Review of Fatigue Crack Growth and Microstructure of Rail

Prof. Priti Vairagi
Department of Mechanical Engineering
Vidyavardhini's College of Engineering and Technology
Vasai West

Tanuj Surve
Department of Mechanical Engineering
Vidyavardhini's College of Engineering and Technology
Vasai West

Shubham Mandavkar
Department of Mechanical Engineering
Vidyavardhini's College of Engineering and Technology
Vasai West

Yash Mhatre
Department of Mechanical Engineering
Vidyavardhini's College of Engineering and Technology
Vasai west

Ronak Hadal
Department of Mechanical Engineering
Vidyavardhini's College of Engineering and Technology
Vasai west

***Abstract*—The aim of the paper is to provide the nature of Fatigue crack growth in rail steel. Study of microstructure of rail is presented. The hardness for the rail at the various cross sections is provided. Numerical as well as experimental methods are used to study the behaviour of the cracks in the rail. Study of Fractography is done to comply the fatigue crack growth and hardness test. FEA analysis for the same is presented to study the fatigue crack growth under stress field. The paris law is used for the purpose of fatigue crack growth studies. Study of FEA analysis is compared with experimental and theoretical studies.**

Keywords—Fatigue crack growth, Fracture surface, Crack, Rail, Fractography, Fracture Surface.

I. INTRODUCTION

The material used for rail is mostly steel of grade 880, 1080Cr, 1080HH, Special rail steel, Niobium, Vanadium, Corrosion resistant rail steel, Copper- Molybdenum, Alloy of Nickel Chromium Copper. The different types of rail are double Headed, Bull Headed & Flat Footed. The standard Flat Footed Section is mostly used. The rail is designated by weight per unit length. A 60 kg/m rail denotes that it's weight is 60 kg per metre. The standard sections used in Indian Railways are 60 kg, 52 kg, 90 R, 75 R, 60 R and 50 R. Indian Railways mostly use medium Manganese rails manufactured by Bhilai Steel Plant having ultimate tensile strength of 72 kg/mm². The various test are done for the acceptance of the rails such as Chemical Analysis, Tensile Test, Sulphur Print, Hardness test, Falling weight test, Hydrogen content, inclusion rating level. The study is carried out on the rail of grade 880. There are various defects in rail under operating conditions. A rail is considered to be failed if it is necessary to remove it immediately from the track on account of the defects noticed on it. Most of the failures in the rail originate from the fatigue cracks caused due to alternating stresses created in the rail section on account of the passage of moving loads. A rail section is normally designed to take a minimum GMT of traffic, but sometimes due to reasons like inherent defect in the metal,etc, there is weakness in the section at a particular point and that section gives way premature, causing failure of the rail.

The main causes for failures of rails are inherent defects in the rail, defects due to fault of the rolling stock and abnormal traffic effects, Excessive Corrosion of Rails, Badly maintained joints, Defect in Welding of joints, Improper maintenance of track, Derailments,etc. Rolling Contact defect is one of the prime concern which is affecting the service life of the rails. Rolling Contact defect is caused due to contact between wheel and rail. The cracks that are formed by rolling contact defect are divided into two categories first are the cracks that are formed on the surface and second are the cracks that are formed under the surface. The cracks formed under the surface are mainly due to vertical load and the material defects. The cracks formed in the surface are due to interaction between wheel and rail and large load transport to a small area. Contact area is elliptical and relatively small. Cracks formed due to the rolling contact fatigue and due to shear stress in the contact area of wheel and rail will grow when the stresses exceed the permissible tension of rail steel. Cracks advance towards the top of the rail and leads to failure of the rail under lower vertical load.

The detection of rail flaws is done by using visual examination or by rail flaw detection equipment. In visual examination the rail ends are cleansed by kerosene oil and visually examined in detail with the help of magnifying glass. In ultrasonic rail flaw detectors, vibrational waves above the hearing range of the normal ear, having the frequency of more than 20000 cycles per second are used. Whenever there is a change in media some of the ultrasonic energy gets reflected and the rest gets transmitted. When ultrasonic waves are fed at location on a rail, they pass through the rail metal and are normally reflected only from the foot. However the flaws near the surface sometimes remain undetected. Also the flaw should be perpendicular to wave detection if not it will not be detected. It also fails to detect the two flaws falling in the straight line. The reflecting surface should be parallel to the scanning surface otherwise there would be no back echo. Wrong selection of probe will defect the purpose of scanning.

For this purpose, in the literature some of the issues are studied using experimental, theoretical and analytical calculations and FEA computations. Information regarding the behaviour of the cracks under stress is also provided. Fatigue fracture test are performed and they are supported by fractography studies. Microstructure analysis is studied to know the characteristics of the rail before and after testing. The hardness is measured using Rockwell hardness test to know the portion where the hardness is maximum. The experimental test are interpreted and compared with analysis and theoretical results.

LITERATURE REVIEW

The contact failure occurs on the rail head surface and it is observed that it increases as the load on the rail head is increased and after certain limit it results into breaking up of rail. We can find out the maximum load and crack length before the failure takes place and thus accidents can be avoided by preventing the cracks from reaching its critical length. The mechanism of crack initiation, growth and behaviour is studied by doing the FEA (Finite Element Analysis). The effect of crack decreased according to the depth of the surface. The crack growth rate was studied by understanding the SIF (Stress Intensity Factor).The evaluation was done on Ansys software.[1]

The fatigue crack growth rate was understood and observed by knowing the nature and intensity of crack, mostly cracking is perpendicular to the applied load but sometimes cracking also takes place out of plane. The main factors are material microstructure and residual stresses.[2]

In this paper various factors like crack initiation, propagation, metallurgical factors, geometric specifications are studied. The hardness test was carried on CT specimen by using Rockwell Hardness Equipment and it was found that the hardness is highest on the rail head surface on the top as compared to other section of the rail head. The geometric specification of the specimen were 50*48mm with 10mm thickness , 8mm chevron notches and 10mm 2 drill holes at a distance of 11mm from the center of specimen. The different ranges of load were applied on the specimen for the analysis purpose. The material of rail was 880 Grade rail steel with chemical properties like carbon to 0.60 to 0.80% , Mn 0.80 to 1.30% , Si 0.10 to 0.50% , S 0.030% , P 0.030% , Al 0.015% . The yield strength of the material is 460 MPa. [3]

The metallurgical study consists of microstructure study and it plays an important role in performance of rail steel. The subsurface defects like casting defects which includes defects such as inclusions, blow holes, cavities leads to fracture during the service and decreases life of the material and causes its failure. The resistance to wear depends upon the tensile strength and hardness value of the material of which the specimen is made. Fine pearlitic steel has a better wear resistance as compared to bainitic steel and the main reason is difference in the microstructure. When the specimen is tested before the fatigue test the microstructure is proper. When it is again tested after fatigue test the flattening of grain and shearing of grain is observed as a result of plastic deformation.[4]

It was observed that the crack propagates parallel to the rail surface and then through the depth of the rail. The different modes of failure were determined like Mode 1, Mode 2, Mode 3. The different loads applied were of 13KN, 14KN, 15KN. [5]

The FEA was used for simulation of crack by varying loads. It was found that less the initial crack length more the fatigue life will be. The initial crack length mainly depends upon manufacturing process and contact area. Thus with increasing crack length the angle also increases and crack propagates more deeper. The stress intensity factor of crack at rail head was higher that at the web and bottom section so the fatigue life of rail head is less as compared to other sections. [6]

Different types of crack were studied for covering wide variation of fatigue crack growth. So the crack growth with respect to various periods were studied. Thus the range of crack advance with respect to per cycle was known. It was studied that as SIF increases fatigue crack growth also increases. [7]

The crack nature was studied like elliptical crack, semi elliptical crack. This crack are more dangerous and grows rapidly on application of repetitive loads for a certain number of cycles. [8]

The crack starts on the rail head and runs and propagate along the rail surface and then tends towards the rail surface most of the times. It also forms the extensive network known as shelling. [9]

Fatigue crack growth studies for rail steel using servo hydraulic fatigue rated utm is studied. The load and Stress intensity factor range are calculated as per the ASTM standards. The graph plot of da/dN vs ΔK is being plot to find the FCG constants. The da/dN is calculated as per the Paris law. The graph of crack length vs No of cycles is plot to evaluate the Fatigue crack growth rate. The test is terminated when the crack growth in the specimen becomes unstable and uncracked ligament is insufficient to take further load. [10]

Scanning electron microscopy is used to examine the morphology of the material. The procedure is straight two sided carbon tape is used the fix the SEM sample. The sample is freeze fractured by immersing in liquid nitrogen for 1h . Sample preparation also involves striking it with a dull blade at a prescored mark. Voids in the sample are readily visible. Impact testing is done as per ASTM F648 for impact characterization of material. This is done using Izod type impact machine. The test comprises of a pendulum impact machine that strikes a double notched test specimen. The amount of energy required to break the sample is measured and normalized by the cross sectional area of the specimen to determine the impact resistance. Before testing, the specimen is clamped in the Izod Vice. The magnitude of clamping force is observed to affect the measured impact strength. A torque wrench or pneumatically actuated vice is used to apply a consistent clamping force on the specimen. The impact strength is calculated as the energy loss of the pendulum divided by the unnotched area of the specimen.[11]

CRACK INITIATION

The initiated crack length can be increase due to increase in stress field in wheel contact zone. If the amount of contact zones stress field is more than yield strength of rail steel then this stress field results into initial crack initiation. Controlling wheel/rail contact geometry is the best way to reduce contact stresses.[1]

The initiation crack length has a great effect on the SIFs such that increasing initial crack length increases the SIFs at the tip of the surface crack. Initial crack plays an important role in fatigue crack initiation in rails. The SIFs under dynamic loading are simulated in the three dimensional model using Franc3D design software.[2]

To determine the positions of crack initiation in the surface metallographic sections are examined. Due to an initiation of crack, gradual degradation happens and it continues till the failure of rail. Crack initiation started under the surface usually are due to severe vertical load combined with material defects. In case of railway track, most of the cracks that are formed in the surface are by the interaction between wheel and large load transport to a small contact area. Crack that are initiated by the effect of rolling contact fatigue and are resultant from the intense shear stress in the contact area of wheel rail, and will grow when stresses exceed the scale of permissible tension of rail steel. Cracks plays an important role in fatigue crack initiation in rails. [3]

The larger the initial irregularities or defects in rail steel larger the chances of early crack initiation. Below the surface defects, a network of sub surfaces cracks develops. The cracks runs for most of their length parallel to the rail surface and tend to turn towards the rail surface, causing spalling. The cracks initiate at the surface pits or at the bottom of spall craters.[4]

High wear rate can lead to crack initiation elimination and prevent their growth, but low wear rate increases the time of high stress field and has negative effect in elimination of initial cracks. Different initial crack lengths and stress intensity factors are calculated in two crack types for the contact condition between rail and wheel. Stress intensity factor in a crack that is placed in rail, along loading direction has an initial crack length changes from 3 to 6 mm, increases up to 67%. Stress intensity factor also increase up to approximately 73% by a change in initiation of crack from 6 to 10 mm. The same changes in crack initiation length in the opposite direction results in a 11% rise in stress intensity factor.[5]

Crack initiation plays an important role in fatigue life such that the less initial crack, the more fatigue life will be. Less initial crack length has negligible impact on stress intensity factor. When the crack initiation length increases from 3 to 6 mm, no significant changes are observed in stress intensity factor. But once the initial crack length increases up to 6 to 10 mm, a significant changes can be observed. Hence, as the crack length increases, the stress intensity factor grows, and it is more significant in cracks of greater initial length, hence increases in crack growth rate.[6]

An experimental Paris-Erdogan Law is obtained by complete plots of stress intensity factor range versus crack growth of two pearlitic rail steels, which shows that initiation of crack mainly dependent on the material (pearlitic) response to initial load acting on the rail steel.[7]

SIFs for multiple cracks are studied in a network for different values of initial crack length. Longer initial crack length results in maximum SIFs. When the initial crack length increses, the difference in the values of SIFs for multiple cracks in a network increases at the tip of the surface cracks. Elliptical and semi-elliptical initiation of cracks are more dangerous than other initiation of cracks.[8]

Cracks and crack like flaws which are responsible for crack initiation are studied in fracture mechanics. Geometric features in a part which acts as a stress concentration can lead to crack initiation, including notches, holes, grooves, and threads. Cracks can also initiate from flaws introduced through pitting due to corrosion or from abrasion due to galling.[9]

The microscopic cracks during the initiation phase usually follow the slip planes with ±45° inclination to the direction of the largest principal stress. This observation implies that the micro-cracks will occur first in some preferential grains in which the slip plane traces are parallel to the direction of the maximum shear stress.[10]

Quick crack initiation can be caused due to complex and irregular topography of fatigue fracture with variety of fracture modes. To minimize the initial crack length ferrite-pearlite steels are chosen because of their high strength combined with excellent fatigue behavior.[11]

CRACK PROPAGATION

The fatigue cracks forming on the contact surface grow according to load and lubricating conditions and may end up breaking the rail.[1]

The Cracking is perpendicular to the applied load. However, material microstructure, residual stresses and other factors can cause the crack to turn out-of-plane and propagate in a mixed-mode manner.[2]

Railway damage due to the rolling contact fatigue, rolling contact fatigue which various form of surface defect caused by network of a subsurface cracks can be seen. Rolling contact fatigue is caused by contact tension, contact forces between wheel/rail, caused the tension of the elastic or plastic material area.[3]

Defects may form intrinsically during processing or may be initiated during service. These are accordingly classified as material defects and service defects, respectively. The prevailing material defect acts as a nucleus and its subsequent growth under the existing loading conditions during service leads to the formation of the latter kind of defect. Among material defects, hydrogen-induced shatter cracks are the most important in pearlitic steels. Internal flaws in the form of material defects act as nuclei for the propagation of cracks under the effect of rolling-contact fatigue. Their unrestricted growth leads to detailed fracture otherwise known as service defects in railroad industry.[4]

The rolling contact fatigue (RCF) in rail is caused by the rail/wheel contact and lead initiation of surface and subsurface cracks. The fatigue performance of the rails is a function of many factors, including service condition, loading, material properties, environmental factors, and manufacturing processes, we concluded that shallow (surface) angled cracks cause pitting or transverse cracks under special condition.[5]

Contact force between rail/wheel affect the fatigue life to a large extent. These forces, affected by the geometry of rail and wheel, are dependent on the frictional and slippage attributes of wheel/rail and their material.[6]

In agreement to ASTM E399-09 standard the crack plane orientations are L-S for the cracks that grow from the top of the rail head to the rail web and L-T for those that grow from one flange of the rail to the other. In both cases the cracks grow transversal to the rolling direction.[7]

The RCF damage starts with the first mechanical operation, although it is very complicated to detect. In fact, microscopic subsurface cracks appear and propagate, caused by the cyclic load applied to the railway wheel.[8]

Parallel to the rail surface and tend to turn toward the rail surface. Track exhibits an extensive network of surface cracks known as shelling.[9]

Fatigue fracture of rails is a possible occur in railway tracks due to the fluctuating stresses due to the varying traffic conditions and low fracture toughness of rail steels. Due to the heat affected zone adjacent to the weld, fatigue becomes critical in welded joints. The fatigue cracks forming on the rail surface grow according to load and lubricating conditions and may end up breaking the rail.[10]

GRAPH

Fig. 9 [3] shows fatigue life curve in terms of fatigue crack length for the CT specimen which is being tested that for the curve obtained from the use of numerical method to calculate stress intensity factors is compared. As seen in this figure there is a rather acceptable agreement between the experimental results and numerical methods that suggests the precision used in obtaining mechanical properties of the tested materials.

The Transition between Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) is obtained by the stress level (transition between plastic and elastic deformations), that implies that there is no fixed transition life (cycle 103), but that transition life depends on the ductility of the material. After a certain time, remaining strength is so low that the rails cannot resist random large loads. If randomly large loads do not occur, crack growth will be continued till the strength of the rails is reduced so that under normal loading the failures occur.

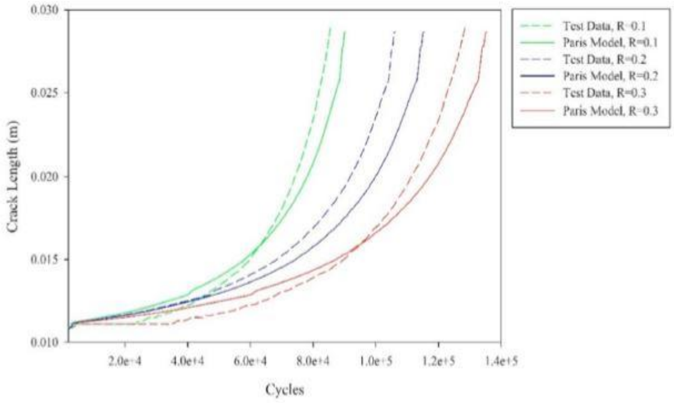

Fig. 9 [3]

CONCLUSION

1. Crack grows continuously due to contact pressure between the rail head and the wheel.
2. Crack growth rate increases as the length of the crack increases with crack propagation along the period of time.
3. The behaviour and direction of crack growth mainly depends upon the nature of applied load.
4. The graph of crack growth and number of cycles required for fracture were found.
5. The resistance of crack depends upon brittleness of material and its microstructure which is found by studying it under electron microscopy.
6. The microstructure of the specimen drastically changes after fracture and its deformation due to applied load. The grain structure also varies as the grain size varies.
7. It was studied that high hardness value was found maximum at the rail head.

REFERENCES

[1] Jung Won Seo, Seok Jin Kwon, Dung Hyeong Lee, Sung Tae Kwon, Ha Yong Choi, Fatigue crack growth and Fracture of Rail Steel (2012) , IJR Vol 5, No.3 pg 129-134.

[2] S.C Forth, D J Herman and M. A James, Fatigue crack growth rate and SIF corrections for out of plane crack growth (2004), Fatigue and Fracture Mechanics 34th Volume ASTM.

[3] Reza Masoudi Nejad, Mahmoud Shariati, Khalil Farhangdoust Department of Mechanical Engineering, IRAN, Prediction of Fatigue crack Propagation and Fractography of Rail Steel, (2019), Theoretical and applied Fracture Mechanics 101, pg 320- 331.

[4] N S Mishra, V Ramaswamy and Sanak Mishra R&D Centre for Iron & Steel, India, Defects in Rails (1986), Sadhana Vol. 9 Part 4, pg 345-369.

[5] Reza Masoudi Nejad, Mahmoud Shariati, Khalil Farhangdoost, Effect of wear on rolling contact fatigue crack growth in rails (2016), Tribology International pg 118-125.

[6] R. Masoudi Nejad, M. Shariati, Kh. Farhangdoost, A. Atrian, Rolling contact fatigue analysis of rail under the influence of residual stresses induced by manufacturing (2019), Sharif University of Technology Scientia Iranica, pg 1427-1437.

[7] S. Maya Johnson, A. J. Ramirez, A. Toro, Fatigue crack growth rate of Two Pearlitic Rail Steels, Tribology and Surfaces Group School of Mechanical Engineering, Brazil.

[8] Reza Masoudi Nejad, Khalil Farhangdoost, Mahmoud Shariati, Majid Moavenian, Stress Intensity Factors Evaluation for Rolling Contact Fatigue Cracks in Rails (2017) , Tribology Transactions.

[9] G. N. Haidemenopoulos, A. D. Zervaki, P. Terezakis, J. Tzanis, A. E. Giannakopoulos, M. K. Kotouzas (2005), Elsevier Engineering Fracture Mechanics.

[10] S. R Shamili, P Gandhi, S. Vishnuvardhan, P Gajalakshmi, Fatigue Crack growth studies on Rails Steels (2015), IJIRSET International Journal of Innovative Research in Science, Engineering and Technology, Vol.4 Special Issue 6.

[11] Stephen Speigelberg, PhD, Adam Kozak, BS and Gavin Braithwaite, PhD, 29.Characterization of Physical, Chemical and Mechanical Properties of UHMWPE, Cambridge Polymer Group, Boston, MA, USA.