Materials Research Proceedings **24** (2022) 159-165 https://doi.org/10.21741/9781644902059-24

Empirical Model of the Rail Head Operational Crack on the Example of a Head Check Defect

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Keywords: Rail Defects, Ultrasonic Testing

Abstract. The paper presents a method and the results of the CT test of the head check defect, which commonly occurs in rails. It is one of the most dangerous defects which cause rail discontinuity. The methods of simulation of the ultrasonic wave and projection possibilities of the real defect have been taken under consideration. The paper outlines the ultrasonic wave simulation method and describes the ultrasonic probe optimization results for the considered discontinuities.

Introduction

The defects of the rails arise at several stages of production and use. The internal defects of the rails appear in the metallurgical process, i.e. at the stage of smelting and casting. The defects that arise can subsequently be included in all internal discontinuities of the material, mainly the remains of the shrinkage cavity and large clusters of non-metallic inclusions. The rolling process of the rails may cause surface defects of the rails in the form of scratches, scale indentations on the rail running surface, or the formation of a coarse-grained structure of the material [1, 2]. On the other hand, straightening the rails after rolling promotes the formation of internal stress in the rails, which may lead to the curvature of the rails and cracking of the rails in the tracks. Due to the common use of non-contact termite welded and electrofusion welded rails in the tracks, the number of damage in the connection zone increased. This was mainly due to the failure to meet the parameters recommended by the welding technology. Joining the rails by electrofusion welding significantly improved the quality of the joints. Therefore the number of defects caused by this technology significantly decreased due to the higher repeatability and control of the welding process. The increase of the train velocity and traffic intensity causes the rails to be subjected to increasing contact stresses and hence the overall increase in their damage. In particular, the number of visible defects as cracks in the railhead surface has increased. They constitute a huge percentage of recorded rail defects, approximately 10% [1]. All head check defects occurring in the tracks in operation are found based on visual inspection. Thus, it is impossible to determine their approximate depth [1]. The analysis of many practical cases and literature shows that the approximate depth of the defect may be determined, for example, by the eddy current method [2]. Unfortunately, it is not used successfully in practice. In addition to this, the estimation of the depth of the defect is more accurate for rails not mechanically processed during operation e.g. grinding. The length of the defect on the surface may correlate less with a crack depth after multiple grinding operations. It was considered to develop an optimized system of ultrasonic transducers dedicated to detecting head check defects. The different degrees of the head of the railhead were taken into account. For this purpose, computed tomography was used as the only available method that allows getting to know the whole geometry of the defect with a required resolution in the entire railhead area.

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Determination of the Crack Geometry

In the presented part of the experiment, the relatively advanced defects were considered, referring to the defect catalog with code 2223. They are characteristic of a straight section of the track. These cyclically repeated defects pose a significant risk due to the possibility of multiple rail breakages over several meters. Due to the thickness of the railhead area and taking into account the limited power of the available CT stations, the prepared samples were made to scan at the available lamp power. The real samples and the final results of the 3D geometry of the head check crack are presented in Fig. 1 and Fig. 2.

Fig. 1. *Head check defect prepared to CT test*

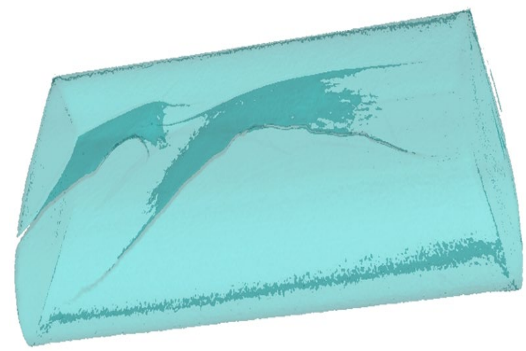

Fig. 2. *Visualization of the fracture using editor „myVGL"*

First of all, it was noticed that the angle of propagation (α) in relation to the longitudinal axis of the rail was in the range of 35º to 52˚. This is a characteristic value for all head check defects. Different sources specify an even wider angular range of crack propagation on the rail surface. It means (35-70)˚, depending on the prevailing geometry of the wheel-running surface contact area. In the analyzed cases, the distances between the cracks were usually 3 to 20 mm, which depends on the used material and local operating conditions. The angle of the defect penetration into the material was also characteristic. It was measured as the crack's angular deviation from the normal. Based on several measurements, it was estimated that the value of this angle (β) for about 50% of the cases is in the range of approximately (60-70)˚. Due to local conditions and the change in the propagation angle in the depth of the material, the measured angle was from 52˚ to 105˚. The last value indicates that the defect may develop deep into the rail material and also may propagate parallel under the running surface. This may result in a risk of detachment of the running surface.

If the crack penetration angle were measured at the point of surface penetration, this angle would usually fluctuate in the range from 0 to 20˚. It would not be a valuable parameter referenced to the rail running surface on which the ultrasonic test heads are placed.

The parameters listed in Table 1 present linear dimensions concerning the depth of the crack under the running surface, measured from the highest point of the railhead. A correlation between the crack length and depth, in this case, was not found. On the other hand, it was proved that the depth of crack penetration ranged from 2 to 10 mm. It impeded ultrasonic testing with typical single transducers and a pulse-echo mode.

The Model of the Head Check Defect

Depending on the required accuracy of the simulation, the expected effects, and the capabilities of the simulation environment, the equivalent defect may have a different nature. The most precise solution is to convert the radiograph layers into a point cloud readable by the simulation environment. This solution enables to implementation of a geometry of the natural defect, taking into account the imperfections of the tested object. Such an environment includes the FEM method, but the application for modeling the propagation of ultrasonic waves in specific objects encounters significant methodological difficulties and practical limitations. To reach an acceptable simulation accuracy, the distance between nodes should be 1/10 of the wavelength [6].

Table 1. *The results of the fracture geometry measurements of the head check defect.*

Sample No.	The length of the crack on the running surface [mm]	The depth of the crack under the running surface [mm]	The angle of crack propagation (angle of attack) on the horizontal plane α [deg]	The angle of crack propagation on the vertical plane β [deg]
5_19	35	10	43	69
	53	5.5	43	67-100
5_19_a	27	9.5	48	72
	30	6.5	46	68-105
	17	8	44	65-85
8_19	36	11	46	65-100
	28	6	52	52
19_19_II	10	3	35	88
	20	3	35	85
	27	2.5	35	88

Optimization analyses were performed based on the system environment based on the ray-tracing method to simulate the ultrasonic beam propagation in the rail. The predefined defect patterns were prepared based on the empirical models. The two solutions were applied there. Firstly, the size, simplified geometry, and location were defined after collecting data from CT scans (Fig. 2). Secondly, the representative equivalent flat bottom hole (*EFBH*) was located in the internal space of the rail model (Fig. 3).

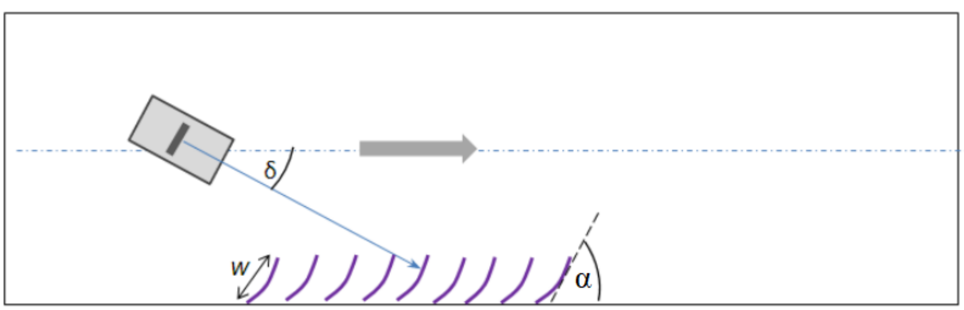

Fig. 2. *Schema of detecting the multiple head check defect using surface wave [6].*

The industry regulations were established and should be remembered during planning ultrasonic simulations and designing material discontinuities. The sensitivity during ultrasonic testing of rail rails was set as EFBH Ø3mm. Graph samples of received sound pressure are presented in the next chapter.

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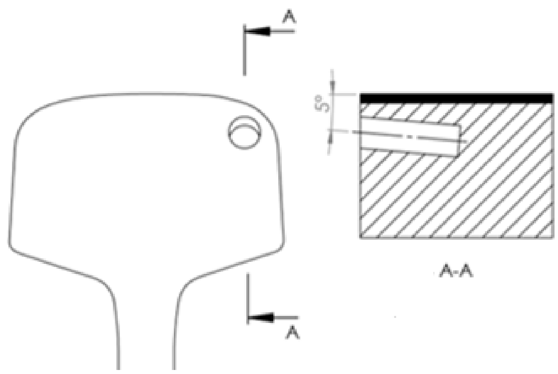

Fig. 3. *Schema of the applied flat bottom hole (FBH).*

Simulation of the Ultrasonic Wave Propagation

The ray-tracing modeling technique allowed the visualization of the ultrasonic wave propagation in whole and cross-section geometry [6]. An example 3D model of testing a rail with the angular head of transverse waves is presented in Fig. 4a. Due to the test object's complicated geometry, the utilization of 3D simulation software is crucial. It allows the presentation of beam propagation after reflections and transformations from non-parallel or curved boundary surfaces. The axis of the beam is visible as a blue line of the transverse wave. It falls to the bottom of the railhead, then it reflects and transforms into a wave of the longitudinal type. Its axis is visible as the red line (Fig. 4b). Both types of waves propagate towards the upper surface of the railhead. Then they are reflected multiple times, and longitudinal wave transformations occur into a transverse wave again. The ultrasonic wave modeling ends after elapsing the assumed time interval, corresponding with the range observation.

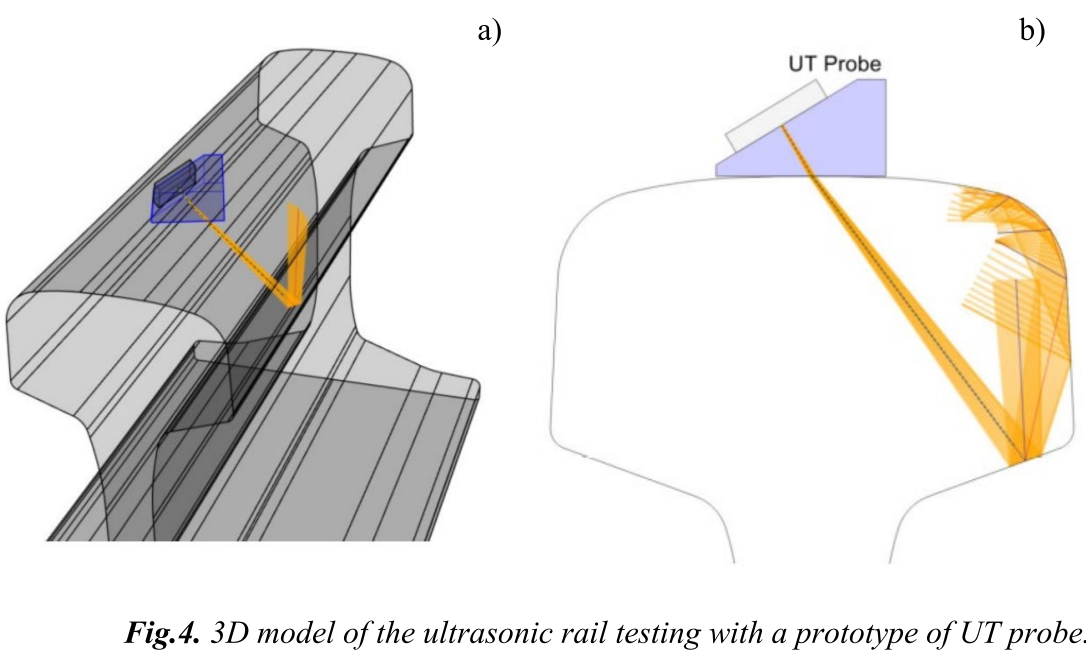

Fig.4. *3D model of the ultrasonic rail testing with a prototype of UT probe.*

The basic limitation of the used simulation environment is its form of the physical foundations based on the ray-tracing model [4]. That means that the ultrasound beam is modeled geometrically as a bundle of rays coming from the center of the transducer. According to the laws of geometry and optics, they are subject to subsequent refractions and reflections from defects or boundary shapes of the tested element. This approach is very beneficial and effective from the point of view of spatial modeling of the wave propagation in the complex shape models. But it does not include the effects of beam diffraction for rays reflected from discontinuity edges [3]. The defect will produce its reflected beam with specific diffraction, and part of that energy will go back to the head of the transducer.

The calculations were based on the ray-tracing model to complete the more advanced and accurate simulation results. The calculation algorithm follows the Huygens principle, performs calculations for all elementary point sources on the transducer surface, and sums the calculated partial pressures at the field point. In this way, we obtain the value of the sound pressure generated at each field point by the entire transducer. Additionally, the used program calculates the defect reflections using the wave solution with the Green's function with Kirchhoff's approximation [5]. It allows taking into account the diffraction divergence of the reflected beams from the model defect. Apart from the finite element method, it is the most accurate theoretical model currently available to calculate the reflection/scattering of ultrasound waves on any model defects.

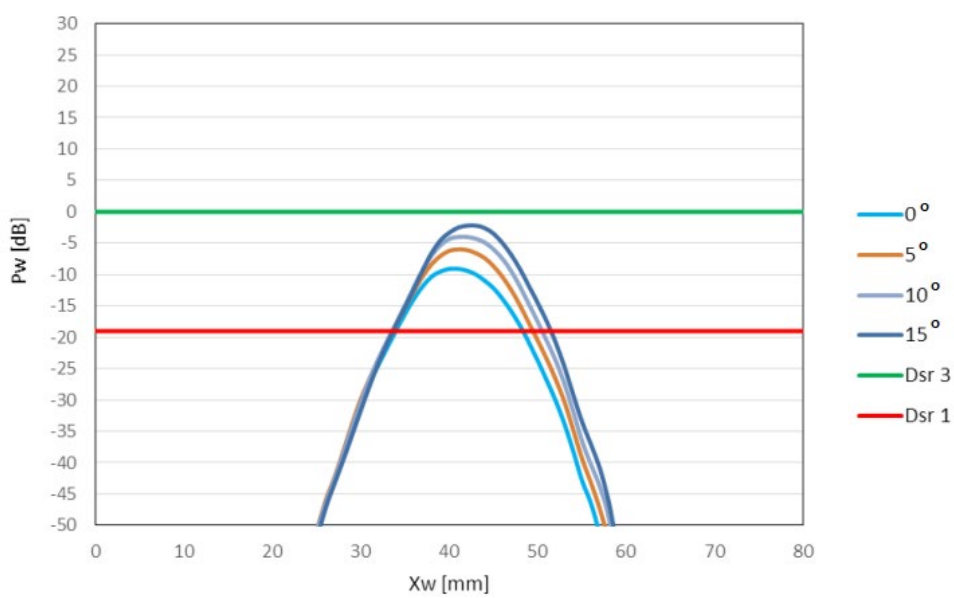

Fig 5. *Echo course of the model defect (DSR 8mm) situated 10mm under the running surface in relation to the deviation from the horizontal plane [6].*

The configuration of the prototype double probe with the longitudinal wave was subjected to numerical tests on the characteristic model defects of advanced head check discontinuities. The model defects DSR 8 mm located at a depth of 10 mm were considered. The variable values in the simulations were the orientation of defects and their distance from the rail axis. Fig. 5 shows the course of the echo envelope of model defects depending on the deviation of their orientation from the horizontal orientation. The Xw value is the distance between the transducer and the crack. The centers of all model defects were at the same distance from the rail axis, equal to 20 mm. The reference reflector, in this case, was a DSR 3 mm, located 50 mm from the head. All model defects gave echo envelopes with a maximum height exceeding the detection threshold by at least 10 dB. As shown in Fig. 6, only defects located less than 20 mm from the rail axis provide useful echoes to detect them.

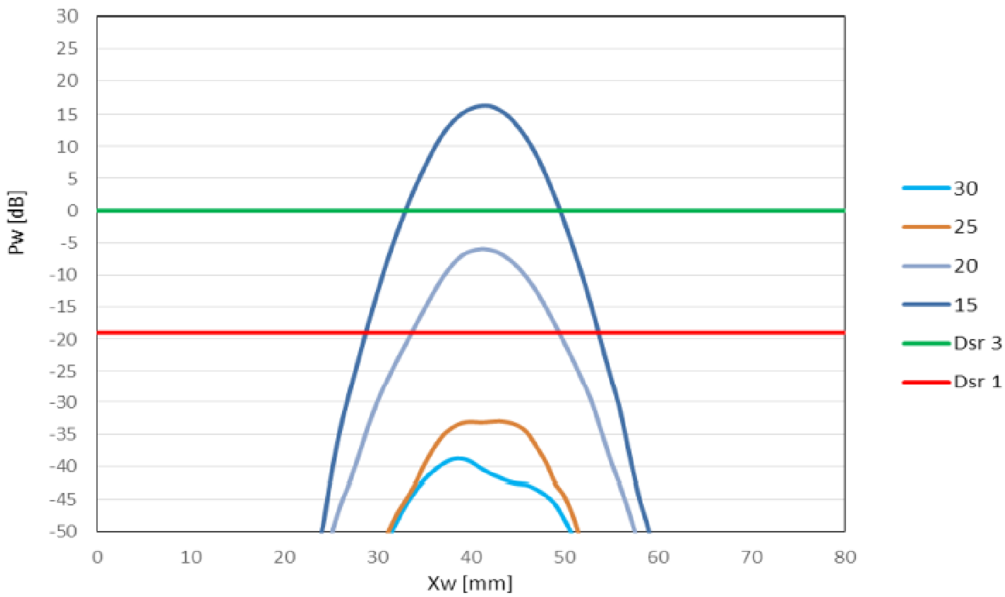

Fig 6. *Echo course of the model defect (DSR 8mm) situated 10mm under the running surface in relation to the horizontal distance between the axis of the defect and the longitudinal axis of the rail [6].*

Summary

Knowing the nature of the fracture and the way of propagation is very helpful in designing model defects. The used software is an essential tool for computer-aided ultrasonic testing of rails. The commercial program (ray tracing) was valuable in projecting the head guiding. It was also helpful to observe the shape of the beam and the wave transformations. In the aftermath, it is well prepared for the initial analysis of various test configurations, especially where different reflections from the rail's boundary surfaces may be important.

The proprietary program used there allows for a much more accurate quantitative modeling of the amplitude distribution of the ultrasonic beam and the waves' reflections from model defects. The diffraction phenomena are considered in the pencil tracing model implemented in the program.

Both programs used together and compared the developed results were a very effective set of software for computer modeling ultrasonic rails tests.

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