Effect of Tread Scratch on Fatigue Life of Wheels in High-speed EMU under Low Temperature Servicing Condition

Song Hao¹, Zhao Deming², Hu Ming³, Yang Liuqing⁴, Zhou Xun⁵, Qin Yudong⁶, Chen Wenhua⁷, Zhao Yongxiang²

¹ National and Local Joint Engineering Research Center of Reliability Analysis and Testing for Mechanical and Electrical Products, Zhejiang Sci-Tech University, Hangzhou 310018, China; ² State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China;

¹921474165@qq.com, ²miancer@163.com, ³huming@zstu.edu.cn, ⁴409709426@qq.com, ⁵5048338@qq.com, ⁶602089581@qq.com, ⁷chenwh@zstu.edu.cn, ⁸yxzhao@home.swjtu.edu.cn

Abstract. In order to study the influence of scratches on the fatigue life of CRH5 EMU wheels under -40°C servicing condition, a dynamic model of the vehicle-rail system is established along with the contact model of the scratched wheels. Considering the irregular and typical working condition of the railway line, a random load spectrum and a cyclical wheel-rail impact load spectrum are obtained. The S-N characteristic of the wheel material is obtained according to a series of fatigue test in serving environment -40°C. Using the finite element quasi-static superposition method, the fatigue life of the wheels with and without scratch are compared, and then the fatigue life of the scratched wheel is evaluated. The results show when the scratch length \( L_R \leq 20 \) mm, the fatigue life of the scratched wheel is less affected by the wheel-rail impact caused by scratch; when the scratch length \( L_R > 20 \) mm, the fatigue life decrease quickly, less than 1e6km, affecting the safety of the EMU.

1. Introduction

Impact fatigue is one of the important causes of fatigue failure of mechanical components under impact load, and it is commonly found in strong impact cases [1, 2]. A strong wheel-rail impact that caused by the wheel tread scratch can cause EMU wheels impact fatigue damage, reducing EMU train safety [3, 4]. Wheel tread scratch usually generates during the EMU emergency braking or acceleration. Most of the existing researches are focused on the fatigue and fracture of the EMU’s Components under ordinary temperature. The lowest servicing temperature for the Harbin-Dalian Line opened in China is around -40 °C, and the train wheels in the low-temperature environment are tend to produce tread scratch.

2. Load spectrum and material properties

2.1. Wheel-rail random load spectrum

According to the basic parameters of the CRH5 EMUs, the high interference spectrum in the German orbit spectrum is selected as the simulated orbit spectrum. Due to the extremely complicated road
conditions of the Harbin-Dalian line, it is impossible to analyze all line conditions. Therefore, typical operating conditions are selected for calculation. The conditions are shown in table 1.

| Condition | Curve radius (m) | Transition (m) | Straight (m) | Running speed (km/h) | Superelevation (mm) | Deficient superelevation (mm) | Time(s) |
|-----------|-----------------|----------------|-------------|----------------------|---------------------|-------------------------------|---------|
| Straight  | 1               | 2              | 200         |                      | 180                 | 80                           | 20      |
| Curve     | 2               | 8000           | 680         | 250                  | 190                 | 82                           | 20      |
| Curve     | 3               | 5500           | 570         | 210                  | 180                 | 82                           | 20      |
| Curve     | 4               | 2000           | 320         | 120                  | 160                 | 82                           | 20      |

Applying the above model, the random loading time history of the non-scratch wheels under various typical operating conditions is obtained. The lateral force is much smaller than the vertical force, and the influence can be neglected.

2.2. Wheel-rail impact load spectrum
Due to the random disturbance of the rail and other factors, the wheel-rail impact produced may be slightly different for each revolution. In order to simplify the calculation, it is assumed that the wheel-rail impact produced by the scratched wheel is exactly the same in every revolution. The dynamic model of the vehicle-rail system is established, the wheel tread scratch is simulated by the variable wheel diameter method. The wheel scratch length should be controlled within 32 mm [5]. Therefore, the wheels with different scraping length (10mm, 20mm, 30mm and 32mm) are respectively simulated and analyzed. Then the impact loading time histories of each wheel under four typical working conditions are obtained. As shown in figure 1.

![Figure 1](image_url)

**Figure 1.** Vertical impact force time history curve of four conditions
As can be seen from figure 1, the longer the wheel scratch length under the same working condition, the stronger the wheel-rail impact. Under the same working conditions, the length of the wheel suffered wheel-rail impact is basically the same.
2.3. The material ER8C properties

To obtain CRH5 EMU wheel material ER8C properties, the static tensile test and $S$-$N$ character test of material ER8C in temperature -40°C are carried out. The results show that the average rim strength $\sigma_b = 993.25$ MPa and the average spoke strength $\sigma_b = 919$ MPa. The fatigue limit of the material ER8C is tested by the ascending and descending method. The fatigue limit $\sigma_{-1} = 392$ MPa and the fatigue limit of the spoke $\sigma_{-1} = 343.5$ MPa. The $S$-$N$ characters of ER8C are shown in figure 2 and figure 3.

3. Fatigue life of wheel

3.1. Fatigue life of the non-scratch wheel

To simplify the problem, the wheel fatigue damage equivalent calculation method is used to complete the analysis, that is: Assuming that the wheel is stationary, the wheel and rail forces always act on the same contact point, and the dangerous point is equivalent to rotating around the wheel center. So the damage of dangerous point is equal to the mean value of the damages of nodes on the same radius and the same plane with the dangerous point. This method ignores the force of inertia, will result in the calculated damage slightly less than the actual situation.

According to the UIC510-5 standard, the wheel model is constrained and the boundary conditions are given. CRH5 EMU wheel using XP55 tread, rolling contact patch area of wheel and rail about $100\, \text{mm}^2$. Accordingly, a unit vertical load (1N) was applied to a tread having an area of $100 \, \text{mm}^2$ and a center of 70 mm from the inside of the wheel. The equivalent stress cloud and equivalent strain cloud of the wheel under the unit vertical load are solved, as shown in figure 4.

As can be seen from figure 4, the maximum equivalent stress point and the maximum equivalent strain point of the wheel under the unit vertical load are the same nodes, and the point is the dangerous point at a depth of 8mm from the tread surface. The fatigue life of the dangerous point is the smallest, and the fatigue life of all the nodes on the radius circle and the same plane with the dangerous point is extracted. The effect of each node under condition 1 to 4 of the primary load block (load block or load time history curve) fatigue damage are shown in table 2.
Table 2. Fatigue life and fatigue damage of each node on the same radius and same section with dangerous point under condition 1 to 4

| Node | Life (load block) | Damage (load block once) |
|------|------------------|--------------------------|
|      | 1                | 2                        | 3                        | 4                        | 1          | 2            | 3            | 4            |
| 1    | 14166            | 18784                    | 21808                    | 1.1027e5                 | 7.0591e-5  | 5.3236e-5  | 4.5854e-5  | 9.0686e-6  |
| 2    | 27273            | 35335                    | 44331                    | 1.9096e5                 | 3.6666e-5  | 2.8300e-5  | 2.2557e-5  | 5.2367e-6  |
| 3    | 26832            | 35600                    | 45002                    | 1.7434e5                 | 3.7268e-5  | 2.8089e-5  | 2.2221e-5  | 5.7359e-6  |
|      | 1620             | 3.5765e7                 | 3.6838e7                 | 3.7911e7                 | 3.8139e7   | 2.7960e-8  | 2.7145e-8  | 2.6377e-8  |
| Mean | /                | 1.3688e-7                | 1.0936e-7                | 9.4040e-8                | 3.9013e-8  |

Can be seen from the table 2, the damages of dangerous node under condition 1 to 4 are 1.3688e-7, 1.0936e-7, 9.4040e-8 and 3.9013e-8. Based on the above analysis, it can be concluded that the fatigue damage of the wheel under condition 1 to 4 (1 km) is 1.23201755e-7, 1.03610611e-7, 9.40401319e-8 and 4.38899514e-8.

Assuming that the conditions 1 to 4 are respectively 50%, 20%, 20% and 10% of the Harbin-Dalian Line, the fatigue damage of the wheel is 1.0552002e-7. According to the Miner damage law, the running distance of the wheel under random loading is 9,476,900 km. If the EMU runs 300,000 km per year, the service life of the wheel is 31.59 years.

3.2. Fatigue life of the scratched wheel.

The scratched wheels are subject to cyclical wheel-rail impact loads and are subject to constant impact. In order to simplify the calculation, it is assumed that the point of impact is the point of vertical load under straight-line conditions. It is assumed that the tread of the EMU wheels is scratched when leaving factory and the length of the scratch does not change with the operation of the high-speed EMU. And the fatigue life of the scratched wheel with different scratch length is analyzed and calculated.

First of all, the scratched wheel with a length of 32mm was analyzed. It can be concluded that the fatigue damage (running 1 km) under each working condition (the scratched wheel is affected by random loading of the track and cyclical wheel-rail impact). As shown in table 3.

Table 3. Fatigue damage of 32mm scratched wheel under each working condition

| Condition | Damage (single impact load) | Damage (1 km) |
|-----------|-----------------------------|---------------|
| 1         | 2.1898e-5                   | 7.8179e-3     |
| 2         | 2.7932e-5                   | 9.9718e-3     |
| 3         | 3.1129e-5                   | 1.1113e-2     |
| 4         | 4.7492e-5                   | 1.6954e-2     |

Table 4. Fatigue life of the scratched wheel with various length scratch

| Length of scratch | Life[km] |
|-------------------|----------|
| LR=32mm           | 101.8    |
| LR=30mm           | 156.4    |
| LR=22mm           | 56.36e4  |
| LR=20mm           | 947.69e4 |
| LR=10mm           | 947.69e4 |
| LR=0mm            | 947.69e4 |

Figure 5. The relationship lines of running distance with length of scratches
Assuming that the operating conditions 1 to 4 respectively account for 50%, 20%, 20% and 10% of the Harbin-Dalian line. The damage of wheel with 32mm scratch is 0.009821482, running distance of 101.8km. Based on this, the fatigue life of the wheel with the scratch lengths of 30 mm, 20 mm, 22 mm, and 10 mm, respectively, is calculated as shown in table 4. The relationship between the scratch length and wheel running distance is shown in figure 5. As can be seen from figure 5, when the scratch length $L_R \leq 20$ mm, the fatigue life of the scratched wheel is less affected by the cyclical wheel-rail impact; when the scratch length $L_R > 20$ mm, the fatigue life of the wheel is significantly affected by the cyclical wheel-rail impact, the life of the wheel is rapidly decreasing.

4. Conclusion

The S-N character of the wheel material ER8C was obtained based on the fatigue test in servicing environment -40 °C. Combined with the finite element quasi-static superposition method, the wheel fatigue life with and without scratches were compared. The conclusions are as follows:

(1) When the wheel tread is free from scratch, the running distance of the wheel is 9,476,900 km. If the EMU runs 300,000 km per year, the wheel can be used for 31.59 years. This estimation meets the design life of 30 years.

(2) When the scratch length $L_R \leq 20$mm, the fatigue life of the scratched wheel is barely affected; when the scratch length $L_R > 20$mm, the fatigue life of the scratched wheel is obviously affected by cyclical wheel-rail impact, the service life of the scratched wheel tend to decrease sharply, which affects the safety of the EMU. The scratched wheel should be technically treated as soon as possible. The above results provide a basis for further analysis of the fatigue life of EMU scratched wheel.

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