Thermal Fatigue Analysis and Evaluation of Wheel-Rail Contact under Braking Conditions

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ABSTRACT

Recently, reliability design considering the fatigue has been demanded for ensuring the driving safety for the high speed railway. In particular, the railway wheel and rail are subjected not only to mechanical load but also to high thermal load due to frictional heat generated when the railway wheel contacts with the brake shoe during tread braking. As repetitive thermal load accelerates damage to the wheel surface, it leads to shorten the replacement cycle and increase the maintenance cost. Therefore, we expect to achieve the economic efficiency by using the wheel over the life expectancy while maintaining the structural health. Initial braking velocity is one of the main factors affecting the behaviors of contact surface between the wheel and rail. Therefore, it is necessary to evaluate the effect of thermal stress according to it. In this study, through the thermal-mechanical analysis considering both mechanical load and thermal load caused frictional heat under braking conditions, thermal stress subjected to the contact surface between the railway wheel and rail was calculated. Based on these results, the thermal fatigue analysis was carried out to evaluate the safety under fatigue and predict the fatigue life.

1. INTRODUCTION

Recently, reliability design considering fatigue is further required to secure driving safety due to the high speed of railway. Under braking conditions, the wheel and rail are subjected to high thermal load due to friction as well as mechanical load. Repeated thermal loads reduce the replacement cycle and increase maintenance cost. The initial braking speed is one of the main factors affecting the contact surface behaviors between the wheel and the rail, so it is necessary to evaluate the effect of the thermal stress based on the initial braking speed.

Also, considerable pressure is generated on the wheel and it makes that the fatigue is the main damage mechanism in the wheel subjected to repetitive high load. Therefore, evaluating the fatigue strength of the wheel is important for the safety aspects of the vehicle.

Many studies have been carried out to evaluate the damage and fatigue of the wheel based on the finite element analysis results. Ahn, You, Kwon, and Kim (2012) calculated the stress distribution between the wheel and the rail considering the vertical load for the weight of the vehicle and the horizontal load for friction. Based on the results, fatigue crack initiation life was evaluated using the strain-life method and the S-W-T method, but the effect on thermal stress was not considered. Peng and Jones (2012) carried out the FEM analysis considering both cyclic mechanical load and thermal load and predicted the crack growth of the rail wheel. Haidari and Hosseini-Tehrani (2014) performed thermo-mechanical stress analysis using FEM model including brake as well as wheel and rail and evaluated fatigue life using the Socie-Fatemi model.

In this paper, the thermal-mechanical analysi considering both mechanical load and thermal load generated on the wheel by the friction was performed when the cases of initial braking speed are 80km/h and 120km/h during tread braking. From these results, the stress generated on the contact surface of wheel and the temperature value were derived depending on the initial braking speed. Using this stress data, fatigue analysis was performed by applying the Smith-Watson-Topper (SWT) method, which is used for fatigue life prediction in multiaxial stress state and the fatigue initiation life was estimated considering thermal stress.

2. THERMAL-MECHANICAL STRESS ANALYSIS

2.1. Analysis Model and Material Properties

To calculate the thermal stress occurring on the railway wheel, the thermal-mechanical analysis was carried out using a commercial finite element program ABAQUS 6.12. The KTX powertrain wheel of 920mm diameter and the UIC60 rail model were used for analysis, and Figure 1 shows the finite element model of the rails and wheel. The contact region between the wheel and the rail was divided into the dense elements and the other regions were largely divided. The number of elements and nodes were 42,760 and 45,000 for the wheel, 23,553 and 27,488 for the rails respectively. The element types were composed of C3D8T which is a 3D hexahedral element, and C3D6T which is a 3D triangular prism element, used for thermal-mechanical analysis.

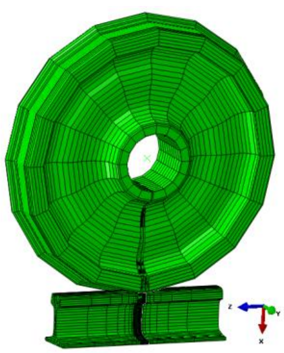

Figure 1. FE model of the wheel and rail

The contact condition between the wheel and the rail was set as the contact pair with the wheel contact face as the master and the rail contact face as the slave, and the friction coefficient of the contact face was 0.25. The wheel and rail are made of the same steel material, and the mechanical and thermal properties of it are shown in Table 1 (Sung, Yang, Cho & Chung, 2001).

2.2. Analysis Method

The thermal-mechanical analysis was carried out with three steps in the tread braking condition. Both ends of the rail were fully fixed for all steps and the gravity condition was applied to consider the weight of the whole model. In step 1, the wheel is moved 1 mm in the x-direction, so the wheel and the rail can contact each other. At this time, the press-in portion of the wheel is constrained for the multi-point constraint (MPC) condition to prevent rotation of the wheel.

Table 1. Mechanical and thermal material properties

Temperature T [°C]	23.3	100	200	300	400
Density ρ [kg/m^3]	7860	7820	7790	7750	7720
Young's modulus E [GPa]	206	202	196	188	180
Poisson's ratio ν	0.3	0.3	0.3	0.3	0.3
Coefficient of thermal expansion α [10^{-5}/°C]	1.06	1.13	1.19	1.26	1.32
Specific heat C_p [J/(kg·°C)]	434	473	512	552	591
Thermal conductivity K [W/(m·°C)]	48.3	46.4	44.6	42.7	40.8

In step 2, considering the situation that the vertical force is applied to the wheel by the axle, a vertical load of 85kN is imposed to the press-in portion of the wheel while the wheel and the rail are in contact. In Step 3, the heat load generated by the frictional heat between the wheel and brake shoe is applied to the wheel. The heat load is imposed to the wheel frictional surface by surface heat flux condition.

The fraction of the heat transferred to wheel, β is calculated as 76.7% by Eq. (1). The heat flux, q is calculated using Eq. (2) (Joo, Kwon, & Kim, 2009).

$$\beta = 1/(1+\frac{\sqrt{k_2\rho_2 C_{p2}}}{\sqrt{k_1\rho_1 C_{p1}}}) \tag{1}$$

$$q = \frac{\beta\mu P u}{A} \tag{2}$$

In Eq. (1), subscripts 1 and 2 are the symbols for wheel and brake shoe, respectively. The pressure force, P is set to 16.6 kN, the average friction coefficient, μ to 0.25 and the contact area between the wheel and the brake shoe, A to 25000 mm^2. The braking speed of the railway, u decelerates at 1.0m/s per second and 0 in 22s or 1.1m/s per second and 0 in 30s, when the initial braking speed is 80km/h and 120km/h respectively. The heat flux calculated from these conditions is applied to the wheel surface as shown in Figure 2.

2.3. Analysis Result

In the result of the thermal-mechanical analysis, the maximum stress is occurred at the contact surface of the wheel. At the initial braking speed as 80km/h and 120km/h, the maximum von Mises stress is 543.69MPa and 772.16MPa, and the maximum temperature is 215.26°C and 368.58°C respectively. Figure 3 and Figure 4 show that the von Mises stress and temperature are changed over time in

Step 3. Especially, the thermal stress at 120 km/h is increased by 42.02% over 80 km/h.

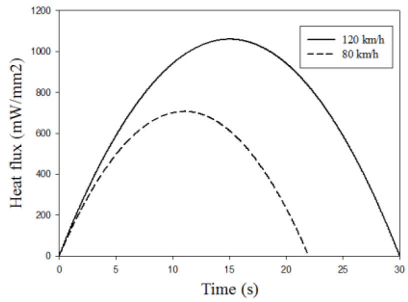

Figure 2. Calculated heat flux

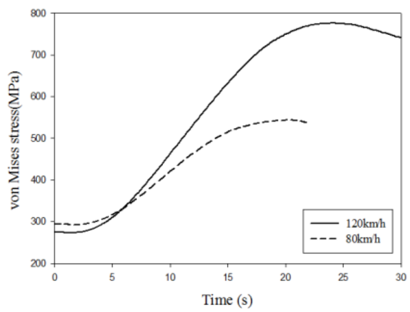

Figure 3. von Mises stress of thermal stress analysis

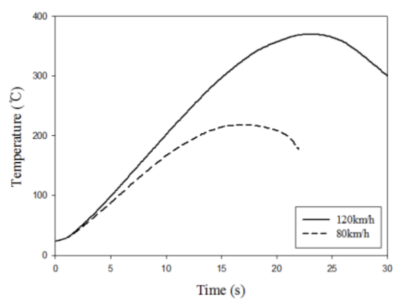

Figure 4. Temperature of thermal stress analysis

3. THERMAL FATIGUE ANALYSIS

3.1. Method of analysis

In predicting the fatigue life of the wheel, it is necessary to consider the effect of the thermal load since the thermal load generated under tread braking condition considerably affects to initiation and propagation of the wheel surface cracks (Ekberg & Kabo, 2005). The fatigue analysis using the stress and strain responses of the thermal-mechanical analysis was carried out only for an initial braking speed of 120 km/h, which showed a larger maximum von Mises stress.

To predict the fatigue crack life of the wheel, Smith-Watson-Topper (SWT) model is used (Ahn et al. 2012). It is known as appropriate to predict the fatigue life in the multiaxial stress state and defined as Eq. (3).

$$\frac{\Delta\varepsilon}{2}\sigma_{\max} = \frac{(\sigma'_f)^2}{E}(2N_f)^{2b} + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \qquad (3)$$

The strain range for the cycle $\Delta\varepsilon$ and the maximum stress in the cycle σ_{max} are obtained from result of the thermal-mechanical analysis and the remaining fatigue properties are used for R7T which is mainly used for high-speed railway material (Haidari & Hosseini-Tehrani, 2014; Štamborská, Mareš, Kvíčala, & Horsák, 2014). This is shown in Table 2.

As a result of the fatigue test carried out at room temperature and at 300 ° C, it was found that the slope of the S-N curve and fatigue limit of them are almost similar (Kim, Goo & Suk, 2007). Therefore, the change of fatigue properties with temperature is not considered.

3.2. Analysis Result

As a result of the fatigue analysis, surface crack initiation under braking condition is predicted to occur at 118,231 cycles of braking. Damage is calculated as $1/N_f$ and it means that the fatigue fracture is occurs when the damage value is 1. In this analysis, the maximum damage is 8.458e^{-6}, so 0.846% of damage occurs every 1000 brakes

Table 2. Fatigue properties of the R7T.

Strain hardening coefficient, K' [MPa]	1081.7
Strain hardening exponent, n'	0.222
Fatigue strength coefficient, σ'_f [MPa]	1375
Fatigue ductility coefficient, ε'_f	0.7197
Fatigue strength exponent, b	-0.1062
Fatigue ductility exponent, c	-0.5975

4. CONCLUSION

In this study, to predict the fatigue life of the wheel while the thermal stress was repeatedly applied on the wheel, the thermal-mechanical analysis considering both the mechanical load and thermal load was carried out. Also based on this result, thermal fatigue analysis was carried out using S-W-T model. The follows are obtained from this study.

1. As a result of the thermal-mechanical analysis, von Mises stress and temperature distributions are obtained for the two cases of initial braking speeds of 80 km/h and 120 km/h. The maximum von Mises stress is 543.69MPa, 772.16MPa and the maximum temperature is 215.26°C, 368.58°C at the initial braking speed as 80km/h, 120km/h respectively. The maximum value is occurred at the contact surface of the wheel. Therefore, the initiation of surface crack can be highly influenced by the thermal load.

2. When the initial braking speed is 120km/h, the thermal stress is 42.02% higher than that of 80km/h. As the initial braking speed increases, the thermal stress increases sharply, so more attention is needed.
3. To evaluate the fatigue crack initiation life considering thermal load under tread braking condition, the S-W-T model was used. The fatigue fracture occurs at 118,231 cycles of braking and 0.846% of damage occurs every 1000 braking.

Because the thermal load generated at the contact surface between the rail and the wheel during tread braking has a considerable effect on the fatigue crack, accurate estimation of fatigue life requires precise calculation of the thermal load.

ACKNOWLEDGEMENT

This research was supported by Korea Railroad Research Institute (KRRI) (Optimization of Web Shape for Reducing Thermal Stress in High Speed Railway Wheel: 2016-11-0776)

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BIOGRAPHIES

Soyoung Lee received B.S. with a double major in Astronomy and Mechanical Engineering at Yonsei University, Korea in 2016. She is a Master student in Mechanical Engineering at Yonsei University. Her research interests include the field of thermal-mechanical analysis using finite element method and aeroacoustics.

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