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# Detection and Maintenance of Rolling Contact Fatigue on Railway Steel Rails

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**Abstract:** *Steel rail has been at the heart of rail transportation systems for nearly a hundred years. With the rapid development of railway transportation, the steel rail operates in high-speed and heavy-duty operating environment. Steel rail is prone to damages; thus, frequent inspection and maintenance is required to prolong its lifespan. Failing to conduct proper periodical inspection and maintenance could lead to accidents, causing injuries and fatality, high repair cost and loss of public confidence. The aim of this study is the detection of common defects on steel rails and the ways of controlling them. The methodology adopted was visual inspection of the steel rails within the premises of Ajaokuta steel company limited, by taking photographs, measuring the defects and suggesting how these defects could be corrected. The study found the following rolling contact fatigue (RCF) defects on the steel rails; Corner gauge shelling, Spalling, Longitudinal vertical cracks, Squats, Corrugation, and Flaking, initiated by the high shear stresses that often develop at the wheel/rail contact region, when such stresses exceed the allowable limits for the rail material, coupled with heavier axle loads, leading to failures of railway components, consequently contributing to economic burden and the safe operation of railway transport, globally. These defects can be controlled by improving the rail profiles, improving the wheel profiles, improving rail grinding and wheel re-truing machining, improving the track geometry, friction management , improving rail and rail metallurgies and improving suspension bogies. The study concludes that periodical inspection and maintenance of the steel rails will prolong the lifespan and reduce the overall costs of maintenance.*

***KEYWORDS***: *Causes of the defects, Detection of the defects, Effects of the defects, Maintenance strategies, Regular maintenance, and Visual inspection.*

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## 1. INTRODUCTION

Railways are important infrastructures and the main mode of transportation in many countries. It has a high danger of fatalities and property damage because of its close connection to both passenger and cargo transit. Accidents still occur despite the constant introduction of new technologies and enhanced safety standards. There will always be some risk associated with derailments and accidents, but this can be reduced by carefully looking into the reasons causing them. Improved competence and efficiency are necessary for some of the causes, such as human mistake (Cacciabue, 2005), while frequent inspections can help with others (Podofillini et al., 2006; Chattopadhyay et al., 2005; Larsson et al., 2005).

Therefore, to regulate the frequency of inspection optimization and/or skill and efficiency increase, an appropriate maintenance plan is required. A detailed examination of the defects that arise in the rolling stock and rail infrastructure is required in order to create the optimal maintenance plan. Finding and repairing rail defects is a major concern for all rail participants globally. Weld problems, internal defects, deteriorated rails, corrugations, and problems caused by rolling contact fatigue (RCF), such as flaking, squatting, shelling, and spalling (Akersten and Espling, 2005).

Rolling contact fatigue (RCF) is a major factor in reducing rail lifespan because it is one of the primary causes of rail failures while in service. If these defects are not identified and or addressed, they may lead to rail failures and derailments. Making cost-effective repair decisions and carrying out effective inspections are challenges for the infrastructure maintenance team. If these issues are properly addressed, inspection and maintenance decisions can reduce the potential danger of rail breakdowns and derailments. Despite the efforts of all rail operators worldwide to reduce expenses, a sizable amount of the railway budget is devoted to rail inspection and maintenance. The European Union spends between €375 and €850 million annually on train inspections (Cannon et al., 2003).

It is well known that derailment costs decrease as inspection, lubrication, and grinding activities increase. The challenge is to reduce the cost of maintenance, which includes grinding, lubrication, and inspection, without raising the expenses associated with derailments.

In order to find a more cost-effective and efficient solution that can meet budgetary constraints on policy creation, renewal, replacement, and inspection frequency, risk assessment has become a critical component of management's decision-making process (Akersten and Espling, 2005). The risky character of a railway running surface with flaws is defined by the cost, potential human casualties, infrastructure failure, traffic delays, and environmental harm that could arise from a train carrying hazardous cargo derailing.

A key component of the social material production process is railway transportation because it is one of the main ways that things are transported. Most nations have constructed a large number of railway lines, which have significantly boosted international cargo transportation as well as transnational import and export commerce (Martin and Fernandez, 2022). This report outlines many kinds of rail flaws and upkeep practices. Nigeria's economic progress depends on expanding its transportation capacity, especially in light of the world economy's continuous expansion.

Railway problems are getting worse as high-speed and heavy-load railways are developed, despite the fact that railway transit provides many benefits. To satisfy the present demand, railway operations and maintenance must be continuously investigated and optimized (Guiyun et al, 2016).

In order to reduce, control, or eliminate rolling contact fatigue (RCF), there are several available practical ways, the ones discussed in this study are:

**Improved track geometry**

Rapid rates of RCF formation in the rail next to vertical and lateral track abnormalities are frequently linked to these anomalies: Track faults clearly result in dynamic impact forces, although they have little effect on contact stress. Greater importance is given to the following:

The crushing and gross plastic flow of the rail under dynamic stress causes rapid profile deterioration. Profile loss affects contact conditions and increases the risk of rolling contact fatigue (RCF). Some minor rail discontinuities can be removed, and dynamic loads can be controlled using rail grinding.

Due to flaws in the track, wheels move laterally with regard to the rail. In tangent track, this can lead to gauge-corner contact. Fatigue resulting from large longitudinal tractions often follows high contact stresses [Kalousek, 1986]. Minor flaws can be fixed or otherwise dealt with by grinding the rail to shapes that can withstand these contact conditions. Repairing track geometry is necessary for the majority of broad or narrow track gauge, cross-level, or alignment problems.

Higher loads will be experienced by track that is either too high or too low for the traffic it travels on. Rail rotation and rolling contact fatigue (RCF) can result from higher wheel loads on the low rail when traffic is moving at a balanced rate. In high cant-deficiency tracks, the high-rail mid-gauge is prone to substantial longitudinal creepages and rolling contact fatigue (RCF) breaking (Magel and Kalousek, 2004).Tight gauge promotes truck hunting, gauge corner contact, and rolling contact fatigue (RCF) in tangent track. In order to reduce hollow wheel damage to the low rail, it is essential to control wide gauge in curves. Hollow wheels on wide-gauge track not only result in high contact stress but also increase dynamic rail rotation, especially on rails with insufficient restriction, which promotes unsatisfactory contact geometry.

Plate-cut sleepers or inferior fasteners may cause the rail to twist dynamically when lateral loads are applied. This rotation usually increases gauge-corner loading on the high rail and promotes rolling contact fatigue (RCF).

In profile rail, rail grinding can be used to eliminate corrugations, minimize hunting, and trim weld discontinuities; however, further track maintenance operations are required to eliminate discontinuities at bridges, switches, crossings, track pumping points, etc. (Magel and Kalousek, 2004).

**Friction management**

Lubricating the rail gauge-face and wheel flange can reduce gauge-face and flange wear by 95–100% (Sroba and Roney, 2003). Lubrication can also aid in reducing the development of rolling contact fatigue (RCF) by reducing tractions. Conversely, lubricating the gauge face lowers the steering moment that a wheel set may produce and increases the leading-axle angle-of-attack in bends (Izbinsky, 1998). Low-rail top wear, the formation of deep-seated shells on the high-rail gauge corner, and rolling contact fatigue (RCF) on both high- and low-rail top surfaces are all caused by the consequent increase in lateral creepage and lateral force.

Additionally, oil or grease contamination of surface fissures accelerates the spread of rolling contact fatigue (RCF). Inadequate tools or improper lubricator settings may cause grease to migrate to the top of rail, compromising traction and braking (Sroba and Roney, 2003). Therefore, gauge-face lubrication that adjusts the grease application rate to the type of grease, dispensing equipment, and track conditions must be used in conjunction with a preventive rail-grinding program that regularly eliminates metal from the rail gauge-corner (Sroba and Roney, 2003).

**Improved rail and wheel metallurgy**

The followings are the benefits of improved rail and wheel metallurgy:

- Steel's resistance to rolling contact fatigue is determined by its strength in shear (K), which is related to its work-hardened hardness. By increasing the shear strength K, greater contact stress may be tolerated without fatigue. Using tougher rail steels with better rail profiles will greatly reduce the chance of rolling contact fatigue (RCF) development and the rate of spread (Magel and Kalousek, 2002).
- When paired with improved profiles, the advantage can be significantly greater.
  By lowering the number of contacts that reach shakedown by a far larger amount than the hardness differential suggests, the harder steels greatly reduce the chance of crack initiation and the rate of spread. The harder steels significantly lower the likelihood of crack commencement and the rate of spread, by reducing the number of contacts that surpass shakedown by a significantly greater amount than the difference in hardness.
- Alloy wheel steels have long been promoted as an efficient way to reduce wheel rolling contact fatigue (RCF). Wheel life was significantly increased during service testing of experimental alloy steel in two Canadian unit train operations, where wheel removal is almost entirely accomplished by mechanical shelling. In one case, the average wheel life was nearly doubled. The degree to which wheel metallurgy decreases rolling contact fatigue (RCF) depends on two operating factors: the type of bogies and braking requirements (NRC Canada, 2004).

**Improved suspension bogie**

Bogie suspension that is flexible in bending can make use of optimized profiles that provide advantageous steering forces. The flexible suspension reduces the development of rolling contact fatigue (RCF) on the wheels and rail in shallow curves, by reducing yaw angles. On the Canadian Pacific Railway, a flexible bogie reduced wheel shelling (Meyler et al. 2001). However, a more versatile vehicle can also respond to adverse steering moments and increase the yaw angle, especially when bogies are using worn-out and improperly maintained parts. (Scales, 1996).

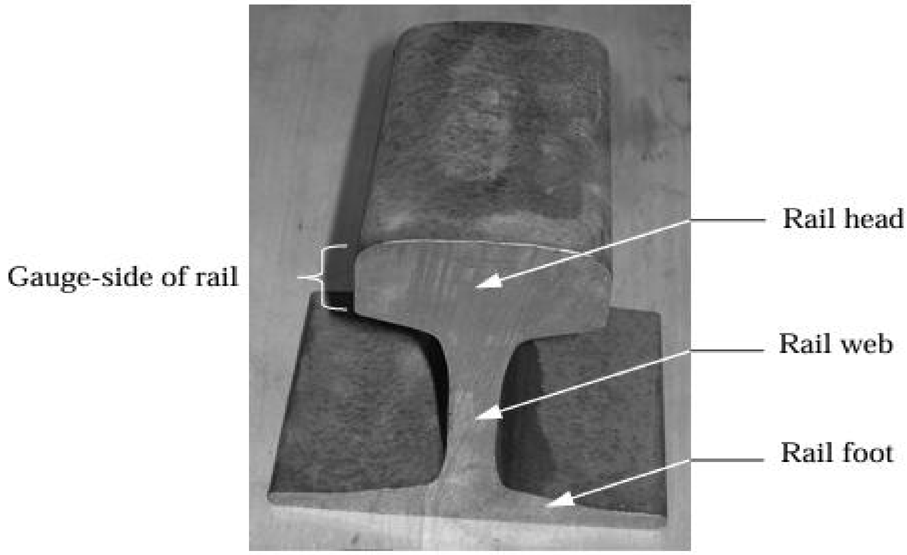


**Fig.1 : Flat bottom rail profile**

The efficiency and precision of the inspection procedure as well as the required tools determine how the rail components known as the rail head, rail web function. The rail foot must be able to support wheel loads and distribute them over the sleepers, to guide the train wheels consistently and uniformly (Esveld, 2001). The rails must be sufficiently rigid to act as beams, and must be able to transmit concentrated wheel stresses to the spaced sleepers without creating excessive bending between the sleepers (Ernest and John, 1994). Rails are made of high carbon steel, which has high fatigue toughness and can include up to 0.82 percent carbon. High-quality steels are being produced, to improve rail fatigue performance and reduce residual stress (IHHA, 2001). The effectiveness of rail inspection also depends on the inspectors' expertise, experience, and Knowledge. Additionally, it depends on traffic control during rail inspection as well as the actual implementation conditions (temperature, visibility, contamination, etc.).

The elimination of false detections and unreported rail problems during inspection is a huge problem. The professional code (UIC, 2007) recommends that visual inspection, optical system by camera, ultrasonic testing by using vehicle, and manual check by ultrasonic testing for rail's running surface.

**Rail inspection**

Using photographs and video images, the rail network should undergo a visual assessment twice a year, or every six months. This approach involves subjectivity and requires a significant amount of man-hours. It is advised for 50-meter sections that are categorized according to the maximum crack length (UIC Code, 2002).

Squats were frequently seen in the weld zones and corrugated areas on the rail head during the visual examination of this rails.

**Visual inspection**

Visual examination during train inspection is controlled by traffic and weather management. Fluorescent penetrations for detection should also be used to improve this technique, especially in tunnels with poor visibility; however, the rail surface needs to be clean. Unfortunately, dirty rails and lubricating the outer rail in curves might negatively impact a visual inspection.

**Background of study**

The Ajaokuta integrated steel complex was conceived and steadily developed with the vision of erecting a Metallurgical Process Plant/Engineering Complex with other auxiliaries and facilities. The complex is meant to be used to generate important upstream and downstream industrial and economic activities that are critical to the diversification of Nigerian economy into an industrial one. It was built on 24,000 hectares (59,000 acres).

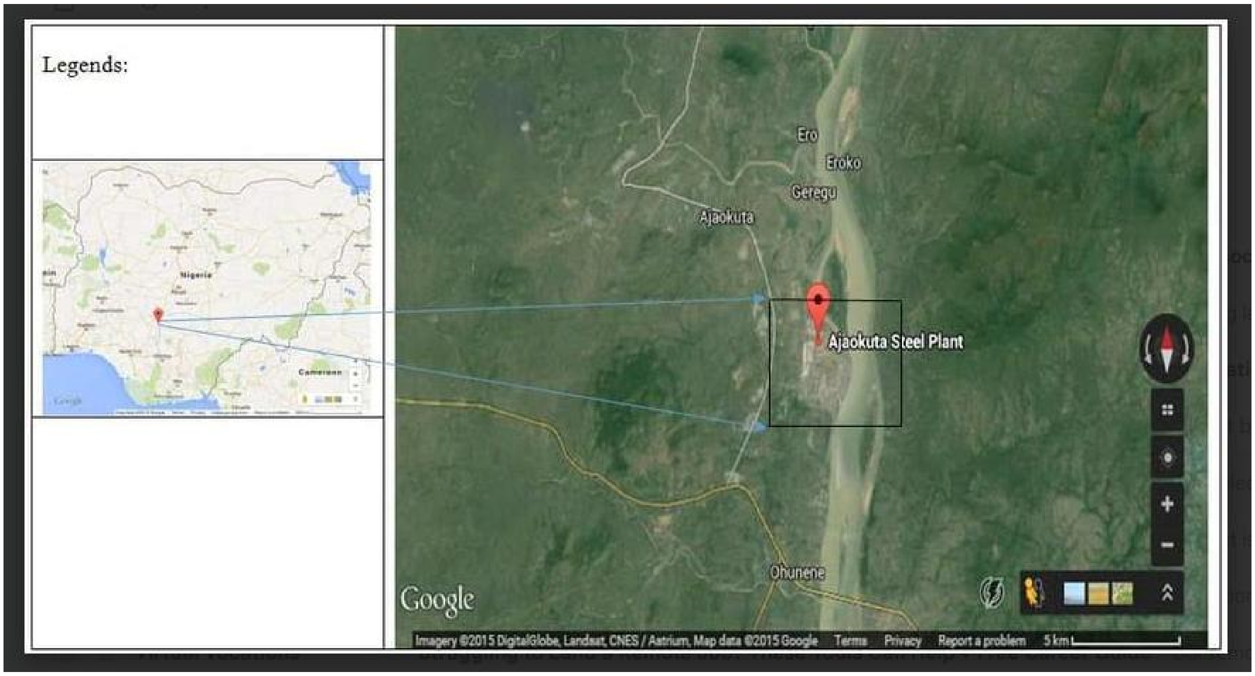


**Fig.2 : Map of Kogi state showing the location of Ajaokuta steel company limited**

Ajaokuta town is located in Ajaokuta Local Government Area of Kogi State, on the left of River Niger. It is situated between Lokoja, and Itobe, in Ofu Local Government Area of Kogi State. It is about 38 km away from Lokoja, the state capital. Ajaokuta steel company limited is located on Latitude $7.50594^0$ or $7^0$ 30' 21" North and Longitude $6.69245^0$ or $6^0$ 41' 33" East on the meridian.

## II. MATERIALS AND METHODS

### A. MATERIALS

a) Digital camera for taking photographs.

b) Writing materials for taking notes where applicable.

c) Straight edge.

d) Taper gauge.

### B. METHODS

a) A study tour to Ajaokuta steel company limited, in Kogi state, Nigeria, was undertaken, to assess the condition of the railway rails within the company, the research on the rolling contact fatigue was conducted by visual inspection, that is by visually examining the rail running surface for signs of defects, and taking their photographs with the digital camera.

b) Information about rolling contact fatigue (RCF) defects, which were observed during the visual inspection, were noted and saved in a database.

c) On returning to the office, the photographs of the defects were studied to identify the names, definitions causes and treatment methods or maintenance strategies to be applied to the defects.

d) A straight edge, a perfectly flat edge was used to identify deviations from a straight line on the rail surface.

e) A taper gauge, a wedge-shaped tool with graduated markings was used to measure the depth and size of irregularities or depressions such as cracks, by inserting the gauge into the defect until it makes contact with the bottom of the cracks.

## III. RESULTS AND DISCUSSION

a) Corner gauge or shelling - Shelling normally takes place at the gauge corner of high rails in curves. An elliptical shell like crack propagates in the subsurface parallel to the rail surface. In my study these cracks emerged on the surface, they caused the metal to come out from the crack area. In some cases, these cracks move in downward direction also, this may probably lead to a transverse fracture of rail. Shelling is a defect caused by loss of material initiated by subsurface fatigue or defect. Steel metallurgy plays an important role in its initiation. Traces of oxide inclusion and residual stress formation during manufacturing contribute to shelling.

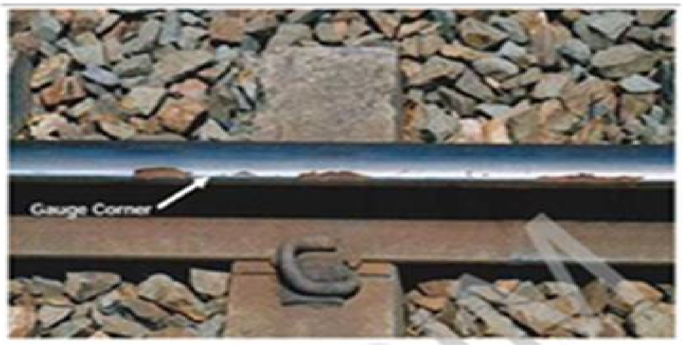


**Fig.3 : Corner gauge or shelling**

**Causes**

i). Corner gauge or shelling defect, is a running surface defect, initiated by the high shear stresses that can develop at the wheel/rail contact region when such stresses exceed the allowable limits for the rail material. If a rail experiences excessive RCF-initiated surface cracking, it needs to be replaced even if it hasn't reached the wear limit.

**Maintenance techniques**

i). The commonest way of managing corner gauge or shelling is the implementation of a grinding or milling program which removes just enough rail material to eliminate the cracks but not so much that good rail is ground away.

**b) Spalling**

The surface initiated crack development path is intersected by other similar shallow cracks on the rail head area, where a shallow chip of rail material falls out as seen in Fig. 4. This defect is known as spalling. It occurs at a much later stage of crack propagation phase if it is left uninspected. Spalling is generally referred to as the displacement of parent metal from the rail head.

**Fig. 4 : Flattened rail head showing displacement of parent metal (spalling)**

**Causes**

Spalling originates from high-contact stresses associated with cyclical loading. In the first stages, spalling may be referred to as a slight flaking. Further deterioration increases the amount of metal displacement.

**Maintenance techniques**

Spalling can be detected by visual inspection and be managed by slight grinding of the running surface.

**c) Rail crown squats**

Unlike shelling, squats is a running surface defect that appears in the crown area of straight rail sections (Fig. 5). They are surface initiated defects formed by rolling contact. A squat is formed by two cracks, a leading crack and a trailing crack. Both cracks propagate in opposite direction. The leading crack proceeds in traffic direction, but the trailing crack propagates faster than the leading one. If preventive measures are not taken quickly, the trailing crack branches out and probably grow downward towards the rail web. Squats seen in this study at the beginning look like a depression in the crown area. The depression is as a result of crack which grows progressively and branches out horizontally just below the running surface, detaching it from the rail body.

**Fig.5: Rrail crown squats**

**Causes**

i). A squat defect is a particular form of surface-initiated damage that is caused by rolling contact fatigue. Cracking initially propagates at a shallow angle to the surface. When the shallow angled cracks reach a depth of about 3 to 5 millimeters, they tend to turn toward the transverse plane. They are characterised by cracking which initiates on the rail surface and grows down to a point about 3-6mm below the surface. The cracking then spreads along and across the rail, without growing substantially deeper. The rail surface becomes depressed and a dark patch appears due to reduced contact from train wheels. Eventually the rail surface may spall out.

**Effects**

Squat defects are of concern because of the following main reasons:

i). There is a possibility that the secondary or minor sub-surface cracks may turn down and grow on a transverse plane similarly to transverse defects, which could result in a complete rail failure if not detected in time.

ii). The depression on the running surface associated particularly with large squats also increases the vertical impact wheel loadings applied to the rails, and consequently exacerbates the deterioration of both track and some vehicle components, in a similar way to dipped welds, rail corrugations and rail joints.

iii). The rail life is decreased, through aggressive and expensive defect grinding.

**Maintenance techniques**

The main preventive measures for squat defects are:

i). Regular or preventive rail grinding to remove the surface layer, which contains the most severely damaged material, including small cracks and/or hard and brittle phases, so that accelerated crack propagation can be prevented. Periodic or regular grinding are applied to prevent the rapid growth of the cracks. During each preventive grinding cycle, a minimum amount of metal (such as 0.2mm) needs to be removed from the contact surface of the rail. In this way, grinding acts as an artificial rail wear mechanism. These defects could be prevented by grinding. Rail grinding has an important role in reducing rail degradation, thus rail brakes, early rail replacements and derailments are reduced. Removing a few millimeters of metal is just as likely to make things worse. Simply carrying out a normal grind (0.2mm minimum metal removal) does assist in reducing the impact from vertical irregularity and broadening the contact area. This will slow the growth of squats and the rail deterioration. Light surface grinding of squatty rail can provide temporary relief to noise and vibration issues. More frequent grinding is also desirable at such locations.

ii). Improved rail or wheel lubrication can reduce contamination of the running surface and gauge corner of the rails, and thus reduce the adverse influence of lubrication on the growth of surface initiated fatigue defects.

**d) Running Surface Checking or flaking**

Flaking, or running surface checking, is also a surface condition that occurs on the running surface of the low and/or high rails (Fig. 6). At the beginning, the defects appear as a mosaic or snakeskin like pattern on the rail head. In the latter stages of growth the cracks produce “spalls”,that can be up to about 10-15 mm wide, up to 3 mm deep, and can be continuous along the rail length. In this study, the width of the squat on the rail was 11mm and 1 mm deep.


**Fig. 6 Running surface checking or flaking**

**Causes**

i). Rail running defects are initiated by the high shear stresses that can develop at the wheel/rail contact region, when such stresses exceed the allowable limits for the rail material.

**Effects**

Rolling Contact Fatigue or defects are of particular concern for two main reasons:

i) They may lead to rail failures if not detected in time, particularly in the case of transverse defects.

ii) They can mask the ultrasonic signal during routine inspection and hence prevent the detection of larger and deeper defects that may be present within the rail head, including any such defects that may have developed from the shallower initial cracks.

**Maintenance techniques**

i) The removal of severe rolling contact fatigue (RCF) or defects, and in particular, running surface checking or flaking, is by grinding, an extensive and expensive rail maintenance process.

ii) Installing higher strength rail steels in the more critical track locations, to increase the allowable shear stress limits. Higher strength head hardened rails can be particularly successful in reducing the development of flaking. This is because hardened rails not only exhibit reduced wear, but also reduced plastic deformation.

**e) Longitudinal vertical crack**

This defect is caused in the process of manufacturing, which usually appears in the rail web and may extend in rail head also. If this crack is intersected by some other crack, it may lead to an early fracture or rail break. Chances of sudden fracture due to this type of crack become predominant in cold climate. Fig. 7 shows a longitudinal vertical crack. Generally, small and medium defects cannot be detected visually, except the large vertical split head defect.

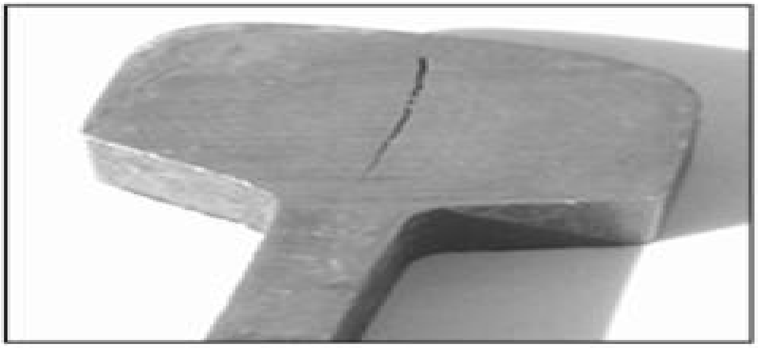

**Fig.7 : longitudinal vertical crack**

**Causes**

i) The vast majority of vertical split heads initiate at elongated seams, inclusion stringers or highly segregated regions. These occur particularly in the older rails produced by means of ingots (rather than the current continuous casting), which generally exhibits much higher levels of irregularities. The inclusion band is generally very evident visually on the fracture surface of the defect, and in this study it was 2 mm in vertical height. Vertical split heads may also occur in clean 60kg/m steel under extreme rail wear conditions.

ii) The initial crack growth occurs vertically from the elongated irregularity, both towards the running surface and the head web transition region. The actual stress condition that produces such crack growth is primarily due to heavier axle loads in association with impact loads and, sometimes, with extremely eccentric loads from tread hollowed wheels and flat rail.

**Effects**

The major concerns associated with vertical split head defects are:

i) Generally the defects cannot be visually detected until they become very large, and hence must rely on detection by ultrasonic inspection.

ii) The defects can be very long, and consequently a considerable proportion of the rail head becomes weakened.

iii) If the defects are not detected in time, a complete vertical failure of the rail head may occur. This becomes critical particularly if the failure is on the gauge side of the rails, since the condition would increase the risk of wheel climb and derailment.

**Maintenance techniques**

i) Improved cleanliness associated with the newer rails reduces considerably the risk of defect development. Thus, replacing older rails with newer ones will reduce the rapid development of defect of vertical split head.

ii) The initiation and growth of the vertical split head defect may be inhibited by: Reducing the levels of applied nominal, dynamic and in particular impact wheel loadings, and the levels of wheel hollowing, so that off centre loading of the rails is minimised.

iii) Grinding the rails, so that the wheel loading is concentrated near the centre of the running surface.

Finally, regular ultrasonic rail testing must be carried out to detect the vertical split heads before they reach a critical size, which may cause rail failure.

**f) Corrugation**

Corrugation is a rail flaw consisting of the wave-like wearing of the rail tread visualized as peaks and valleys, in other words, it is a periodic irregularity of the rail surface. Rail corrugations are the result of a damage mechanism, such as wear, fatigue or plastic flow operating at some characteristic frequency. Rail corrugations do not cause immediate derailment, but they may cause loosening of rail fastenings, ballast deterioration, increase in noise and vibration level leading to passengers discomfort, etc. Two main types of corrugations which generally occur in rails are: short pitch corrugation and long pitch corrugation.

**Fig.8 : Short Pitch Corrugations**

**Short Pitch Corrugations**

Short pitch corrugations are considered to be self-excited stick-slip vibration of a wheel set. Defective wheel or defective wheel setting and heavy traffic load may be some of the reasons for this type of corrugation. It is mainly seen in tracks under heavy haul operation. Short pitch corrugation varies between 3 cm to 8 cm.

**Long Pitch Corrugation**

Long pitch corrugation is characterized by very shallow depth between peaks having very long waves of 8 cm to 30 cm. They are mainly caused by manufacturing defect associated during rolling process of the rails. They are predominant in rails with high traffic density and high speed. However, in this study, it was the short pitch corrugation that was detected because; the measurement of the corrugation detected on the rail surface was 5 cm.

**Causes**

i). Short pitch corrugations are formed due to the differential wear caused by a repetitious longitudinal sliding action of the wheel on the rail, whether through acceleration, braking or lateral motion across the rail. The longitudinal oscillations were probably developed due to the excitation of the torsional resonance of the wheel set.

**Effects**

i). Rail corrugations are of concern because they increase the dynamic wheel loads and vibration, leading to the deterioration and failure of various track and vehicle components.

ii). Higher dynamic loads also increase the rate of corrugation development and the rate of rail profile deterioration. The rails therefore require more maintenance effort, such as grinding, at shorter intervals. Corrugations also increase, considerably, the wheel/rail noise.

**Maintenance techniques**

The most popular method used for reducing or eliminating rail corrugations is essentially:

i). Application of regular rail maintenance in the form of grinding, to control the growth of corrugations. Rail grinding is also required to implement the improved profiles. Another major benefit of cyclic rail grinding is that it allows the softer rail steels to deform in a controlled manner.

## IV CONCLUSION AND RECOMMENDATIONS

### 4.1 CONCLUSIONS

Different types of rolling contact fatigue or defects and degradation processes have been studied. From the literature review done by the author, it shows that there is a need for better prediction of rail defects over a period of time based on operating conditions and maintenance strategies. In this study, the issues and challenges related to periodic rail maintenance are emphasised. The aim is to reduce costs and risks related to rail operation by taking effective decisions related to rail inspection, grinding, lubrications, rectifications and rail replacements.

The following conclusions can be drawn from this study:

a) Cracks are the primary source of rail deterioration, even though not all of them provide a derailment risk. However, the bulk of rolling contact fatigue (RCF) cracks should be removed by grinding. Research and experience have shown that rail grinding significantly reduces rail degradation. Corrective, preventive, and cyclical operations are all part of the present rail grinding strategy. Furthermore, in recent years, changed rail profiles in bends have grown in popularity. Early rail replacements and rail brakes can be decreased by rail grinding. Derailments may be avoided in this way. Rail grinding can reduce the need for brakes and early rail repairs. This may help prevent derailments. Therefore, early detection of rolling contact fatigue (RCF) rail defects is essential.

b) Rolling contact fatigue is a difficult but controllable problem. A methodical assessment of the wheel and rail profiles and metallurgy, track geometry, friction management, rail grinding procedures, and bogie type will determine the best possibilities for improvements as well as the requirement for improved inspection and identification.

c) Since each practical strategy will be highly specific to a particular railway, the benefits and drawbacks of each must be compared. The potential costs and benefits can be used to create a business case. A field test is frequently carried out to verify and document the expected improvements following the approval of the business case. Agreements with suppliers for goods and services, as well as the development of training, quality assurance, and ongoing monitoring programs, will be necessary for broader system adoption.

d) An effective program to reduce rolling contact fatigue (RCF) includes installing better steels in curves, correcting the worst track geometry issues, improving the wheel profile wherever possible, and preventively grinding rail to a variety of forms that include various profiles for tangent, high, and low rails. In addition to other benefits such as reduced fuel consumption and lateral forces, improved suspension trucks can often lead to a significant reduction in rolling contact fatigue (RCF). Despite the lack of field data, friction management shows promise as a powerful technique to reduce rolling contact fatigue (RCF).

e) Although the requirements and limitations will vary, sometimes significantly, from one railway to another, a comprehensive analysis of the vehicle/track system should be carried out in order to identify a number of minor, practical, and oftentimes affordable changes to the current materials and maintenance procedures for controlling rolling contact fatigue (RCF), in order to extend rail and wheel life, and lowering risks.

## 4.2 RECOMMENDATIONS

a) Newly formed surface cracks are only a millimeter long and extend between five and fifteen degrees from the surface. These newly formed cracks usually propagate fairly slowly at first, then quickly at a medium length of roughly 5–10 mm and at a depth of roughly 1-3 mm where the contact forces are less severe. These cracks could be stopped by using abrasive brake shoes, rail grinding, wheel re-truing, or normal wear as soon as they begin to spread across the running surface. Regularly re-truing wheels to an ideal form can increase wheel life. Abrasive brake shoes, such as those with cast iron carvings, can be used in order to remove metal from the wheel tread, prevent wheel-slide damage and early fatigue cracks.

b) Lubrication is a more efficient way to reduce wear, and by regularly grinding the rail, a little bit of the rail surface material can be removed to truncate existing cracks and remove extremely shallow damage.

c) In order to regulate the initiation of both surface and subsurface cracks and to eliminate short cracks while their rate of propagation is still slow, the best course of action is to remove precisely the proper amount of metal at "The Magic Wear Rate".

c) Preventive rail grinding at 'The Magic Wear Rate' is recommended, because it increases system rail life and system rail fatigue life substantially.

d) The rail profile must allow for the mix of new and old wheel shapes that batter the rail at any given location on the track. The low-rail design should ideally improve steering in addition to lowering contact stress. Especially in high axle load systems. The high rail must provide sufficient relief to avoid gauge corner failures while also encouraging steering to control wear and RCF.

e) To reduce the rolling contact fatigue (RCF) of the rail, a family of rail designs that make contact with the wheel at different operating bands will greatly benefit the wheel. A well-designed system of wheel/rail profiles that controls stress and wear offers long-lasting, stable, and ideal wheel/rail performance. Rail shapes should be designed to disperse wheel wear and slow the emergence of a false flange or geometrical stress raiser.

f) Because wheel and rail profiles cannot be altered immediately, the transition from existing to new shapes must be properly taken into account during profile design and then managed during implementation.

g) Employ a special wheel profile with a better wheel shape to reduce wheel shelling and increase the railway lifespan.

h) To control creep forces, wheel profile curving capabilities should be matched to curving requirements, to make a new wheel profile take on a shape similar to the rail profiles it rolls on. Poor rail profiles or low-strength steels limit the benefits that a wheel alone can offer. However, using matched rail profiles increases the benefits. For example, shakedown can be significantly improved by using the WRISA2, a wheel profile designed for the UK railways.

i) Grinding rail profiles in tangents and curves could reduce hollowing and help maintain the wheel's intended shape over time to optimize the performance of an improved wheel profile.

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