

## Safety Margin Evaluation of Railway wheel Based on Fracture Scenarios

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### Abstract

Derailment due to wheel failure would cause a tremendous social and economical cost in service operation. It is necessary to evaluate quantitatively the safety with respect to high-speed train. Although the safety of railway wheel has been ensured by an regular inspection, all critical defects cannot be detected in inspection cycles and the wheel has been replaced because a defect quickly become critical for safety. Therefore, it is important to calculate quantitatively the fracture limit and remnant life of damaged railway wheel in wheel-rail system. In present paper, the critical crack size of wheel for high-speed train is simulated based on fracture scenario and the safety of wheel is evaluated.

**Keywords :** Wheel, Safety evaluation, Critical crack size, Remnant life

### 1. Introduction

Recently, the operating conditions of railway vehicle get more severe. The fatigue damage is initiated due to impact load and durability decrease by deterioration because the wheel and rail have operated under complex loads and environments. The damage at the wheel - rail system is generated in the interface area of a wheel/rail by the rolling contact fatigue and this is embossed as the important environmental problem. Moreover, the damage occurs in the wheel surface by the cooling and heating of the friction heat at brake application. Fig. 1 shows the damage case generated in the wheel tread.

It is necessary to evaluate quantitatively safety of railway wheel because the derailment due to malfunction of wheel-rail system in highly speed operation have produced enormous economical and social cost. In case the crack generated by brake application, thermal stress of a wheel and rail or the rolling contact fatigue develops, it is guaranteed the safety of wheel by the regular inspection but all defects cannot completely detect the regular nonde-

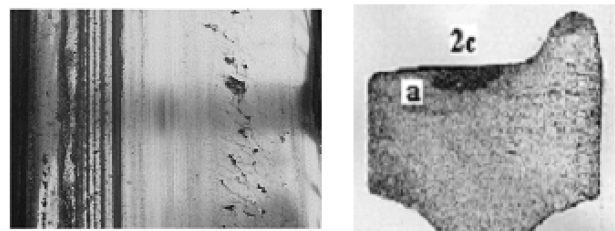


Fig. 1 Damages of railway wheel

structive inspection. Therefore, it is necessary to evaluate the fracture limit with respect to crack initiation and remnant life at crack propagation in wheel-rail system

R.A. Smith *et al.* [1]. had performed the examination of remnant life using the fracture mechanics with respect to the railway axle and S. Cantini *et al.* [2]. had utilized as fatigue design data of wheel and axle in consideration of the fracture mechanics test. Also, F.Bumbieler *et al.* [3]. had studied for the inspection interval of the wheel according to the crack propagation.

In the present paper, the critical crack size of wheel for high-speed train based on fracture scenario was simulated and the safety of the wheel was evaluated.

### 2. Simulation conditions

#### 2.1 evaluation model and assumption condition

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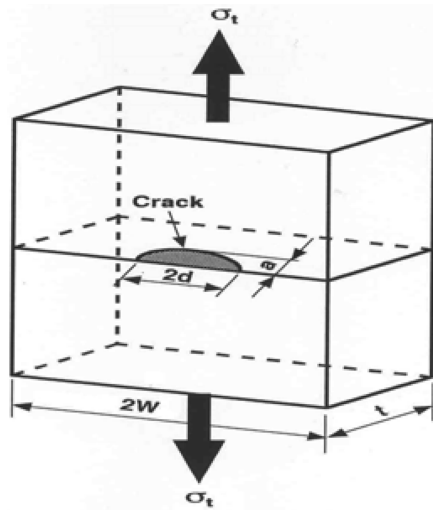


Fig. 2 Crack model for simulation

Table 1. Conditions of Simulation

Wheel width (W, mm)	Wheel thickness (t, mm)	C (mm/cycles)	m	$K_{IC}(\text{MPa m}^{0.5})$	
				R. T	-20°C
135	60	$1.513 \times 10^{-11}$	3.69	82	66

It is necessary to the estimation model which is proper for the safety assessment by the damage scenario is assumed. According to the damage cases of the wheel for the high-speed train and conventional line, the crack is propagated from the direction of the wheel rim to the direction of wheel boss. The calculation condition assumed crack geometry of semi-ellipse at wheel surface. However, the shape of a wheel was not simple, it is difficult to simulate the critical crack size and remnant life using the distribution of stresses of a wheel under dynamic load condition and assumed the model such as Fig. 2.

The aspect ratio of crack model of semi-ellipse is 0.4 at center of wheel surface. The width and the thickness of wheel for high-speed train are 135 mm and 60 mm respectively. The stress ratio (the minimum stress is the zero) is 1 and Newman-Raju equation is used to the calculation of the stress intensity factor. The condition of numerical simulation is enumerated in the Table 1.

## 2.2 variable parameters

### (1) Material characteristic

The fracture toughness at the room and low temperature was performed with respect to the wheel for the high speed according to ASME 399 [4]. The fracture toughness at room temperature is  $82\sqrt{\text{MPa}\cdot\text{m}}$  and  $66\sqrt{\text{MPa}\cdot\text{m}}$  at

-20°C. The predicted fracture toughness at high temperature test is  $152\sqrt{\text{MPa}\cdot\text{m}}$ . The fracture toughness of upper and lower limit is used to this simulation.

### (2) Fatigue crack growth

The fatigue crack growth rate was obtained at the wheel specimen for the high-speed train according to ASME 647 [4].

The exponent (m) fixed by 3.69 which is actually measured in the wheel material. The size of the load, a direction, and the strain of wheel from the rail at brake application, acceleration, and the curve running is complexly changed. Moreover, the heating of brake application and the thermal stress at the cooling process become the important stress source.

### (3) Cyclic stress

The wheel load and lateral force are measured in the wheel. In this case, 100 MPa was added and the acting stress was diversified into 200 MPa and 300 MPa and the safety evaluation was performed about the size of the critical crack and affected of the remnant life.

### (4) Ultimate maximum load

In case of the yield stress at the room temperature of the wheel for the high speed was 540 MPa but the near to this stress of 550 MPa applied, the remnant life of the wheel is calculated. That is, as shown in Fig. 1, we can look at over the damage scenario in which the wheel tread heats rapidly due to the abnormal operation of the brake block and which accompanies a quenched. In this case, the crack growth rate of this suddenly applied load did not consider in this numerical calculation.

### (5) Initial flaw size

The crack size assumed to the flaw depth 10 mm  $\times$  length 20 mm, 5 mm  $\times$  10 mm, and 2 mm  $\times$  10 mm. The initial flaw size was deeply diversified into the basis as the influence factor about the completeness check with 1 mm  $\times$  2 mm. This tries to know if it is to some extent have an effect on the assurance operation period, in case of the minimum defect dimension in which it can clearly detect crack.

## 2.3 equation of Newman-Raju

The equation of the evaluation model which uses in this study for the safety assessment is as follows [5].

where, the tensile stress is  $s$  [MPa], the semi-ellipse surface crack length is  $a$  (mm), the wheel thickness is  $t$  [mm], and a wheel width indicate  $2W$ .

$$K_I = \sigma_t F \sqrt{\frac{\pi a}{Q}}$$

$$Q = 1 + 1.464 A_d^{1.65}, F = [M_1 + M_2 A_t^2 + M_3 A_t^4] f_\phi g f_w$$

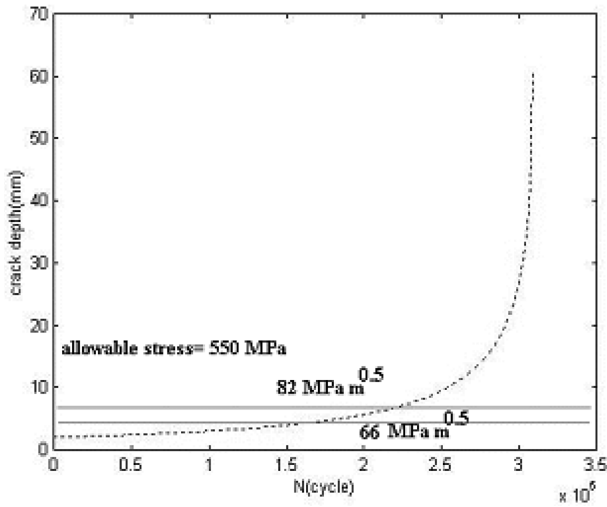


Fig. 3 influence of fracture toughness

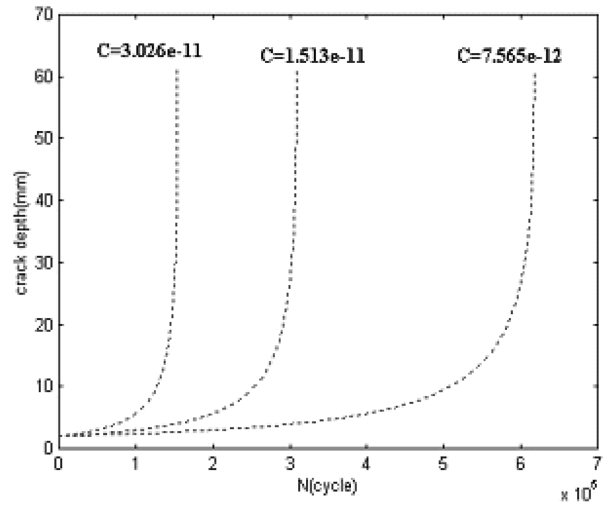


Fig. 4 influence of fatigue crack growth rate

### 3. Safety Evaluation of Wheel

#### 3.1 influence of fracture toughness

Fig. 3 shows the shape of the crack growth (depth) as the function of the repeat cycles. The simulation is applied to the repeated stress amplitude of 100 MPa, the initial crack depth of 2 mm, and the Paris law  $C$  of  $1.513 \times 10^{-11}$  mm/cycles. Because the crack growth rate did not consider the material dependability, the critical crack depth in which it reaches the unstable fracture depends on the fracture toughness of a material and it increases or decreases. Particularly, in case of assuming that the large-scale stress applies, a lifetime is decreased at (here, 550 MPa) in the material in which the fracture toughness is low. Moreover, it is required to the small critical crack is not detected in the routine inspection because the critical crack dimension transferred to the unstable fracture is small in case the fracture toughness is small, in addition authentically detect.

#### 3.2 influence of fatigue crack growth rate

The fatigue crack growth rate changes the coefficient  $C$  of the Paris law data with respect to the wheel for the high speed in the room temperature into the basis in  $1.513 \times 10^{-11}$  as the range of 1/2~2 times. Fig. 4 shows the influence of the crack growth rate. The number cycles reaching fracture is varied to range of 1/2~2 times and the characteristic of fatigue crack growth rate indicates the significance of the thing. It is necessary to characteristic of fatigue crack growth rate that is statistically evaluated by the deviation of the characteristic according to the object difference between a wheel and a site considering. Moreover, an investigation is needed for the aging effect of characteristic of fatigue crack growth rate.

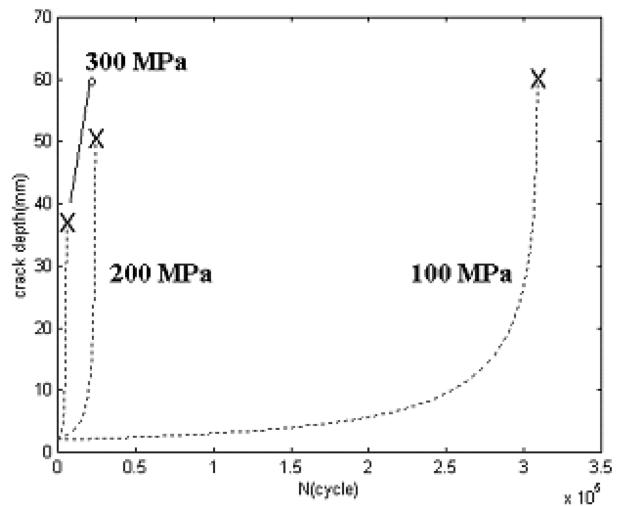


Fig. 5 influence of cyclic stress

#### 3.3 influence of cyclic stress

The monotonic tension stress was assumed and as shown in Fig. 5, in case of the repeated stress of 100 MPa, 200 MPa and 300 MPa, the crack growth rate was compared. The affect of the lifetime of the repeated stress to be very large and a lifetime is more and more decreased depending on range of 100 MPa~300 MPa. As a result of this, it shows that the quantitative evaluation of the repeated stress under the dynamic load is the most important research field. However, the load amplitude under the dynamic load is not simple. The existing knowledge which is the prediction of crack growth rate under the random stress wave is very little. Therefore, the establishment of evaluation method for the crack growth rate based model of dynamic load is very important.

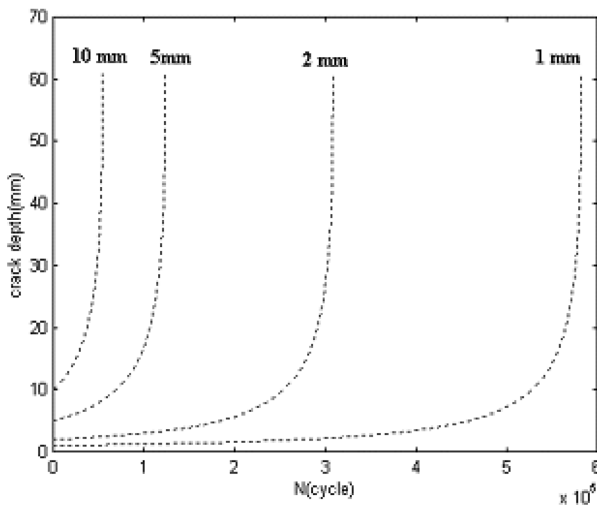


Fig. 6 influence of initial flaw size

### 3.4 influence of initial flaw size

Fig. 6 shows the change of the remnant life depending on variation of initial crack depth of 1 mm~10 mm. The guarantee of remnant life due to the improved detection limit (10 mm to 1 mm) can be increased. The warranty life is different even if the detection limit compares the case of 2 mm and 1 mm. It means that inspection interval can be remarkably extended due to the precision of the defect inspection method.

Particularly, the life of railway vehicle with sensitivity NDT technique which can directly observed at internal defect of wheel and press fitted axle is extended.

### 3.5 critical flaw size

Fig. 7 and Fig. 8 show the critical crack depth of wheel for the high speed depending on the applied stress. When the stress of 100 MPa applied, the crack depth of 34 mm in fracture toughness of  $82\sqrt{\text{MPa}\cdot\text{m}}$  can be occurred the wheel fracture. The damage of the wheel occurs if the crack depth reaches 29 mm under low temperature. In other words, it has the critical point of wheel if it reaches up to 1 / 2 of the wheel rim.

However, in case of the ultimate load application, the critical crack depth depending on the fracture toughness of the room temperature reaches to 7 mm and the fracture of wheel for high-speed train has occurred less than crack depth of 10 mm. Therefore, it should perform in the fatigue design of the wheel in consideration of fracture toughness at low temperature with damage tolerance design.

### 3.6 safety margin

The safety margin can express as the  $K_{IC} / K$  or the  $a_{cr}/a$ .

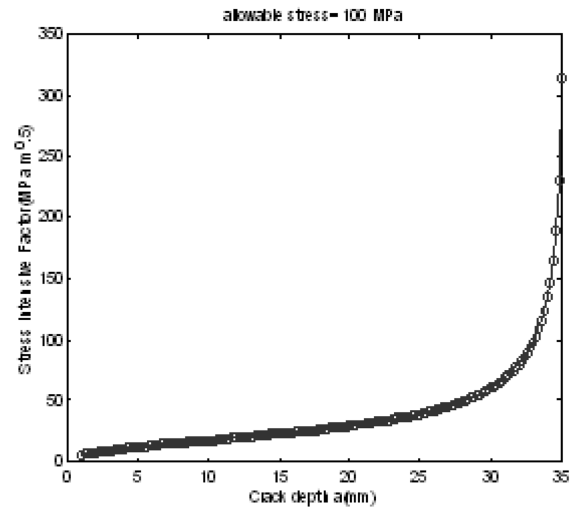


Fig. 7 critical flaw size (100 MPa)

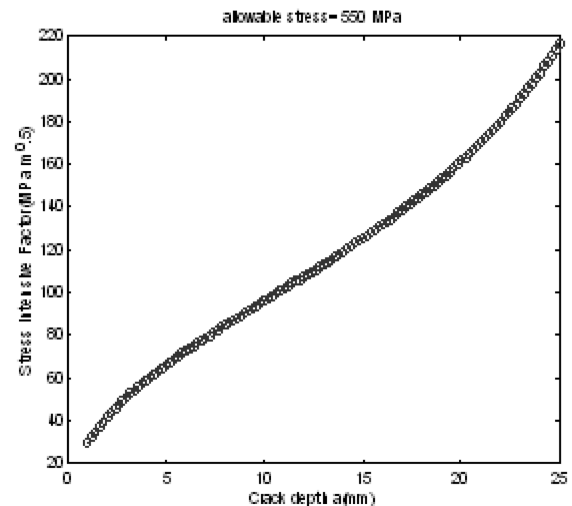


Fig. 8 critical flaw size (550 MPa)

The safety margin of the wheel at the critical condition can calculate with the next formula in case wheel defect and failure detection limit assume to 2 mm.

The stress intensity factor at the wheel tread is  $41.5\sqrt{\text{MPa}\cdot\text{m}}$  if the ultimate load 550 MPa is applied. The safety margin of a wheel was 1.98 and the safety margin was calculated as 1.59 in the low temperature. Generally, the safety margin of a wheel is 2.0 or greater. The safety margin is 2.0 in the condition that the ultimate load acts but the safety margin is reduced and the brittle fracture condition of a wheel by the maximum load can be formed in the low temperature condition that the fracture toughness is decreased. Therefore, the design review about the cold brittleness damage is needed.

#### **4. Conclusion**

By using the numerical model, the fracture mechanics safety of the wheel for the high speed based on the damage scenario is evaluated. Then, a lifetime of fracture is  $3 \times 10^5$  cycles in the initial flaw size of 2 mm and the critical crack depth is 30 mm. However, the fatigue design has to be performed in consideration of the characteristic with respect to the cold brittleness and excessive load. It is important to ensure the reliability of railway wheel related to study of material characteristics, dynamics load and NDT.

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