Modern instruments for detection and quantitative assessment of hidden rail cracks

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Abstract. The development of high-speed and heavy-haul railway traffic leads to an increase in dynamic stresses in rails, resulting in the formation of hidden fatigue cracks. Such defects are among the most dangerous because they cannot be detected by visual inspection and failure occurs suddenly without warning. In recent years, the primary direction of railway safety improvement has shifted from mere defect detection to quantitative assessment of defect severity and prediction of the rail residual life. This paper analyzes modern rail non-destructive testing (NDT) instruments, including ultrasonic, eddy current, magnetic, acoustic emission, and intelligent diagnostic systems. Their operating principles, sensitivity to various defect types, inspection depth, and fields of application are considered. Particular attention is given to phased array ultrasonic testing and high-speed inspection vehicles providing continuous in-motion monitoring of track condition. A methodology for quantitative assessment of hidden crack severity based on the fracture energy criterion and the stress intensity factor is proposed. A calculation model is developed to determine the probability of rail failure considering defect parameters, stress state, and traffic conditions. A calculation example for a standard R65 rail is presented. The results show that integrating multi-channel defectoscopy with mathematical residual life prediction reduces the probability of rail fracture by more than three times. The obtained relationships can be applied for transitioning from periodic inspections to a risk-based track maintenance system.

Keywords: rail defectoscopy, hidden cracks, ultrasonic testing, stress intensity factor, residual life, non-destructive testing, railway track.

1. Introduction

Train safety directly depends on the reliability of the track gauge. With increasing speeds and loads, the rail experiences a complex cyclic load: repeated contact stresses in the area of interaction between the wheel and the rail cause the accumulation of fatigue damage and the formation of hidden cracks [1]. Such defects take a long time to develop unnoticeably: cracks originate in the subsurface layers of the metal and do not affect the geometry of the path. But after reaching a critical length, a catastrophic destruction of the rail cross-section occurs - sometimes in just a few days. Rolling fatigue cracks (RCF) in the rail head are the most dangerous. Traditional examinations are no longer sufficient: the presence of a crack does not determine its severity. Therefore, the key task is not only to detect defects, but also to assess the risk of failure. Modern methods of non-destructive testing (ultrasonic, eddy current, etc.) detect damage in the early stages [2]. Digital signal processing and intelligent algorithms analyze the defect parameters and help predict the remaining resource [3]. The modern safety concept is based on risk-based maintenance:

decisions about replacement or repair are made based on the probability of failure. The purpose of the study is to study the means of detecting cracks and to develop a methodology for assessing their severity in order to predict the remaining life of rails.

The scientific novelty of this study consists in integrating modern non-destructive rail inspection methods with fracture mechanics approaches for quantitative assessment of hidden crack severity and prediction of rail residual life. Unlike conventional defectoscopy focused only on defect detection, the proposed methodology enables risk-based maintenance decisions based on crack growth kinetics and operational loading conditions.

2. Materials and methods

The development of hidden rail cracks is a multifactorial process of fatigue failure. Under the influence of contact stresses, microcracks (tens of microns) occur in the surface layers of rail steel, which eventually turn into macrodefects. At different stages of destruction, the physical properties of the metal change, so no single control method is universal. Modern systems use a combination of methods.

2.1. Ultrasonic testing

Ultrasonic inspection is the main method of rail diagnostics: elastic waves are reflected from defects, allowing them to be detected [4]. Longitudinal waves reveal vertical fractures, and transverse waves reveal inclined cracks. Due to the dependence on the orientation of the defect, multi-channel control systems are used.

2.2. Manual flaw detectors

Hand-operated ultrasonic flaw detectors are used for local verification and precise characterization of detected defects. Their primary advantage is the ability for the operator to perform detailed analysis of the signal waveform. The drawback is the subjectivity of interpretation.

2.3. Multi-channel systems

Multi-channel ultrasonic monitoring systems (Fig. 1) - evolution of trolleys with one sensor. They work as scanning devices and create a three-dimensional acoustic representation of the rail cross-section. Their development is due to the different orientation of fatigue cracks: vertical, transverse and inclined (RCF, Fig. 2).

A single probe cannot reliably detect all types of damage; therefore, a set of transducers with different incident angles is used.

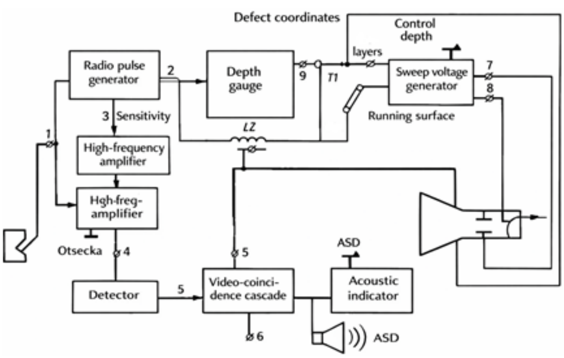

Fig. 1. Multi-channel inspection scheme and insonification methods. Source: developed by the authors

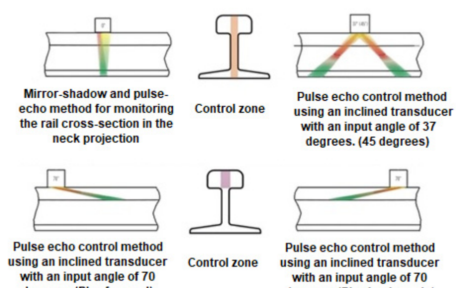

Fig. 2. Basic schemes for sounding rails. Source: developed by the authors

2.4. Phased array systems

Phased array systems is an advanced method of ultrasonic rail inspection. They contain 16-128 piezoelectric elements, each of which is individually delayed, allowing wavefront control, unlike conventional fixed-beam transducers. This makes it possible to electronically vary the direction, focal position, and penetration depth of the ultrasonic beam without mechanical movement of the probe. In essence, a single transducer performs the function of an entire array of sensors.

2.5. Eddy current testing

Fatigue cracks during rolling occur in a layer of 1-3 mm (Fig. 3). Ultrasonic testing is ineffective here, so the eddy current method is used: it detects changes in electrical conductivity due to microcracks, rather than the geometry of the defect [5]. The method is sensitive at an early stage - the rail can still be repaired by grinding.

The main limitation of the method is the shallow inspection depth; therefore, it is used in combination with ultrasonic testing.

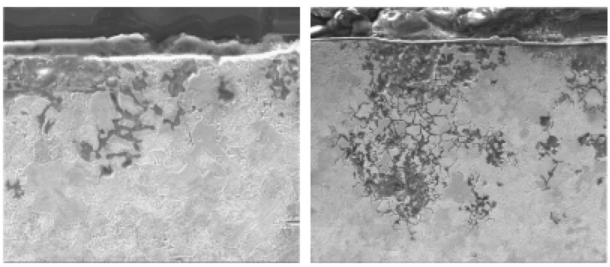

Fig. 3. Ultrasonic rail scan (B-scan). Source: developed by the authors based on ultrasonic inspection principles described in [6-10]

2.6. Magnetic testing

Magnetic flux leakage (Fig. 4) is used for high-speed rail inspection. In case of a crack, part of the flow flows out of the magnetized rail. The method reacts to the volume of damaged metal, is effective for transverse defects, but is less sensitive to fine surface cracks [11].

The principal advantage is high inspection speed and independence from the rail surface condition.

Fig. 4. Specialized rail inspection vehicle. Source: developed by the authors based on modern rail diagnostic systems described in [11-13]

2.7. Acoustic emission

Acoustic emission does not directly detect a defect, but the process of its growth: when a crack spreads, elastic energy is released in the form of wave pulses [12]. Sensors register them – this is how they detect active defects that can lead to failure. The method is valuable for assessing the severity.

2.8. Integrated diagnostic systems

Modern inspection vehicles integrate all of the above methods. Each technique detects a specific stage of defect development, while combined data processing enables assessment of failure risk. In effect, a digital history of crack evolution is created - from initiation to critical size [13]. The vehicles perform a continuous monitoring of hundreds of kilometers of track in one run. Calculation scenarios are being developed to convert flaw detection data into operational solutions [14-15]. The case of a heavy-duty highway is considered: a freight train moves along an all-welded rail section with a given type of rails (Table 1). The most dangerous defect is analyzed – an inclined fatigue crack in the rail head, detected by ultrasound control with a phased array antenna.

Such defects are among the most dangerous because they propagate into the rail cross-section and lead to transverse rail fracture [16, 17].

Table 1. Rolling stock type, rail type and defect parameters

Parameter	Value	Parameter	Value	Parameter	Value
Wagon type	Gondola freight wagon	Rail profile	R65	Depth	6 mm
Axle load	23.5 tf	Steel grade	E76KhF	Length	18 mm
Wheel load	115 kN	Young's modulus (E)	2.1×10^{11} Pa	Inclination angle	25°
Operating speed	70 km/h	Poisson's ratio (\nu)	0.3	Location	4 mm below the running surface
Traffic intensity	70 trains/day	Yield strength	880 MPa	–	–
–	–	Fracture toughness ($K_{\{IC\}}$)	50 MPa√m	–	–

3. Results and analysis

The purpose of the calculations is to obtain the relationship between hidden crack size and the time to rail fracture. In the previous section, a specific defect with a depth of 6 mm was considered. A series of calculations is now performed under the same operating conditions (freight train, axle load 23.5 tf, R65 rail), varying only the crack depth shown in Table 2.

Table 2. Dependence of defect severity on crack depth

Depth, mm	K_I, MPa	Condition	Remaining cycles	Time
2	30	stable growth	1.2×10^6	~1.5 years
3	36	stable	4.8×10^5	~7 months
4	42	accelerated growth	1.6×10^5	~2 months
5	47	pre-critical	2.7×10^4	~10 days
6	52	critical	950	~1–2 hours
7	57	failure imminent	<100	minutes

The critical fracture depth for the R65 rail is assumed to be 10 mm.

The obtained results demonstrate nonlinear crack propagation behavior. At crack depths below 3 mm, defect growth remains stable and controllable. However, when the crack depth exceeds 4-5 mm, accelerated propagation occurs due to the increase in stress intensity factor. At 6 mm, the stress intensity factor exceeds the fracture toughness threshold, resulting in rapid rail failure.

The calculation procedure includes: 1) determination of the stress intensity coefficient; 2) calculation of the crack growth rate (according to the Paris law); 3) calculation of cycles to a critical depth; 4) conversion into working hours. The defect develops non-linearly: it remains safe for a long time, but at a depth of 4-5 mm, growth accelerates. An S-shaped curve is observed: hidden period → accelerated growth → rapid fracture.

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4. Discussion of the results

Based on the calculations, operational defect categories can be formulated (Table 3).

This classification converts defectoscopy data into specific maintenance actions.

Most rail fractures occur shortly after the defect is detected, not because of a control error, but because the crack enters the stage of unstable growth. Therefore, it is important to assess not only the size of the defect, but also its severity.

Table 3. Maintenance actions depending on crack depth

Crack depth	Decision
Up to 3 mm	Scheduled monitoring
3-4 mm	Repeated inspection once per month
4-5 mm	Speed restriction
More than 5 mm	Urgent rail replacement
More than 6 mm	Track closure

5. Conclusions

The proposed methodology enables transition from periodic rail inspection to predictive risk-based maintenance strategies. The study aims to move from detecting rail defects to assessing their severity. The methods of non-destructive testing are analyzed: eddy current, ultrasonic, magnetic, acoustic emission - each reveals its own stage of damage [18-20]. A calculation system based on fracture mechanics has been developed. The key parameter is the stress intensity coefficient [21-24]. Calculations for the R65 rail (load 23.5 tons) showed that cracks up to 3 mm are safe, but at 5-6 mm the resource drops to hours. A scale of defect severity has been created for selecting maintenance measures (monitoring, speed limitation, replacement). A risk-based approach reduces the likelihood of sudden failure and eliminates premature rail replacement. The technique is applicable in automated diagnostic systems. The developed approach can be integrated into intelligent railway diagnostic systems for automated assessment of defect criticality and residual rail life prediction.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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