [6]. The crack extension phase has been studied through several fracture mechanics based crack growth models [7]. The growth behaviour of the RCF surface cracks can be classified into two cases: spalling of the rail material due to the coalescence of several cracks into a critical one and rail fracture due to the downward growth of the cracks through the rail head and web [8].

Several researchers have studied the RCF of rail steels through computer simulation and finite element modelling along with experiments. Ringsberg [4] developed a multiaxial fatigue crack initiation models which was used together with the critical plane concept to predict fatigue life of RCF crack initiation caused by ratchetting and low cycle fatigue. A FEM model for surface crack observation was proposed by Donzella et al. [1] to study the competitive relationship between RCF and wear in rails. Fatigue crack initiation criteria for elastic shakedown, plastic shakedown and ratchetting material responses were studied by Ringsberg *et al.* [9] for a pearlitic rail steel BS11 in FE simulation via twin disc test. Their material model assumed non-linear isotropic and kinematic hardening of Chaboche in the simulation using ABAQUS. Dang Van criterion was used for the crack initiation identification for elastic shakedown material response.

2.1. Table of rail rolling contact fatigue failure cycles obtained experimentally.

Author	Wheel disc speed (rpm)	Test condition	Contact pressure (MPa)	Slip ratio (%)	Rail RCF life (cycles)
Franklin <i>et al.</i> [2]	500	Wet (water)	1500	1	26711
Beynon <i>et al.</i> [10]	"	"	1800	"	5813
		Wet (water)	1500	0.16	52725
		"	"	0.63	65024
		"	"	1.35	115414
Donzella <i>et al.</i> [11]	500	Wet (water)	700	0	2400000
		"	900	"	800000
		"	1100	"	1000000
		"	900	0.06	800000
		"	1100	"	1200000
Wang <i>et al.</i> [12]	400	Wet (water)	1500	0	120766
		"	"	2	62298
		"	"	4	51915
		"	"	6	44993
		"	"	8	41532
Clayton <i>et al.</i> [13]	400	Wet (water)	500	0.3	650000
		"	750	"	490000
		"	1000	"	300000
Tyfour <i>et al.</i> [14]	406	Wet (water)	1200	1	96897
		"	1500	"	37422
Clayton <i>et al.</i> [15]	500	Wet (water)	910	10	2200000
		"	1150	"	1400000
		"	1300	"	850000
		"	1450	"	350000

3. Wear in rails: Some past researches

Wear plays an important role in determining the service life of rails. It can lead to several track related issues such as widening of the gauge, high rail-wheel forces and poor vehicle dynamics due to loss of rail profile, deterioration in material's strength and rigidity. Mild, severe and catastrophic are the regimes of wear often found in the literature [2]. Various numerical modelling and experiments were performed to characterize its behaviour in rail steels. Birth and death criteria was adopted by Franklin *et al.* [16] to introduce a model for computer simulation of wear through Brick model. Bricks which got detached upon failure from the surface was termed as wear debris. Wear rate was found to be increased in linear proportion with the maximum pressure and friction co-efficient. Alwahdi *et al.* [17] studied the effects of partial slip on wear rate of rails to reach at a conclusion that wear rate is directly proportional to the traction co-efficient and creepage. Kapoor *et al.* [18] investigated the critical role of wear at the wheel/rail interface in enhancing fatigue life of the rail by using a ratchetting failure model in the form of bricks. The controlled wear of rails was found to be helpful in enhancing its fatigue life.

3.1. Table of Wear rate and Traction co-efficient obtained experimentally.

Author	Wheel disc speed (rpm)	Contact pressure (MPa)	Slip ratio (%)	No. of cycles	Test condition	Wear rate ($\mu\text{g}/\text{cycle}$)	Traction co-efficient	
Maya-Johnson <i>et al.</i> [19]	400	1100	5	9000	Wet	5.8	0.077	
					Dry	4.9	0.498	
					Wet	4.2	0.068	
					Dry	5.9	0.489	
					Wet	11	0.061	
					Dry	5.7	0.493	
Wang <i>et al.</i> [12]	400	1500	0	4000	Wet	0.7	0.02	
					Wet	1.8	0.11	
					Wet	1.7	0.16	
					Wet	1.67	0.19	
					Wet	1.5	0.15	
Hardwick <i>et al.</i> [8]	400	1500	1	4000	Dry	4.20		
					25000	Dry	8.51	
					Wet(water)	156.54		
					TOR F.M.	4.75		
					Lubricant	2.31		
					Oil	114.79		
					Grease	8.46		
					TOR hybrid	7.57		
Lewis <i>et al.</i> [20]	400	1500	20	4000	Dry, no sand	200	0.43	
					Dry, sand	614.5	0.36	
					Wet, sand	1082.8	0.46	

Zhou *et al.* [21] reported that with the increment in slippage, damage of wear zone got transformed from mild to severe regime which resulted in sub-surface crack formation and delamination. Ma *et al.* [22] provided a similar judgment that increase in slip ratio affects the hardness, wear rate and friction co-efficient of both wheel and rail specimen. Ramalho [23] analysed the effect of contact conditions such as contact pressure, creep ratio and linear speed on friction and wear behaviour of rail steel. The wear rate was found to be maximum at lower tangential speed and wear volume increased as contact pressure increased. Zapata *et al.* [24] presented the competitive wear behaviour of pearlitic and bainitic rail steels. Results showed that under pure rolling, both the steels exhibited greater deformed subsurface layers and more significant work hardening when compared to rolling-sliding conditions. Perez-Unzueta *et al.* [25] found that Wear rate was reduced with the increase in rail hardness and reduction in interlamellar spacing.

4. RCF and wear competition within the rail

Railway network is an open system, operates in corrosive environment. These affect wear and RCF behaviour of rails. Rain water, lubricants and friction modifiers as well as leaves on the rail head influence the RCF and wear rates [2]. Tyfour *et al.* [14] from their experimental investigation estimated correlation between the degree of ratchetting and the deterioration in RCF life. Crack initiation and rate of wear can be

controlled by the usage of friction modifiers [26]. Proper lubrication suppresses the wear rate significantly. RCF defects are attributed for derailments. Hatfield train accident in the United Kingdom demonstrated the devastating effects of RCF initiated catastrophe. Although wear may not be the direct cause of broken rails, but it somehow does contribute in it. Wear, in general, changes the rail-wheel contact profile. Thus making the change in the contact condition which may trigger RCF crack initiation and extension rates. Wear triggered corrugation may induce the severe dynamic loads in the system which can possibly help in sub-surface RCF crack formation [27]. Sometimes wear can be beneficial as it reduces the RCF crack propagation rate to some extent via crack truncation, thus cracks will be worn away with the wear debris before attaining the critical size. Wear up to certain limit improves the conformity of contact between rail and wheel for newly installed rails. This increases actual area of contact distributing contact pressure to a larger area there by reducing contact stress. But at the same time if the wear rate is low, then cracks may propagate to a dangerous size which ultimately result in the sudden rail fragmentation. Too much wear reduces the material's ability to sustain larger contact stresses and further accumulation of plastic deformation. Thus to find an optimal combination of both RCF and wear is of great value in order to optimize the rail-wheel contact conditions.

The problems driven by RCF and wear can be controlled by selection of wear and RCF resistant rail material, better wheel-rail contact profile design, regular rail inspection and grinding process.

5. Conclusion

Current state of art research status on rolling contact fatigue and wear of rail steels are explored. The framework required in formulating rail material characterisation by experiments in regard of RCF and wear measurement procedures are elaborated. To expose the interdependence of wear and RCF, their involved material conditions in terms of material microstructure, heat treatment condition, the contact pressure, operating speed in addition to dynamic disturbances introduced by operational control variables are to be investigated. The results, as indicated in table 2.1, by referred authors suggest RCF life of rail material drops with the increase in contact pressure and slip ratio. Remarkably the increase in slip ratio raises wear rate and traction co-efficient as evident in table 3.1. This can change the rail profile as well as promote crack initiation. However, an ideal combination of RCF and wear is beneficial for safer railway transportation because of finer surface cracks removability of the wear process. This study attempted to augment the understanding of the involved mechanisms associated with the issues in focus.

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