Rail Surface Fatigue Assessment Using Numerical Simulation of the Concurrency of Short Crack Propagation and Wear

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Over the past few years, rail head checking have been found on the gauge corner of heat-treated rails. Simulations were carried out of a vehicle running through curves using multibody-dynamics simulation software to comprehend wheel loads, lateral forces and contact positions of the wheel and the rail etc., occurring during these runs. The results of the simulation were input into a finite element analysis algorithm of wheel/rail rolling contact to obtain the stress and traction distributions on the railhead. Finally, the concurrence of short crack propagation and wear on the railhead was simulated to study the effect of the curve radius and grade of steel used for the rails.

Keywords: crack, wear, head checking, SIMPACK, rolling-contact, FEM

1. Introduction

In recent years, we have seen reports of head checking or gauge-corner cracking on heat-treated rails on the outer rail of curves with comparatively large radii. According to the reports, the fractures may occur as gauge-corner cracks. Head checking is the appearance of small cracks occurring across the width of the rail or its aggregate, which has a constant angle in relation to the direction of travel of trains. When head checking are connected, flaking may occur. In addition, gauge-corner cracking, which is damage generated in the upper rail-gauge corner (rail-head side), often occurs near head checking.

Although the causal relationship between head checking and gauge-corner cracking has not been clarified yet, if head-checking can be suppressed, it would not only facilitate the search for gauge-corner cracks which could propagate to horizontal or lateral cracks but also help control flaking.

This paper makes a comparative assessment of initiation and propagation of small cracks by studying the rail surface fatigue assessment process, considering the concurrence of short crack propagation and wear, and by analyzing it under various parameters such as curve radius for various rail steels including those currently undergoing installation tests.

2. Outline of rail surface fatigue assessment

The rail surface fatigue assessment process considering the concurrency of short crack propagation and wear is outlined below.

2.1 Simulated passage through a curve

Simulated passages through curves using SIMPAK, which is a general-purpose multibody dynamics simulation software, are used to estimate certain parameters such as wheel load, lateral force, and wheel-rail contact point whilst the vehicle is running through the curve.

The input parameters for this analysis are first prepared, namely, track condition (including radius and cant), rail geometry, rolling-stock characteristics, wheel profile, train speed, etc. Next, for vehicles satisfying certain sets of conditions, other mechanical parameters were calculated, such as axle forces in the vertical, longitudinal, and lateral directions, wheel-rail contact points, and angles of attack. Then, a finite-element analysis program to solve wheel/rail rolling and contact problems is used for processing (addressed in detail in the next section).

2.2 Rolling contact finite element analysis for wheels and rails

Stresses induced by the rolling contact between the wheels and rails can be obtained using 3D FEM analysis considering 2-object contact by providing several constraint conditions. In order to correctly analyze the contact condition in a curve, wheels, rails, and axle are independently modeled, to reproduce the contact of a rolling wheel on the rail. The analysis uses a commercially available software product, ADINA. Distributions of stress and strain induced inside the rail on the contact of wheels and rails, and of traction and so forth of the contact surface are to be handled as the input for the concurrence analysis between initiation and propagation of short cracks and wear described below.

2.3 Concurrence analysis between initiation and propagation of small cracks and wear

Analyses are carried out using a program by designating a 2D cross section on the rail surface (perpendicular...
to sleepers) [1]. The program, which has a variety of functions, some of which were applied in this study, is outlined below:

(1) Initiation of small cracks

As the volume of strains that can be accumulated in a material is limited, it is regarded here that cracks may be initiated once the material ductility reaches a threshold value when the accumulated strain has reached the limit value. For the purposes of this study, a short crack is deemed to have appeared when the accumulated shear strain caused by the maximum value of the orthogonal shear stress (absolute value) reaches the given threshold.

(2) Propagation of small cracks

Propagation of small cracks belongs to one of two phases, namely: Stage I (microscopic crack region as large as that of the material itself) and Stage II (larger than the material itself but with a continuum-fracture mechanical region dissatisfying the small-yielding condition due to visually and physically tiny dimensions). These conditions are calculated in this study according to Hobson’s law. The small-crack propagation in Stage I represents a growth of fatigue crack within the first several particles of a multifaceted material. Those cracks are assumed to propagate with shear stress on the crack surface along the slip line. When the crack grows large enough to open at the edge, crack growth belonging to Stage II takes place. In Stage II, the influence of the microstructure is limited to an expression mechanism for continuous mechanics. The crack is assumed to propagate with the total vertical strain on the crack surface.

(3) Wear model

An Archard model is used for wear.

3. Curve-passing simulation

3.1 Vehicle model

(1) One vehicle model containing 1 body, 2 bogies, and 4 wheelsets,

(2) Connective elements including secondary springs, axle springs, axle dampers, and lateral dampers to be modeled with springs and dampers,

(3) The wheel/rail creep force calculated by FASTSIM which is a high-speed calculation algorithm for simplified linearity based on Kalker’s creep theorem, and

(4) Simulation of a typically loaded commuter train (fully loaded) mounted on bolster-less bogies.

3.2 Analytical conditions

The numerical test was conducted on a 1,067 mm gauge section of line, starting straight and transitioning into a curve. Table 1 shows the main conditions. The running speed was adjusted for each case to allow the cant deficiency to come close to the standard value (21 mm) in Case 1 and Case 2 (R=800 mm, C=95 mm, at a speed of 105 km/h). A new and worn wheel-tread were used (the worn tread having travelled 150,000 km), on a rail-head cross section based on a new 60 kg rail. In order to avoid track irregularity influencing the passage through the curve in this simulation, stabilized values were used after convergence of transient responses generated by the vehicle going through the transition curve and which gradually disappear after entering the actual curve.

3.3 Analysis result

Figure 1 shows the wheel loads for Axles 1 and 2 on the outer rail: lateral force, longitudinal creep force, frictional energy, and rail-contact points. Frictional energy $T\gamma$ is defined by (1).

$$T\gamma = T_x \gamma_x + T_y \gamma_y$$

Where, $T_x$: longitudinal creep force, $\gamma_x$: longitudinal creep ratio, $T_y$: lateral creep force, $\gamma_y$: lateral creep ratio.

Figures 1(a) and 1(b) show that the wheel load and lateral force decrease on Axle 1 as the curve radius increases, whereas the same load and force increase for Axle 2. This therefore means that the lateral force on Axle 2 exceeds that exerted on Axle 1 on radii over 600 m. Figure 1(c) shows roughly the reverse situation for longitudinal creep force against the traveling direction, with values for Axle 1 exceeding those of Axle 2. $T\gamma$ of Axle 2 is smaller than that of Axle 1 as shown in Fig. 1(d), remaining lower than 15 J/

| Table 1 Analytical condition |
|-----------------------------|
| Condition | Curve radius R (m) | Cant C (mm) | Running speed (km/h) | Wheel profile |
|------------|-------------------|-------------|----------------------|---------------|
| Case1      | 800               | 95          | 105                  | New           |
| Case2      |                   |             |                      | Worn          |
| Case3      | 600               | 105         | 95                   | New           |
| Case4      |                   |             |                      | Worn          |
| Case5      | 500               | 100         | 85                   | New           |
| Case6      |                   |             |                      | Worn          |
| Case7      | 400               | 97          | 75                   | New           |
| Case8      |                   |             |                      | Worn          |
m in all cases. $T_γ$ for Axle 1 decreases as the curve radius rises. According to Fig. 1(e), the rail-contact point comes closer to the gauge corner on Axle 1 as the radius gets smaller. Comparison of Axles 1 and 2, reveals that the contact points on Axle 1 are closer to the gauge corner in all conditions.

3.4 Selection of wheelsets for rolling-contact FEM for wheels and rails

Comparison of analysis results for Axles 1 and 2 shows that the lateral force and wheel load are dominant in Axle 2 with larger radii. However, longitudinal creep force is closely linked with rolling-contact fatigue (RCF) and wear becomes dominant for Axle 1. In addition, the analytically derived wheel/rail contact point is closer to the crack locations actually observed on the rails for Axle 1 than for Axle 2. While $T_γ$ is commonly used in Europe as an assessment index for RCF and wear, reference [2] specifies a risk level of an area satisfying $T_γ < 15$ J/m as safe (no damage against RCF). As crack propagation is considered to be dominant under Axle 1 because $T_γ$ for Axle 2 is below 15 J/m in all conditions, the results for Axle 1 will be chosen for the rolling-contact FEM for wheels and rails.

4. Rolling-contact FEM analysis for wheels and rails

4.1 Analytical model

Figure 2 shows the outline of the analytical model. This model, comprising rails, wheels and an axle configuration, reproduces the conditions of a wheelset rolling along rails by intentionally displacing the axle center through rotational movement. The rail model is 120 mm long, and is in contact with the wheel only by solid elements (cube). It is sandwiched by beam elements to produce the length of 290 mm. In order to generate a fine representation of the details of the rail surface and the contact point, 1-mm mesh size is used for the rail in the traveling direction, 0.8 mm mesh size is used for the cross-sectional direction around the gauge corner and 1 mm mesh size for the rail head surface. In order to obtain precise calculations of the stress distribution inside the rail close to the surface layer, mesh size of 0.5 mm is used to a depth of 0 to 3 mm from the surface of the rail.
The 30-degree portion of the wheel in circumferential direction close to the rail-contact point is defined as solid elements (cube), and the other circumferential part is modeled by plural beam elements so as to form a geometry equal to that of the wheel cross-section. The solid-element block on the wheel tread is finely meshed in the same way as the rail surface, with 0.9 mm (circumferential direction) and 0.8 mm (cross-sectional direction). The axle is modeled by a beam element and is connected to the wheel with a rigid element. The brake disk is modeled by a mass model located at its gravitational center. To control the unsuspended mass within a certain value range, mass elements are attached to the both axles for fine adjustment. By exerting an axle-spring force in 3 directions that was obtained at the curve-passing simulation at a location corresponding to the axle bearing, it is possible to simulate the vehicle running under any kind set of track conditions. The relative location between the rail and wheelset is determined by rotating the model wheelset according to the angle of attack and also by moving it in parallel ensuring that the contact point between the outer rail and wheel coincides on the model.

In the calculation, the wheelset was made to make contact at a spot 37.5 mm away from the solid-element end of the rail; it then spent the first 0 to 1 second with a given spring force; then the wheelset was rotated around the axle and spent 1 to 2 seconds at 0.128 rad/sec. The time step for each rotation was 0.02 second.

4.2 Analysis results

The parameters affecting wear in this concurrence analysis of short crack propagation and wear are mainly the contact pressure between rails and wheels, and shear stress \( \tau_{yz} \) on the YZ plane inside the rail affecting the initiation and propagation of cracks. The data used as input to the concurrence model of short crack propagation and wear are the results of the analysis: one step at an instant. The result at 1.6 seconds where the wheelset almost reaches the center of the rail model is shown here.

Figure 3 shows maximum values of shear stress \( \tau_{yz} \) for new wheels (Cases 1, 3, 5, and 7) classified by depths from the rail surface. It shows that the rail surface gives the maximum of \( \tau_{yz} \). Figure 4 shows the shear stress \( \tau_{yz} \) at the surface layer of the outer rail in Case 2. It shows the maximum value of 296.8 MPa with a distribution width of 3.5 mm at a spot -21.9 mm from the rail surface center. Figure 5 shows the maximum values and their locations for appearance of \( \tau_{yz} \).

5. Concurrence analysis of short crack propagation and wear

5.1 Analytical program

An analytical program developed by RTRI, entitled “Concurrence model of short crack propagation and wear” was used for this part [1]. It simulates the propagation of 2D cracks in a cross section close to the rail surface (perpendicular to the sleeper direction) shown in Fig. 6. As well as crack propagation, it also simulates wear by gradually...
decreasing the rail-surface height, and also analyzes plastic deformation and work hardening by straining crystal grains. Crack initiation and plastic deformation are determined by (2) to (4) [3].

\[
\begin{align*}
\gamma_{i+1} &= \gamma_i + \Delta \gamma_i \\
\Delta \gamma_i &= C \left[ \frac{\tau_{\text{max}}}{{k_{\text{eff}}}} - 1 + \exp \left( -\frac{\tau_{\text{max}}}{{k_{\text{eff}}}} (1 + 0.439 \tau_{\text{max}}) \right) \right] \\
{k_{\text{eff}}} &= k_{\text{max}} (1, \beta \sqrt{1 - \tau_{\text{max}}^{2}}) 
\end{align*}
\]

Where \(\gamma\) is tangent of shear strain accumulated through wheel passages, \(C (= 2.37 \times 10^{-3})\) is constant. \(k_{\text{max}}\) (Pa) is initial shear-yielding stress defined by (5).

\[
k_{\text{max}} = 8.0 \times 10^4 H_a
\]

Where, \(H_a\) is Nano-indentation hardness (compressive load: 30 mN), with different values applied depending on material phases. \(\beta\) is also a material-dependent constant (pro-eutectoid ferrite: 1.48, pearlite: 1.5[4]), and \(\tau_{\text{max}}\): maximum value of orthogonally crossing shear stress within the cross section. \(\gamma_{cr}\) (critical value of \(\gamma\)) is taken here as 2.89 (\(= \tan (90^\circ - 19.08^\circ)\)), by applying the head checking angle as 19.08° (mean value) according to [5].

### 5.2 Analytical conditions

Assuming the steel materials used in the analysis, Table 2 shows the hardness levels of pro-eutectoid ferrite and pearlite. Materials A and B are intended for both pro-eutectoid ferrite and pearlite, and C, D, and E are only for pearlite. Assuming the bulk hardness of base materials to be determined from the volume ratio of pro-eutectoid ferrite and pearlite, the pearlite hardness is calculated by taking the pro-eutectoid ferrite as 100HV. Each of the Nano-indentation hardness is determined from each of the bulk hardness multiplied by 2.5 [4]. The abrasive amount of rails is defined from the onsite test result for commercial operations [6].

This analytical program, which runs multiple calculations that are randomly fed with crack origins and initial cross-sectional geometries of grain boundaries, may give differences in how the cracks propagate even if calculations are operated with same conditions and materials. It therefore may sometimes stop the calculation halfway before the crack reaches an expected level or may carry it over the calculation range. The system then sets a reasonable number of iterations, i.e. 100, that can control the medians of maximum crack lengths.

In order to quantitatively assess the analytical result by considering the cracks passing over the calculative range, the 50th length of a crack out of the 100 trials counted from the smallest result of the maximum crack length shall be used here as an assessment index for results calculated for each condition and materials phase.

### 5.3 Analytical results

As a result of crack-propagation analysis, cracks were initiated for all conditions and materials, and propagated beyond the analytical region (crack length over 2-3 mm). Figure 7 shows Case 2 as an example. The crack-propagation life elongates with steel hardness. The result plots once per 5,000 wheel passages and a jump over 0.2 mm per 5,000 plots is called here a radical crack. As cracks appear for all conditions and materials, this analytical result shall be studied by assessing the number of wheel-passages until this radial crack appears.

Figure 8 shows the frequency of wheel-passages until reaching radical cracks linked with curve radii of the track. It shows that worn wheels may delay radical cracking in all materials.

| Table 2 | Hardness of pro-eutectoid ferrite and pearlite for analytical steels |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Analytical steels | A | B | C | D | E |
| Bulk harness (HV) | 270 | 310 | 360 | 375 | 390 |
| Nano-indentation hardness | Pro-eutectoid ferrite | 250 | 250 | — | — | — |
| | Pearlite | 724 | 836 | 900 | 938 | 975 |
5.4 Discussion

The number of wheel-passages leading to radical cracking is below $10^5$ for all analytical conditions. Head checking is also observed after rails are replaced on commercial lines in service with a passing tonnage of 1 million ($10^5$ times with a 10-tonne wheel load) [7]. It is important, in the case of curves (such as curves with large radii) prone to head-checking, to quantitatively assess the factors affecting the propagation mechanism after radical cracking (horizontal fissure, flaking and resulting transverse defects).

Comparing the number of wheel passages underlying radical cracking with curve radii, shows that worn wheels delays radical cracking more significantly than new-wheels, particularly for curves with $R (=400 \text{ m})$. This is considered to be due to the difference in the shear stress being exerted.

In this analysis, radical cracks also appear on curves with $R (=400 \text{ m})$ although there may be variations depending on wheel-tread profile. Although the rail wear rate was varied intentionally to have the right analytical conditions, there was no significant difference in the number of wheel passages causing radical cracking. There may be various factors affecting the appearance of radical cracking. In conditions where wear progresses rapidly, such as on curves with $R (=400 \text{ m})$, deformation of the rail cross section may occur even with $10^5$ wheel passages. It may also cause a shift in wheel-rail contact point. It is possible that in the present analysis, the non-consideration of shift in wheel-rail contact point and variation in shear stress due to rail wear, although the wear rate on the analytical cross section is included, causes an underestimation in the number of wheel passages which will lead to radical cracking on sharp curves.

The order of wheel-passages until the initiation of radical cracks from the lowest to the highest is as follow: material A, B, C, D, and E in all analytical conditions. This is due to a decrease in cumulative shear strain as the materials hardened, as shown in equations (2) to (5), when the shear stress in action is the same. Radical cracking for Materials A and B (both were ferrite-pearlite composite) is comparatively faster than in the others. This is because cracks appeared at an early stage from the pro-eutectoid ferrite phase (soft structure), such as grain boundaries.

Materials C, D, and E (all are single-structured pearlite) are relatively slow in cracking because they do not contain a pro-eutectoid ferrite phase. Judging from this analytical result, materials of pearlite-single structured steel with higher bulk hardness could have longer crack initiation life. As this analysis uses a fixed value for strain hardening ratio $\beta$ and critical shear strain $\gamma_c$ for materials, however, there is a possibility of deriving different results when these values vary with materials. Considering that harder materials are said to exhibit lower ductility (small $\gamma_c$), the analysis may need compensation for materials with different cracking angles.

6. Conclusion

A rail surface fatigue assessment process considering head checking has been developed. The process consists of simulated passages through curves, rolling-contact FEM analysis of wheels and rails, and concurrence analysis of short crack propagation and wear. In order to compare and assess the differences in small crack initiation and propagation in steel materials used for rails using the simulation model used in this study, a concurrence analysis of short crack propagation and wear was carried out, taking into
consideration volume ratios and hardness of pro-eutectoid ferrite and pearlite.

As a result, the following two issues have become clear:

1. Crack initiation begins before 100 thousand wheel passages have been reached, which is significantly less than the number of wheel passages in the normal life span of a rail.
2. Relatively speaking, crack initiation occurs later (is delayed) in single-structured pearlite steel material with higher bulk hardness.

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