Evaluation of thermal stress analysis and fracture mechanics evaluation of wheel for high-speed train due to the failure of tread cleaner

S.J. Kwon, K. Ogawa, T. Shoji

Fracture Research Institute, Tohoku University, Japan.

Abstract

Safety of the wheels for high-speed train was investigated when the tread cleaner, which play a role in the increase of adhesion and the removal of dirt, is failed and stuck in wheel tread. The present study was performed on the basis of analyses of a combination of mechanical and thermal load due to the failure of tread cleaner during severe conditions. The finite element method was used to analyse the thermal stress between the tread cleaner and wheels. The critical crack sizes at the locations of wheel tread, plate and disc hole were calculated, and the safety factor in the critical locations of wheels was evaluated. The result shows that the behaviour of wheels during the failure of tread cleaner is similar to the temperature distribution of wheels under block braking applications and the maximum equivalent stress is in the disc hole location. In conclusion, the wheels due to the failure of tread cleaner can be occurred the severe situations and the sticking of tread cleaner with respect to wheel tread must be avoided if possible.

1 Introduction

The service conditions of railway vehicles have become severe due to increasing of the speed in recent years. Wheels and axles, the running unit and most important components in railway vehicles with regard to safety, are exposed to the several critical situations. The railway systems have to be absolutely safe and death rate of passenger must be zero. The high-speed train (Inter City Express, ICE) accident happened in Germany in Jun 1998, and resulted in the death of about 100 passengers. The cause of derailment accident was the wheel fracture [1].
As seen from the ICE accident, we cannot definitely state that a railway accident doesn’t happen. Fortunately, the accidents caused the fracture of wheel and axle for high-speed train have not occurred recently. The regular inspection has attributed the wheelset safety for high-speed train.

The studies on critical condition of wheel are focused on the effect of residual stress under braking application. Akama reported that the critical crack size of wheel by means of the residual stress and thermal stress analysis is calculated \[2\]. Ramanan emphasized in the thermo mechanical analysis using the wheelset model that the critical region is the tread and disc hole locations \[3\]. However, the study on the wheel for high-speed train with respect to a critical situation does not exist. Especially, the safety evaluation study of the failure of tread cleaner does not exist despite the possibility of accident.

The evaluation of the high-speed train wheel was carried out considering the worst scenario - the tread cleaner, which play a role in the increase of adhesion and the removal of dirt, is failed and stuck in wheel tread. The Figure 1 shows schematic diagram of the tread cleaner unit.

As seen from presented information, there is a need to consider the worst scenario involved in the analysis of the wheel in order to safety evaluation. The present paper address these issue such as the thermal stress analysis and the evaluation of fracture mechanics during the failure of tread cleaner.

![Figure 1: Schematic of tread cleaner unit for Shinkansen](image)

**2 Thermal stress analysis**

Finite element analysis of the wheel for the coupled forces was performed in two stages. At first the heat transfer problem were solved. The results of this analysis were stored as nodal temperature for a subsequent analysis. The second stage of the sequential analysis was to couple the nodal temperature derived from the heat transfer along with mechanical forces.

The assumed critical situation is the high-speed train running between Omiya and Morioka line (505 km) at speed 275 km/h, the tread cleaner is failed and stuck. The interval has a negative slope. The thermal stress analysis was carried out to evaluate safety of the wheel for high-speed train in the critical situation.
2.1 Heat transfer analysis

2.1.1 Finite element modeling and boundary conditions

Simulation of the wheel using finite element is 790 mm in diameter of worn wheel. Commercial finite element code ABAQUS was used for the analysis and PATRAN was used for modelling. The finite element models used in this study were predominantly solid 8-noded linear brick element. The thermo-mechanical properties as a function of temperature used in this material model are listed in Table 1 [2].

![Finite element modelling and boundary conditions for thermal stress](image)

**Figure 2: Finite element modelling and boundary conditions for thermal stress**

Table 1. Material properties as a function of temperature

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Density (kg/m³)</th>
<th>Young’s (GPa)</th>
<th>Poisson ratio</th>
<th>Thermal expansion (10⁻⁶/K)</th>
<th>Specific heat (J/kgK)</th>
<th>Thermal conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>273</td>
<td>7810</td>
<td>197.3</td>
<td>0.3</td>
<td>10.5</td>
<td>468.8</td>
<td>49.77</td>
</tr>
<tr>
<td>373</td>
<td>7810</td>
<td>187.7</td>
<td>0.3</td>
<td>11.7</td>
<td>506.5</td>
<td>48.14</td>
</tr>
<tr>
<td>573</td>
<td>7810</td>
<td>153.5</td>
<td>0.3</td>
<td>14.0</td>
<td>619.5</td>
<td>41.40</td>
</tr>
<tr>
<td>773</td>
<td>7810</td>
<td>106.8</td>
<td>0.3</td>
<td>15.5</td>
<td>682.3</td>
<td>35.12</td>
</tr>
<tr>
<td>973</td>
<td>7810</td>
<td>51.5</td>
<td>0.3</td>
<td>16.7</td>
<td>770.2</td>
<td>30.12</td>
</tr>
</tbody>
</table>

The heat transfer analysis of tread cleaner was performed for the critical situation - running speed of 275 km/h, sticking time of 7600 sec and clamping force of 490 N. A friction coefficient (\(\mu\)) of 0.30 was used for heat transfer analysis. The applied heat flux at the wheel tread caused by the failure of tread cleaner was calculated by the following equation.

\[
q = \mu \cdot F \cdot V \cdot \alpha \tag{1}
\]

In this equation, \(F\) is clamping force (N) and \(V\) is velocity (km/h). \(\alpha\) is the thermal efficiency, which is set at 0.7 since the value has been confirmed by an experiment to be appropriate. The simulation conditions of the service and critical conditions are applied on the heat transfer analysis as shown in Table 2. The
wheel boss nodes are fixed in axial and radial directions. The friction and clamping force are applied at the wheel tread as shown in Figure 2.

### Table 2. Simulation conditions in the service and critical conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Wheel</th>
<th>Tread Cleaner</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (mm)</td>
<td>V (km/h)</td>
<td>Area (m²)</td>
</tr>
<tr>
<td>Service</td>
<td>790</td>
<td>275</td>
</tr>
<tr>
<td>Critical</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All other surfaces of the wheel exposed to the atmosphere are considered with convective of heat transfer, except for symmetry boundary conditions in the 1-3 plane and tread surface. The heat convection coefficients as functions of the train speed are analytically calculated [4]. The radiation is not considered in this study (radiation must be taken into account only for temperature greater than 900°C) [5].

#### 2.1.2 Temperature distribution during service and critical condition

The temperature distribution during the service condition is shown in Figure 3 and the predicted maximum temperature is 68.9°C at the wheel tread. The predicted temperature in disc hole and boss region of wheel is in the range of 25-29°C.

The temperature distribution during the failure of tread cleaner resulting from heat transfer is shown in Figure 4. The maximum temperature occurs at the friction surface of wheel tread and is 292°C. The temperature at disc hole region is in the range of 142-149°C. It is observed that the behaviour of wheels due to the failure of tread cleaner is similar to the temperature distribution of wheels under block braking applications at 100 km/h [6]. As can be seen from Figure 5, the temperature distribution of tread region during service condition is in the range of 60-70°C.

![Figure 3: The distribution of temperature during service condition](image-url)
Figure 4: The distribution of temperature during critical condition

Figure 5: The distribution of temperature in wheel tread

Figure 6: Maximum principal stress during critical condition due to thermal load
2.2 Coupled mechanical force analysis

2.2.1 Finite element modeling and boundary conditions

Actually, the passenger and payload cause the vertical force acting on the wheel. The horizontal force acting on the wheel is caused by the irregularities in the level of track [3]. The vertical and horizontal force, which measured in field test, are applied at the flange and center of wheel tread as shown in Figure 2. The nodes of wheel boss are fixed in radial and axial directions. The symmetry boundary conditions are applied in the 1-3 planes in order to consider both (full model).

2.2.2 Distribution of maximum and minimum principal stress

The results of thermal stress analysis due to the effect of thermal loads in the critical condition are shown in Figure 6. The maximum principal stress occurred in disc hole region and is 438 MPa. The results of coupled mechanical analysis on the service condition are shown in Figures 7 and 8. The results show that the maximum principal stress is in disc hole region and is 20.2 MPa.

Figure 7: Maximum principal stress during service condition

Figure 8: Minimum principal stress during service condition
The maximum and minimum principal stress contours of the wheel model due to coupled mechanical forces during the critical condition are shown in Figures 9 and 10. The results show that the maximum principal stress is in tread region (843 MPa). This value approaches the yield strength of 869.2 MPa.

![Figure 9: Maximum principal stress during critical condition](image1)

![Figure 10: Minimum principal stress during critical condition](image2)

It can be observed from the result that the maximum principal stresses in the tread region, near the tread center are in the range 790-850 MPa. The maximum principal stresses of the disc hole are in the range 390-430 MPa. The overall stress values in the other regions of the wheel are found to be around 110 MPa. The stress at the tread and disc hole region is found to be very high compare to results of principal stress during service condition.
3 Evaluation of fracture mechanics

3.1 Critical crack size

The critical crack size of wheel due to the thermo mechanical analysis is evaluated and calculated with respect to the tread and disc hole region. The Newman-Raju equation is used [7]. The fracture toughness ($K_{IC}$) of wheel has been confirmed by an experiment (ASTM E399). It depends on the locations of wheel. The tangential and radial stress derived from FEM results are applied to the calculation of critical crack size in tread and disc hole region. The calculation conditions of critical crack size are shown Tables 3 and 4.

<table>
<thead>
<tr>
<th>Region</th>
<th>Tangential Stress ($\sigma_t$, MPa)</th>
<th>Width W (mm)</th>
<th>Thickness t (mm)</th>
<th>$K_{IC}$ (MPa m$^{0.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tread</td>
<td>92.5</td>
<td>62.5</td>
<td>25.0</td>
<td>70.40</td>
</tr>
</tbody>
</table>

Table 3. The calculation conditions of critical crack size in tread region

![Diagram of critical crack size calculation](image)

Figure 11: The critical crack size of tread region

The calculation results of critical crack size with respect to the aspect ratio ($a/c$) are shown from Figures 11 and 12. As can be seen Figures 11 and 12, the critical crack size existed at aspect ratio 0.2. Resolutely, the critical crack depth of tread region is 15 mm and crack length (2c) is 75 mm and in case of disc hole region, crack depth is 0.65 mm and crack length (c) is 3.25 mm.

<table>
<thead>
<tr>
<th>Region</th>
<th>Radial Stress ($\sigma_r$, MPa)</th>
<th>Radius of hole R (mm)</th>
<th>Thickness t (mm)</th>
<th>Width B (mm)</th>
<th>$K_{IC}$ (MPa m$^{0.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc</td>
<td>429.5</td>
<td>13.5</td>
<td>26.0</td>
<td>40</td>
<td>59.79</td>
</tr>
</tbody>
</table>

Table 4. The calculation conditions of critical crack size in disc hole region
3.2 Safety factor

By supposing that the limit condition is reached by proportionately increasing both the mean stress and stress range, the safety coefficient is given by

$$\eta = \frac{1}{\frac{\sigma_a}{\sigma_w} + \frac{\sigma_m}{4\sigma_w}}$$

where, $\sigma_m$ is mean stress and $\sigma_a$ is stress range. $\sigma_w$ is fatigue strength (156.9 MPa). The value of safety factor during the service condition shown above give $\eta = 3.2$, a very high value that easily guarantees resistance to fatigue, due to the effect of the high average compressive stress. However, the safety factor during critical condition such as the failure of tread cleaner is lower than during service condition. The safety factors of tread, plate and disc hole region are from 1.7 to 2.3. This means that the preceding the failure of tread cleaner drastically reduced the fatigue resistance of the component due to the effect of the thermal stress.

4 Conclusions

The present study was performed on the basis combined of analyses of mechanical and thermal load caused by the failure of tread cleaner during critical conditions. The following conclusions can be obtained:

1) When the tread cleaner of the high-speed train wheel fails at 275 km/h, the distribution of temperature is similar to that of wheel under block braking application at 100 km/h.

2) The maximum temperature of wheel due to the failure of tread cleaner is 292 °C and the maximum equivalent stress is at the disc hole location. However,
in case of coupled mechanical analysis, the critical values exist at the wheel tread and disc hole region.

3) In case of the failure of tread cleaner at 275 km/h, the safety factor of wheel for high-speed is sustained from 1.7 to 2.3 and the sticking of tread cleaner with respect to wheel tread must be avoided if possible.

Acknowledgements

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References