Formulation of Axle Check Interval

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Abstract. Axle is an important component related to the safety of high-speed train operation. Axle failure will cause a series of safety problems. Therefore, in order to ensure that the axle will not fail during operation, it is necessary to establish a reasonable inspection interval to ensure that cracks can be detected in time before the axle breaks, so as to avoid the occurrence of axle failure events. In this paper, the axle inspection interval is calculated by the axle damage tolerance design method and the remaining life curve of the axle obtained by the full-scale axle crack propagation test. The evaluation of the remaining fatigue life of the axle is closer to the reality, which has certain design guiding significance and engineering application value.

Keywords: High-speed train ; axle ; damage tolerance ; equipment flaw detection ; axle inspection interval.

1. Introduction

1.1 The importance of axle

The axle is an important component related to the safety of high-speed train operation. About 2/3 of its failure problems are caused by fatigue [1]. Although the railway axle is designed with infinite life, fatigue fracture still occurs in operation [2-3]. Most of them are caused by the impact or corrosion of foreign objects on the surface of the axle, and lead to the initiation and propagation of fatigue cracks under cyclic loading. Therefore, in order to ensure the safe operation of the axle, it is necessary to strictly monitor the state of the axle and carry out regular maintenance [4-5], as shown in Figure 1. In recent years, the damage tolerance method based on fracture mechanics has been widely considered as an effective means to evaluate the remaining life of axles and determine the non-destructive testing cycle [6]. Some kind of damage will inevitably occur in the process of production, transportation and service of railway axles. Once the damage is formed, it provides convenient conditions for the subsequent crack propagation. At this time, it is necessary to use the damage tolerance analysis method to determine the crack propagation in a maintenance cycle, and carefully select the non-destructive testing cycle to improve the safety level of vehicle operation.

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Fig. 1. Axle inspection diagram.

1.2 Current status of domestic and international research

As for the method of damage tolerance design, Zhao [7] discussed the damage tolerance design method, studied the estimation method of fatigue crack growth life of long cracks and the determination method of initial crack size a0, and provided the experimental data of fatigue crack growth rate and fatigue crack growth threshold of mechanical materials. Based on the concept of damage tolerance design and the theory of fracture mechanics, Zhao [8] applied the famous Paris crack growth rate formula on the basis of initial defects in zero components. Taking the estimation of the life times of 1020 cold-rolled steel sheet under uniaxial constant amplitude cyclic load as an example, a simple and practical fatigue life estimation method is introduced. Xu et al. [9] took the axle of rail vehicle with defects as the research object, and carried out damage tolerance analysis and residual life assessment. The results showed that the axle press-fit caused the extremely uneven distribution of residual stress near the axle press-fit area, resulting in serious stress concentration and eventually cracks in this area. Based on the safety life design, Liu [10] used Paris formula and NASGRO formula to fit the crack growth rate, and estimated the residual life of the inner and outer axles based on the damage tolerance design method.

In this paper, the axle inspection interval is calculated by the axle damage tolerance design method and the remaining life curve of the axle obtained by the full-scale axle crack propagation test. The evaluation of the remaining fatigue life of the axle is closer to the reality, which has certain design guiding significance and engineering application value.

2. Basic method of axle damage tolerance design

2.1 Axle damage tolerance design process

The basic theory of damage tolerance design is to assume that there is an initial crack in the axle. As the running crack of the vehicle continues to expand, the crack is found by non-destructive testing technology before the crack expands to the critical size. This method does not allow the axle to run with cracks. Once a crack is found, it should be replaced in time. The ultimate goal of this method is to develop a reasonable inspection interval for axles, analyze and estimate the life of crack propagation, and determine an economical and feasible maintenance cycle and a reliable and reasonable flaw detection standard.

The basic information that needs to be input is as follows:

1.The basic dimensions and geometric shapes of the axle and its accessories.

2.The location, shape, size and propagation direction of the initial crack.

3.Load conditions in actual service.

4.The mechanical properties of the material, including crack growth rate curve, stress-strain curve and fracture toughness.

5.Detection ability of flaw detection equipment (POD curve).

The first four items are used to calculate the remaining life of the axle. The remaining life of the axle from the initial crack to the critical crack is calculated by simulation or experiment. Combined with the detection ability of the fifth flaw detection equipment, the inspection interval under a certain failure probability is determined.

2.2 Description of flaw detection capability of flaw detection equipment

The non-destructive testing methods used include direct visual observation, penetration testing, magnetic particle testing and ultrasonic testing. Different methods have different crack detection probabilities.

The crack detection probability curve (POD curve) is an important parameter to characterize the flaw detection ability of flaw detection equipment. For different detection methods, there are different crack detection probability curves. The POD curve of typical flaw detection technology is shown in Figure 2. Ultrasonic flaw detection is the most widely used. For solid axle flaw detection, this method can be divided into far-end scanning and near-end scanning. The difference is that the distance between the probe and the crack and the incident angle of the sound wave are different, and the detection probability of the same crack size is different. Magnetic particle inspection has a higher probability of crack detection than other methods, but it can not achieve 100 % crack detection probability for larger cracks. At the same time, this method is costly and cannot be used as a daily detection method. In addition to the detection method, it is also limited by the detection ability and operation level of the inspectors.

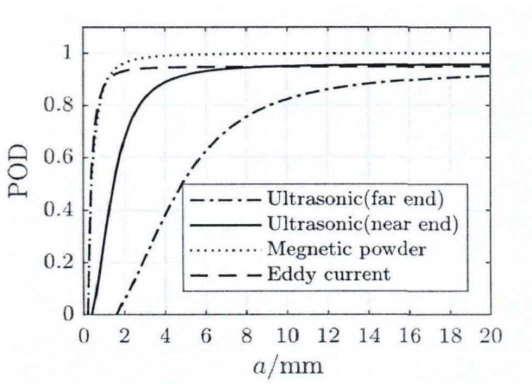

Fig. 2. Crack detection probability curves of different flaw detection techniques[11].

2.3 Design method of check interval

After obtaining the residual life curve of the axle and the crack detection probability curve of the non-destructive testing method, the axle inspection interval can be formulated, as shown in Figure 3. A method for determining the inspection interval is to select a crack size that can be detected with a very high probability according to the crack detection probability curve (POD), and the life of the crack from the size to the critical size is used as the inspection interval. This method can ensure that there is at least one chance that the crack depth is not less than the critical size before the crack extends to the critical size. However, for the commonly used ultrasonic testing, the detection probability is low. Therefore, this method is often used to give the general requirements of the equipment 's flaw detection capability when the inspection interval is known.

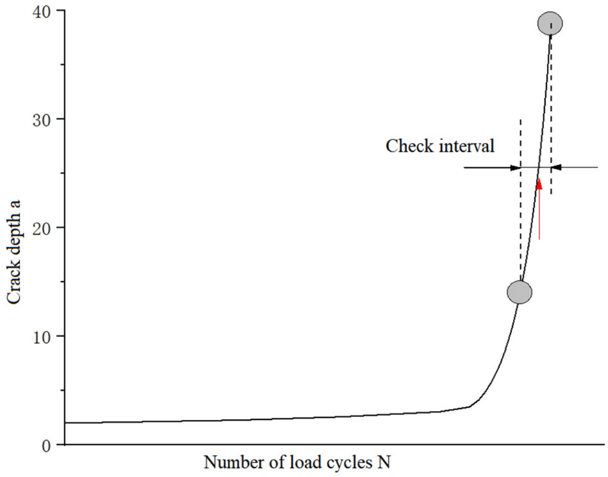

Fig. 3. Design of check interval.

The second method is to calculate the crack detection probability or failure probability of multiple flaw detections under a given failure probability until the selection of the inspection interval meets the requirements of the failure probability. For example, it is considered that at least 3 times of cumulative flaw detection are required to be safe within the remaining life N, and M = 3+1 can be taken as the flaw detection cycle T = N/M, as shown in Figure 4. The failure probability calculation Formula (1) is as follows :

$$P_f = \prod_{i=1}^{3} \left(1 - POD\left(a_i\right)\right) \tag{1}$$

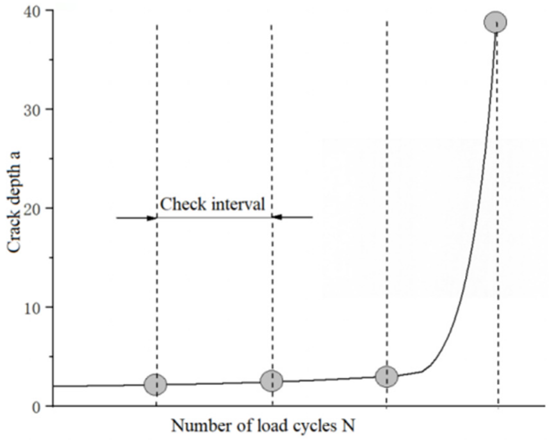

Fig. 4. Cumulative detection probability diagram.

3. Axle inspection interval formulation

In this section, the second design method of axle inspection interval is adopted. For railway axles, the failure probability is usually required to be less than 10^{-5} [12]. Based on the residual life curve of the axle obtained from the full-scale axle crack propagation test in Figure 5 and the POD curve of the 45 ° oblique probe hollow axle ultrasonic detection in Figure 6 [13], the axle inspection interval is formulated.

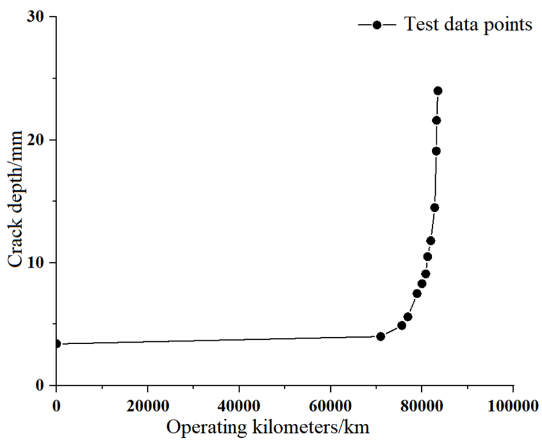

Fig. 5. Residual life curve of full-size axle crack propagation test axle.

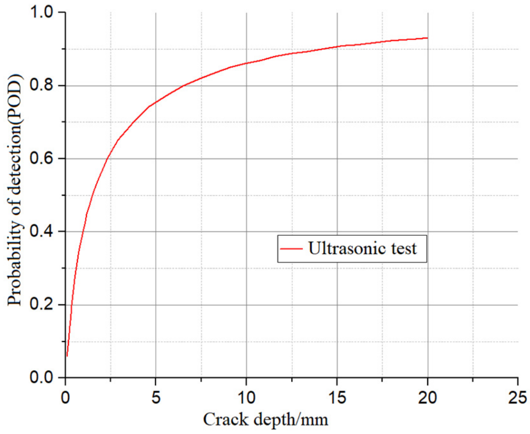

Fig. 6. Ultrasonic testing POD curve of hollow axle[13].

When M = 8, there are seven detection opportunities before the axle fails, and the inspection interval is 10434 km. The calculated failure probability is 4.14×10^{-5}, less than 10^{-4}, and the calculation process is shown in Table 1. When M = 9, there are 8 detection opportunities before the axle fails, and the inspection interval is 9275 km. The calculated failure probability is 9.23×10^{-6}, less than 10^{-5}, and the calculation process is shown in Table 2.

Table 1. The failure probability is calculated when the check interval T = 104354km

Test sequence	Crack depth/mm	Probability of crack detection	Accumulated invalid probability
1	3.52	0.73	0.27
2	3.56	0.73	7.29×10^{-2}
3	3.63	0.74	1.89×10^{-2}
4	3.78	0.75	4.74×10^{-3}
5	3.85	0.77	1.09×10^{-3}
6	3.96	0.80	2.18×10^{-4}
7	4.43	0.82	4.14×10^{-5}

Table 2. The failure probability is calculated when the check interval T = 9275km

Test sequence	Crack depth/mm	Probability of crack detection	Accumulated invalid probability
1	3.49	0.73	0.27
2	3.60	0.73	7.29×10^{-2}
3	3.63	0.74	1.89×10^{-2}
4	3.67	0.74	4.93×10^{-3}
5	3.82	0.76	1.18×10^{-3}
6	3.88	0.77	2.71×10^{-4}
7	4.00	0.80	5.43×10^{-5}
8	4.64	0.83	9.23×10^{-5}

4. Conclusions

n order to ensure that the axle will not fail during operation, it is necessary to establish a reasonable inspection interval to avoid the occurrence of axle failure events. In this paper, the axle inspection interval is calculated by the axle damage tolerance design method and the remaining life curve of the axle obtained by the full-scale axle crack propagation test. The following conclusions are drawn : when the inspection interval is 10434 km, the calculated failure probability is 4.14×10^{-5}, which is less than 10^{-4} ; the inspection interval is 9275 km, and the calculated failure probability is 9.23×10^{-6}, which is less than 10^{-5}. The evaluation of the remaining fatigue life of the axle is closer to the reality, which has certain design guiding significance and engineering application value.

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References

[1] Liu Yuxuan, Wu Shengchuan, Li Cunhai, etc. Fatigue performance and life evaluation of railway axles with built-in axle box [J]. Journal of Transportation Engineering, 2019,19 (03) : 100-108.

[2] Zerbst U,Beretta S,Köhler G, et al. Safe life and damage tolerance aspects of railway axles-A review[J]. Engineering Fracture Mechanics,2013,98,214-271.

[3] Smith A R,Hillmansen S. A brief historical overview of the fatigue of railway axles[J]. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,2004,218(4).

[4] Makino T,Kato T,Hirakawa K. Review of the fatigue damage tolerance of high-speed railway axles in Japan[J]. Engineering Fracture Mechanics,2009,78(5).

[5] Wu S,Zhang S,Xu Z, et al. Cyclic plastic strain based damage tolerance for railway axles in China[J]. International Journal of Fatigue,2016,93.

[6] Gänser H,Maierhofer J,Tichy R, et al. Damage tolerance of railway axles – The issue of transferability revisited[J]. International Journal of Fatigue,2016,86..

[7] Zhao Shaobian. Damage tolerance design method and design data [J].Mechanical design, 2000,17 (5): 4-7.

[8] Zhao Zhiping, Li Xinyong. Estimation of fatigue crack growth life based on damage tolerance design [J]. Mechanical research and application, 2010,000 (003) : 42-43.

[9] Xu Zhongwei.Fatigue assessment method for foreign object damage axle of high-speed railway [D].Chengdu: Southwest Jiaotong University, 2018.

[10] Liu Yuxuan. Assessment of damage tolerance and residual life of railway built-in axles [A].Solid Mechanics Committee of Chinese Society of Mechanics, Department of Mathematics and Science, National Natural Science Foundation of China. Summary of 2018 National Solid Mechanics Conference (Part I) [C].Solid Mechanics Committee of Chinese Society of Mechanics, Department of Mathematics and Science, National Natural Science Foundation of China : Chinese Society of Mechanics, 2018 : 1.

[11] Ding Ran.Research on axle fatigue reliability evaluation and flaw detection cycle formulation [D].Beijing: Beijing Jiaotong University, 2019..
[12] Li w W. Wheelset integrated design and effective maintenance: Procedure to define NDT periodicity as function of vehicle service profile[R/OL].(2005-01-01) [2022-11-30]. http://www.widem.org/news.php.
[13] Rudlin J. Wheelset integrated design and effective maintenance:Report on NDT performance (various techniques) for conventional wheelsets[R/OL]. (2008-06-30)[2022-11-30].