Estimation of fatigue life parameters of an Alumino Thermic weld on UIC60 rail joint using LEFM

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Abstract. At wheel track contact point, the high stress concentration, poor weld quality, and heterogeneity of weld material are the main factors that cause fatigue crack on any rail weld. Railway network agencies are concerned about the safety of the railway track when it comes to detecting and fixing weld faults to avoid vehicle derailment and loss of lives. This study analysed a numerical simulation of fatigue crack and its evolution under loaded service condition. A 3-D CAD wheel rail weld assembly model was built to study an AT welded joint under fatigue, and for stress concentration factor (SIF) calculation. The results are found by inserting a semi elliptical crack on the rail weld head surface with ANSYS, and then numerical simulation has been performed to get the different three modes of SIF at rail weld crack. The analysis findings data was recorded with critical fracture parameters of SIFs and its number of cycles to failure using LEFM technique and respective results have been plotted. With ANSYS the stress intensity on a crack will be resulted. By using numerical method, the critical crack size and number of cycle load with fatigue life of rail would be determined. The numbers of rail weld inspection per year has been determine by using the maximum number of cycle. The aim of this paper is to develop an effective inspection and maintenance frequency based on rolling contact surfaces crack propagation analyse. This will help to prevent the occurrence of rail failure by taking the required action at the right time, and extend the rail life expectancy, reduce the rail maintenance work and its cost.

Keywords: Crack, fatigue, rail weld, maintenance, LEFM, FEA

1. Introduction

Railway infrastructure maintenance is essential for a well-functioning transportation system. The real maintenance work entails a huge number of diverse operations that necessitate a large number of resources and a large budget. Rails have been converted to long welded rails on the majority of BG track. Short-welded Rails with a length of 39 metres and Single Rails are only allowed in places where welded rails are not allowed due to technical reasons. The overall length of welded tracks on Indian Railways' major lines as of 31.3.2020 was 90,625.7 km, with 81,912 km of long welded rails. Short-welded rails were used for 8,713.7 kilometres [1]. Actually railway development in our country is also a main task to strengthen the transportation sector and to meet the country’s National Growth and Transformation plan. A rail is a piece of hot-rolled steel with a certain cross-sectional profile (an asymmetrical I-beam) that is used as the main component of a railway track. The train's conical, flanged wheels are guided by rail, which keeps it on the track without active steering. This allows
trains to be much longer than road vehicles. Rail has the following characteristics: rigidity, ductility, hardness, and top surface roughness [2]. Railway rails are made up of 25-120 m long sections that are bolted or welded together in the track. Welded rail sections have two advantages over bolted rail sections: lower maintenance costs and improvement in dynamic performance of the train-rail system. Continuous welded track (CWR) are welded into 100-200m long rail in factory, and then welded again into1000-2000m long rail in the laid place within 25 m of rail. Continuous welded track (CWR) has smooth driving, low maintenance cost and long life advantages. Skyttebol et al found that welding with thermite technique has a high failure rate and about ten times more than flash butt welds [2]. Despite this, thermite welds are widely utilised in the field of railway in all over the world.

The linear-elastic fracture mechanics (LEFM) approach work as to improve ideas to find the equations for the elastic stress field around a fracture crack tip using mathematical foundation. A tiny zone of plasticity nearby to the crack tip is assumed for the field equations. Assuming the geometry has very small displacement and the material is elastic, homogeneous and isotropic, LEFM is thereby applied. Using linear elastic fracture mechanics (LEFM) principle, the amount and distribution of stress around the fracture tip are linked to distant loads applied to the crack, thus size of the crack, rate of crack propagation, material characteristics of the cracked components and other factors can be studied [3]. Life of a rail weld, in track, can be allocated into two stages first the process of starting of crack and then propagation of it. Crack initiation refers to the period of time (or the tonnage passing over the rail), but cannot be detected by existing inspection technique. Crack propagation refers to the period of time it takes a detectable defect to grow to a size that will fall under traffic. High traction forces caused by quick vehicle movement over the track can cause cracks to form at or below the surface. After penetration, sub-surface fractures spread towards the rail surface and behave in a manner similar to initial surface cracks [4].

![Figure 1. (a) Rail weld wheel loading condition and (b) crack location](image)

Figure 1 represents the rail weld wheel field view and the crack location at AT weld. Surface cracks on railways are discussed in the literature [5]. The loading conditions, heavy surface plastification, and microstructure under which one mm and longer cracks generations are qualitatively explained and modelled using L.E.F.M. principles have been introduced by authors. The main question is whether a crack will spread to the point where the entire rail will break. This is expected to happen only if the fracture is fairly long and the SIF\textsubscript{Mode I} exceeds the threshold value in Mode I due to high tensile stresses generated by rail temperatures. Ringsberg et al. looked into the influence of welding residual and thermal stresses for development of fatigue fractures in rail welds [6]. Estimation of residual stresses in a flash-butt weld using finite element analysis was done, and the findings were in a good similarity with experimentally observed residual stresses in a welded rail, conducted in a laboratory. Investigating sensitivity was done using the findings of the rail welds stabilised stress response after several wheel-rail contact load passes on it. Canadinc performs elasto-plastic numerical simulations about the evolution of rail-head cracks. Cracks with a length of 3 mm or more are investigated, and it is taken into account to compare wear and crack propagation [7]. The rate of growth of fracture in a small crack is considered to slow when the fracture tip advances away from the rail weld surface's contact stress field. Because compressive contact forces become weaker at crack which is of critical
length, thus its expansion arises suddenly. The work is said to be the first comprehensive study of the crack driving forces that account as unique elastic-plastic distortion data findings.

Thus above studies have made some findings on fatigue life of rail surface crack propagation by using finite element (FE) analysis and linear elastic fracture method. Rail steels are susceptible to fatigue failures resulting in rail breaks that can lead to unplanned downtime and safety concerns in railway operations [8,9]. According to Ramirez et al., research has been looked into the rate of fatigue crack growth in two standard rail steels [10]. Zhao et al. used FEM with LS-DYNA to discover the SIFs of head cracks under three dimensional approach [11]. Masoudi et al. utilized Franc-3D to investigate the SIFs of rolling contact fatigue fractures in rolling contact [12]. The SIFs considering various surface locations and size were calculated using FEM for AT weld and steel rail [13]. The ASTM code E399-17 [14] and ASTM code E647-15 [15] standards has been followed to evaluate fracture toughness and fatigue respectively. The results of fatigue crack growth curves for rail steels were found and values of rail steel material were derived from the results revealed by Motameni et al. [16]. The aim of Powell et al. [17] was, to find lateral bending of weld under out of plane study, which has been performed under standard BS EN 14730-1[18] and then it was applied to the specimen to obtain the result. According to Yang Liu et al. [19], rail weld crack growth and behaviour of transverse surface cracks in rail and AT weld subjected to in and out of the plane loadings was explored. SIF results of five different crack initiation locations at the rail weld cross section were found using FE model for crack in transverse direction.

Here in this paper study has been done for fatigue cracks in rail weldment performing Finite element method (FEM) to provide rail inspectors for quick determination of harshness of surface breaking and mixed cracks in rail weld. Then, effective number of rail inspection frequency is determined as three times a year to prevent the occurrence of rail failure by taking the required action at the right time, and extend the rail life expectancy, reduce the rail weld maintenance work and its cost.

2. Geometry, material and methodology

A 3D elastic-plastic finite element CAD model is created as a realistic model of the wheel-rail-weld contact assembly. This model has a length of 35 mm of AT weld, on which wheel weld contact stress may be calculated with the 3D stress response with accuracy, and it should account for both material and geometric nonlinearity. The assembly model is made in space-claim in ANSYS student edition. To model the principal transverse radii of the rail is for national railway network of India for analysing the rail weld parameters. Figure 2. shows The three-dimensional rail and geometry by which UIC60 profile with 0.6m length, wheel and weld was modelled for the analysis. The model assembly is shown in figure 2 (c) and imported to ANSYS mechanical workbench student. Figure 2 (b). Shows a semi-elliptical crack with crack start and end tip abbreviated as 1 and 2.

| Mechanical Property                  | Value  |
|-------------------------------------|--------|
| Poisons Ratio                       | 0.3    |
| Young’s Modulus (GPa)               | 207 GPa|
| Ultimate tensile strength (MPa)     | 996.7 MPa |
| Yield strength (MPa)                | 675.7 MPa |
| Percentage reduction of area        | 4.22   |
| Percentage Elongation               | 3.09   |
After giving the connection bond between wheel and rail and weld, meshing of all parts have been done. The wheel/rail-weld model considered in this paper consists of 39648 numbers of elements and 93357 numbers of nodes. The mesh size consideration is limited with analysis time and result accuracy. The mesh considered for the wheel/rail-weld is fine having size of 2 mm as shown in figure 2 (d). Fixed boundary condition is applied to the rail and weld on the bottom. Force is applied on the wheel and the rotational velocity of the wheel is applied to the wheel centre. Also the standard earth gravity is applied. All model components are only allowed to move (displace) vertically i.e. in y-axis, so the model is restrained on left and right side because of continuity.

The semi-axes lengths of 0.01m and 0.005m, respectively, are used to describe single front elliptical cracks. As seen below in figure 3, once a flaw (crack) was defined, it was placed (translated and rotated) into the proper spot relative to the rail’s unflawed body. To increase the element quality, the final mesh is applied. Paris and Erdogan laws is used to study growth of crack in this model that the stress intensity factor has an exponential relationship with crack growth rate. The SIF range is related to the development of subcritical cracks under the influence of fatigue stress according to Paris law [20]. Properties of material as in Table 1, 2 and 3 has been used for simulation purpose [21].

Table 2. CAD parts material properties.

| Part name        | Rail | Wheel | Axle |
|------------------|------|-------|------|
| Modulus of elasticity (GPa) | 206.9 | 205   | 205  |
| Modulus of plasticity   | 22.7 | 22.7  | -    |
| Yield stress (MPa)      | 483  | 640   | -    |
| Poisson’s ratio        | 0.295 | 0.3   | 0.3  |

Table 3. Chemical composition of UIC 60 rail.

| Grade | Carbon (C) | Manganese (Mn) | Silicon (Si) | Sulphur (S (max.)) | Phosphorous (P (max.)) | Aluminium (Al (max.)) | Liquid H2 |
|-------|------------|----------------|--------------|--------------------|------------------------|------------------------|-----------|
| 880   | 0.6-0.8    | 0.8-1.3        | 1.3-0.5      | 0.04               | 0.04                   | 0.02                   | 3.0       |
3. Simulation results and discussion

The stress intensity factor (K) is used in fracture mechanics to predict stress intensity near the crack tip generated by a remote load or residual stresses. Without doing any crack propagation, the goal of this analysis is to compute stress-intensity factors for this crack. Because the crack propagates in a downward direction, the Stress Intensity Factors are negative. The crack motivating force is the stress intensity factor, or $K_1$, and its critical value is the crack extension resistance force, which is a material property known as fracture toughness. Figure 3 shows the simulation view and crack insertion with mesh and loading direction.

![Figure 3. Schematic for simulation and weld part having semi elliptical crack with mesh.](image)

Figure 3. Schematic for simulation and weld part having semi elliptical crack with mesh.

Figure 4. gives the values of $K_I$, $K_{II}$ and $K_{III}$ respectively with its graphical representation. $K_I$ has a maximum value of $-1.5318e7$ MPa/$\sqrt{m}$.Fracture crack that occurs in a short period of time, under simple loading conditions (static, i.e. constant either quasistatic or changing slowly) is taken into account. A static crack analysis is a single-step deformation study with no crack progression. Now $K_{II} = -9.161e6$ MPa/$\sqrt{m}$ and $K_{III} = 1.24e7$ MPa/$\sqrt{m}$ are two another maximum values of K. Fracture toughness $K_{IC}$ is a characteristic that describes a material’s capacity to resist fracture in the presence of a crack. The critical value of this SIF helps to estimate the maximum fatigue crack a

![Figure 4. SIF KI to KIII and Their Graph w.r.t normalized distance along crack front.](image)
structure can sustain given specified strength requirements. The mean value of rail fracture toughness shall be 26 MPa/$\sqrt{mm}$ [22] when crack propagation becomes unstable. By using equation (1), the stress intensity factor calculated in below in table 4.

$$K_i = 0.086\sigma\sqrt{a_c}$$  \hspace{1cm} (1)$$

Where, $\sigma$ is the localized stress field and $a_c$ is the size of crack.

A fatigue life analysis is performed based on Paris law. Paris law defines that rate of growth of a crack is an exponential function of stress intensity factor given by $\Delta K$ as in equation (2):

$$\frac{da}{dN} = C\Delta K^m = C(\Delta\sigma Y\sqrt{\pi})^n\hspace{1cm} (2)$$

Here C and m are input parameters depending on material properties, $Y$ is a correction factor based on geometry and $\Delta\sigma$ is range of tensile stress. For metals the values of $m$ varies from 2.5 to 3.5 and the value of $C$ varies from $1 \times 10^{-9}$ to $1 \times 10^{-11}$ [23]. So, $m=3$ and $C=1 \times 10^{-11}$ are taken as the specific input parameters. For calculation of fatigue life of rail $\sigma=1511.22$MPa at the rail head are taken.

$$K_1 = \frac{(1.12\sigma\sqrt{\pi a})}{\varphi} = 0.086\sigma\sqrt{a_c}$$

Where $\varphi$ is the elliptical integral of the second kind, given by:

$$\varphi = \int_0^\pi \sqrt{1 - \left(1 - \frac{a^2}{c^2}\right)\sin^2 \theta} \, d\theta = 2.464$$

here $a/c$ is aspect ratio and $\theta$ is the angle that defines any point around the perimeter of the elliptical crack.

$$\Delta K_2 = 0.086 \times 1511.22 \times \sqrt{0.0005} = 27.23$$

$$\Delta K_4 = 0.086 \times 1511.22 \times \sqrt{0.001} = 38.51$$

We know $\frac{da}{dN} = C\Delta K^m$

$$\frac{da}{dN}_2 = 10^{-11}(27.22)^3 = 20,204.27 \times 10^{-11}$$

$$\frac{da}{dN}_4 = 10^{-11}(38.51)^3 = 57,146.31 \times 10^{-11}$$

Mean of $(\frac{da}{dN})_2$ and $(\frac{da}{dN})_4 = 38,675.28 \times 10^{-11}$

$$dN = \frac{0.0005}{38,675.28} \times 10^{-11} = 1,292.81$$

The equivalent alternating stress increases as the load increases. In contrary as the load increases, the crack length is increasing that means the fatigue life of rail weld is decreasing, in general means the more load is applied the fatigue life of the rail weld will be smaller and smaller. It is seen from the table 4 and 5 and figures 5 (a) and (b) that, the fatigue life of rail weld is concerned with the suitable cyclic axle load and proper maintenance before crack initiate and propagate may be regarded as the best possible life improvement operation.
Table 4. SIF vs. crack length.

| Crack size, a (mm) | Stress Intensity Factor (mpa/√mm) |
|--------------------|-----------------------------------|
| 0.0                | 0                                 |
| 0.5                | 861.28                            |
| 1                  | 1218.04                           |
| 1.5                | 1491.78                           |
| 2                  | 1722.56                           |
| 2.5                | 1925.89                           |
| 3                  | 2109.7                            |
| 3.5                | 2278.74                           |
| 4                  | 2436.08                           |
| 4.5                | 2583.853                          |
| 5                  | 2,723.62                          |

Table 5. Crack length vs. No. of cycles for rail weld.

| Initial Crack length (a₀)(mm) | Increment of Crack growth (Δaᵢ) | Final Crack length (a)(mm) | ΔN (cycles) | N (cycle) |
|-------------------------------|----------------------------------|-----------------------------|-------------|-----------|
| 0.5                           | 0.5                              | 1                           | 1.292.81    | 1.292.81  |
| 1                             | 0.5                              | 1.5                         | 1.233.57    | 2.526.38  |
| 1.5                           | 0.5                              | 2                           | 1.125.20    | 3.651.58  |
| 2                             | 0.5                              | 2.5                         | 1.032.19    | 4.683.77  |
| 2.5                           | 0.5                              | 3                           | 956.35      | 5.640.12  |
| 3                             | 0.5                              | 3.5                         | 894         | 6.534.12  |
| 3.5                           | 0.5                              | 4                           | 841.99      | 7.376.11  |
| 4                             | 0.5                              | 4.5                         | 797.85      | 8.173.96  |
| 4.5                           | 0.5                              | 5                           | 759.85      | 8.933.81  |

Figure 5. (a) Stress intensity factor versus crack length (b) Fatigue life of rail weld.

According to the predicted traffic volume the forecasted number of trains varies from section to section. Similarly, the annual traffic density for the Indian Railway Network of India is taken as 22.67 MGT (Million Gross Tones). So, to determine the number of trains per day, we use the Vopecenter empirical formula which is as a function of annual traffic density as follows:

\[ X \text{(No. Of trains per day)} = \frac{T}{0.006312/365} = 10 \]
Ultimately the fatigue life of weld in the terms of MGT (Million Gross Tones) is obtained as follows: Assume one train passes a certain track section two times per day. So, the total number of cycles per year for loaded standard vehicle with four axles or eight wheels is:

\[ 8 \times (10 \times 365) = 29,200 \text{ cycles/year.} \]

\[ 29,200 \text{ Cycles} = 22.67 \text{ MGT} \]

Although the frequency counts of rail welds assessments varies for track to track, and it is often depending on the factors like time and tonnage of traffic. From the previous crack analysis done and with the assumption of 22.67MGT (Million Gross Tones) annual traffic density the fatigue life of rail based on the maximum critical number of cycles for rail head is taken as 6.9MGT (Million Gross Tones). Therefore, the frequency of rail inspection required will be:

Frequency of rail inspection per year = \( \frac{6.9 \text{ MGT}}{22.67 \text{ MGT}} = 0.30 \)

i.e. number of rail inspection per year should be three or (in every four months the rail needs inspection)

4. Conclusion

This study may be utilized to prevent the occurrence of rail failure by taking the required action at the right time, and extend the rail life expectancy, reduce the rail maintenance work. Therefore, based on outputs with stress increment value the conclusions obtained are:

- The maximum stress distribution is represented by Von-Misses stresses, which is found to be 178.62MPa is less than the ultimate tensile strength of rail, so the rail can resist the pressure applied at the contact area.

- In conclusion as far as fatigue life of rail is concerned, the suitable cyclic axle load and proper maintenance before crack initiate and propagate may be regarded as the best possible life improvement operation.

- The rail should be inspecting in every three months (four times in a year).

- Based on the present rail weld crack value and the recommended remedial action plans the weld should be replaced when head crack of more than 5mm is observed.

In order to avoid rail welds from breaking during their service life, the Indian Railways currently have two alternatives in rail defect management. The first is to improve the material, making it more robust, and the second is to increase the frequency of rail and weld inspection. This work focuses on the rail surfaces crack propagation with an effective inspection frequency. However, there are a number of difficulties that require more research to get more accurate output which approaches the real world scenario. Some of the recommendations for future works include:

- Considering a three dimensional (3D) finite element model with an increased length of the transition zone to get more accurate result and to better simulate the research problem with the real (practical) problem in the service life of the track structure.

- Considering other factors that affect track modulus, like environmental factors, sleeper suspension due to ballast flying, imperfection of rail joining. For instance, on the rainy season the effect of water should be given higher attention because it lubricates the rail and highly contribute to the rail crack growth in addition to its effect on the sub grade by affecting its bearing capacity which intern contribute to track settlement.

- Further extend this work by doing Life Cycle Cost (LCC) analysis for the rail found on this transition section which includes optimal repair and maintenance schedule.
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