The simulation of crack growth in rolling stock running wheel disk

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Abstract. The article reviews scientific and technical literature in the field of the survivability of railway wheels. The computer simulation of the flat crack growth at different temperatures is performed with the estimation of the crack propagation rate and survivability parameters. In conclusion, the estimation is provided to refine the calculation model, followed by the recalculation of the obtained results.

1. Introduction

The analysis of the operating conditions of railway wheels manufactured, for example, according to GOST 10791 [1], shows that the strength criteria specified in regulatory documents cannot fully guarantee their reliability and safety of operation. With insufficient viscosity of the metal and its high sensitivity to stress concentrators, a crack will propagate from the acquired defect up to its critical length, which is dangerous because of the possibility of brittle fracture of the wheel due to seasonal factors.

The review of the scientific and technical literature [2–8] did not allow revealing the results of full-scale wheel survivability tests, taking into account the influence of negative climatic temperatures characteristic of the geographical zone of operation. The data about the effect of negative temperatures from literature sources concern only wheel metals in terms of fracture toughness parameters, the range of stress intensity factors and the kinetic diagram of fatigue fracture [2] and do not allow us to unambiguously judge of the survivability of the study object.

In this regard, it seems interesting to conduct virtual experiments on the propagation of cracks on computer models of railway wheels at different ambient temperatures, followed by the plotting of function graphs illustrating the dependence of the characteristic crack size (depth, width, etc.) on the number of cycles under the corresponding loading conditions.

2. Calculation model

Currently, there are many constantly improving computer systems that allow such modeling. There are also alternative models [9] linking the crack growth rate in the section of its stable growth with stress intensity factors. Thus, there is an apparatus that allows to estimate the time interval during which a crack in a structure will develop from a minimum detectable size to a critical one at which the structure becomes incapable of performing its functions (loss of bearing capacity).

Figure 1 shows the kinetic diagrams of fatigue failure for wheel steels at different temperatures.
The kinetic diagram of fatigue failure of wheel steels [2]:

\[
\begin{align*}
\text{▬▬} & : -20^\circ \text{C}, \\
\text{‒} & : -20^\circ \text{C}, \\
\text{+} & : -40^\circ \text{C}, \\
\text{□} & : -60^\circ \text{C}.
\end{align*}
\]

Having obtained \( \Delta K \) from the model and specifying the functional relation \( dN/dl = f(\Delta K) \) by numerical integration it is possible to calculate the crack growth rate over the section of its stable growth [\( \Delta K_{th} \); \( \Delta K_{fc} \)] from the threshold to the critical value of the mechanical stresses intensity factor.

As the object of study, a wheel of a wheel set according to GOST 10791 was selected, the scheme of its operational loading is shown in figure 2 [10], and the loading scheme of the studied finite element model is shown in figure 3.

**Figure 1.** The kinetic diagram of fatigue failure of wheel steels [2]:

**Figure 2.** The scheme of the wheel set operational loading.

**Figure 3.** The scheme of a loading finite element model simulating rotational bending.
The forces F1 and F2 are harmonic, phase shifted by $\pi/2$, they create the corresponding mechanical stresses in the wheel zone which is the most loaded during operation.

The relationship between the crack growth rate and the stress intensity factor was described as a power-law dependence by the Paris formula [9]:

$$\frac{dl}{dN} = C \cdot (\Delta K)^n,$$  \quad (1)

where $dl/dN$ – the crack growth rate; $\Delta K$ – the range of stress intensity factors; $C, n$ – empirical factors.

The basic data for the calculation are presented in table 1.

| Temperature, °C | Threshold value of stress intensity factor $\Delta K_{th}$, MPa√m | Critical value of stress intensity factor $\Delta K_{fc}$, MPa√m | Range of stress $\Delta \sigma$, MPa | Factor $n$ |
|----------------|-------------------------------------------------|-------------------------------------------------|-----------------|--------|
| +20            | 7.0                                             | 90                                              | 150             | 3.2    |
| -60            | 8.0                                             | 32                                              | 150             | 3.2    |

A crack was introduced into the model by artificial means on the surface in the most loaded zone of the wheel (in the disk part near the hub) and increased incrementally, with $\Delta K$ calculated at each step.

3. Simulation results

The resulting dependence of the crack propagation rate on its length is shown in figure 4. The dependence of the critical crack length at different temperatures on the section of stable growth is shown in figure 5.

When a crack becomes a through-crack, a qualitative change occurs during its further development, since instead of one continuous elliptical front two fronts are formed, and the concepts of “crack length” and “crack depth” in this case lose their original meaning. Figure 6 shows the external view of a through-crack.

Figure 4. The dependence of the crack length on the number of loading cycles at different temperatures:

- - - - at +20 °C; ...... - at -60 °C.
Figure 5. The dependence of the critical crack length at different temperatures: – – – at +20 °C; – – – – at -60 °C.

Figure 6. The external view of a through-crack.

4. Conclusion
The simulation showed that when a flat crack grows, the maximum values of the stress intensity factor are at its edges, thereby the crack propagates more in length than in depth, turning the initial semicircular defect into a part of an ellipse.

After passing through the entire thickness of the wheel disk, the crack becomes a through-crack, forming two fronts. In this case, the values of the stress intensity factor at its tips exceed the cyclic fracture toughness of the wheel material $\Delta K_f$.

It is necessary to carry out experiments on full-scale wheels to clarify the parameters in the Paris equation (1) and to correct the created model.

References
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