Fatigue life of damaged rails

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Abstract. Experimental studies of the residual static strength of rails with transverse cracks in the head are carried out. The transverse cracks were detected by means of flaw detection in railway track. The average values of the relative area of the crack and the breaking load are determined. In order to verify mathematical models for determining the residual life cycle of rails with cracks in the head, a methodology for fractographic estimation of the speed and duration of fatigue crack propagation has been developed. The methodology was developed on the basis of fractographic analysis and studies of macroline fatigue in a crack that developed in a rail on a single-track section with a regular change in the direction of train movement. A linear part of the graphic dependence of the crack growth rate on the maximum value of stress intensity factors (Paris diagram) for rails under real operating conditions was calculated.

The classification of defects and damages of rails during operation is developed. It is based on many years of laboratory metallographic studies and periodically modified [1]. A statistical analysis of the causes of rolling stock derailments, rail breaks in track without derailments and planned replacements of defective rails (Table 1) has shown there is a difference between them.

Table 1 – Distribution of derailments, rail breaks in track without derailments and planned replacements of defective rails causes in %

| Causes of derailments, derailments, planned replacements | Derailments and crushes | Rail breaks | Planned replacements of rails |
|---------------------------------------------------------|------------------------|-------------|------------------------------|
| Wear                                                    | -                      | -           | 13                           |
| Head checking, flaking                                  | -                      | 45          | 52                           |
| Fatigue cracks in rail head                             | 15                     | 11          |                              |
| Fatigue cracks in rail web, most frequently in bolted joints | 7                      | 3           |                              |
| Fatigue cracks in rail bottom                           | 50                     | 28          | 11                           |
| Welded joints                                           | 5                      | 30          | 20                           |

The defects in rail bottom in weld zone can lead to derailment very rarely. This is due to the fact that in both cases there is a vertical transverse fracture of the rail, a free joint appears and a red traffic light...
lights up. The relatively small number of wheel pairs that pass this free joint before the traffic stops does not cause the wheels to derail. The opposite phenomenon can occur if the transverse fatigue crack originates in the rail head. In this case the brittle crack reached the neck and turned along the neck under the influence of residual stresses with subsequent loosing of the head fragment and interrupt the continuity of the surface. The greatest danger of derailments is also represented by all defects formed in the neck of the rail. The critical size of fatigue cracks in the bottom and neck of the rails is significantly smaller than in the head. That is due to the greater magnitude of tensile stresses acting in the lower part of the rails. In this regard, the difficulties of detection of growing fatigue cracks with dimensions smaller than critical in the bottom and neck is significantly greater than in the head.

This determines the particular importance of studying and monitoring the residual life cycle of rails with fatigue cracks in the head, allowing them to work in a damaged state until they are detected by the methods of track flaw detection. The standard for rails [3] introduced a number of technical requirements that provide the necessary level of rail residual life cycle. The impact strength should be more than 15-25 J/cm² depending on the category of rails. Static crack resistance $K_{IC}$ should be more than 26-32 MPa·m$^{1/2}$. Cyclic crack resistance $K_{fc}$ detected full-profile rails must be at least 26-32 MPa·m$^{1/2}$. The fatigue crack growth rate in the test samples at a stress intensity factor range $\Delta K = 10$ MPa·M$^{1/2}$ should be no more than 17 m/10$^9$ cycles, and at $\Delta K = 13.5$ MPa·M$^{1/2}$ – no more than 55 m/10$^9$ cycles. Traffic safety of trains is ensured by periodic testing, which should identify the rails with growing transverse cracks under fatigue slow development before leading cracks in brittle fracture. Scientifically based values of inspection frequency and configuration of detectors should be based on knowledge of the laws of crack growth. At the same time, on the one hand, the removal of the not yet broken rail with a crack should be ensured, and on the other hand, excessively frequent inspections, which greatly increase the cost of domestic track flaw detection, are excluded.

The residual static strength of rails with transverse cracks in the head of 89 1.2 m long rail samples was experimentally tested. The samples were cut from rails removed from the track after detection of transverse cracks in their heads during flaw detection.

The theoretical and experimental dependence of the breaking load on the area of internal transverse fatigue cracks, built on the average values, corresponded well enough (Fig.1). The wide spread of experimental data is associated with a wide variety of forms of real cracks developing in the rails during operation, and different values of residual stresses acting in the zones of transverse cracks.

Average values for crack areas and breaking loads were 10% and 570 kN, respectively. If we compare the average value of the area of transverse cracks in the rails identified by flaw detectors of the Experimental ring VNIIHTHT and identified on the Railways, the difference is quite striking: 10% of the cross-section of the head on the Experimental ring and 33% - on the Railways. For Fig.2 three size distribution curves of transverse fatigue cracks in the rail head are given: 1-detected on the Experimental ring, 2-detected on the Railways, and 3- detected in rail fractures that occurred on the track. The last curve is most strongly shifted to the area of large cracks. The average size of fatigue cracks, not detected in a timely manner during flaw detection and led to the destruction of the rails in the way, is 71%. A comparison of these three distribution curves is shown that about half of the rails with transverse cracks on the Railways are at risk when an adverse combination of circumstances (low ambient temperature, impact of wheels of faulty cars with sliders and ovality) can occur brittle destruction of the rail with a transverse crack in the head. On the Experimental ring, the quality of flaw inspection almost eliminates brittle fracture of rails with growing transverse cracks in the head.

The calculation of the residual life of the rail with a crack to obtain predictive estimates of the number of loading cycles, operating time of tonnage and crack growth time is usually carried out by methods of fracture mechanics. The greatest difficulties thus arise at verification of the received results in connection with a complicated stress state of rails in a track and absence of direct experimental data on speed of development of fatigue cracks in a way. The difficulties of calculation results verification can be overcome by means of the developed method for determining the speed and duration of the fatigue crack propagation in the head using the fatigue macrolines on fracture surface are developed [5]. This method of fractographic analysis of fatigue cracks in rails is applicable to transverse fatigue cracks
developing in rails lying on single-track sections where the direction of trains at known times changes periodically. The type of fatigue cracks in the rail heads at such sites is characterized by a large number of fatigue macrolines on the fracture surface at the last site of the development of fatigue cracks, which can already be detected by flaw detectors (Fig.3). By measuring the distance between the fatigue macrolines, it was experimentally determined that as the transverse fatigue crack grew, it increased from 100 to 300 microns. The increase in the crack growth rate is obviously related to the growth of stress intensity factors along the crack front, as it approaches the critical size. The critical value of the stress intensity factor KIC was determined by testing in accordance with GOST 25.506 and GOST R 51685-2013 on 3 samples cut from this rail. The average of 45.3, 44.2 and 46.2 MPa·M$^{1/2}$ was 45.3 MPa·M$^{1/2}$. Values of stress intensity coefficients at fatigue crack lengths from 16 to 37 mm were determined on the basis that at crack length equal to 37 mm, the critical value of stress intensity factor KIC was equal to 45.3 MPa·M$^{1/2}$, and at other lengths the value of KIN was proportional to the square root of the crack length. As a result, a linear part of the dependence of the crack growth rate on the maximum value of stress intensity factors (Paris diagram) for railway rails in real operating conditions was constructed (Fig.4), which can be used to verify the relevant calculations.

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![Figure. 1 – The dependence of the breaking load on the transverse crack area](image-url)
Figure 2 - three size distribution curves of transverse fatigue cracks in the rail head: 1-detected on the Experimental ring, 2-detected on the Railways, and 3- detected in rail fractures that occurred on the track

Figure 3 - A transverse fatigue crack in the head of a rail operated on a single-track section of a railway during two-way train traffic
Figure.4 - The linear part of the dependence of the growth rate of a transverse fatigue crack in a rail head on the maximum value of stress intensity factors (Paris diagram)

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