ANALYSIS AND INVESTIGATION ON DEFECTS – DELAMINATION AND SPALLING OF METAL ON ROLLING SURFACE OF RAIL HEAD UNDER CODE X 10.1

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Abstract. One of the main defects in rail steel is a defect on the rolling surface of the rail head. A sign of the defect appearance is delamination and spalling of the metal on the rolling surface. The development of this type of defect to a length of more than 25 mm and a depth of more than 4 mm requires a decrease of the train speed up to 70 km·h^{-1}, and with a depth of more than 8 mm - to 25 km·h^{-1}. Reducing the speed significantly affects the quality of service and railway performance. As a result, there is a disruption in the accuracy of train traffic, which subsequently leads to material costs for restoring the movement of trains at set speeds. The primary task of the study presented in this article is the collection and analysis of statistical information on the Latvian Railway defective rails in the period from 2011 to 2021. A secondary task is to investigate the causes of the appearance of rail defects under code X 10.1. The research process included: detection of these defects on the Latvian Railway using a modern ultrasonic flaw detector of the “RDM-24” type, determination of the metal hardness (EN 13674-1:2011 standard 350-390 HB) in the rail head and on the rolling surface using a certified modern device “Tinius O Olsen” Firmware Version 1.07, FH - 31 Series as well as the study of the chemical composition of the rail head using the optical emission analyzer PMI - Master PRO and determination of the microstructure of the metal in the rail head. At the final stage, to compare the results obtained in an independent certified laboratory, based on the results of the research to draw conclusions about the causes of this type of defect.

Keywords: rail, metal delamination, defect, hardness, chemical elements, metal microstructure.

Introduction

Rails during operation impact, measured as the tonnage in million gross tons passed, are usually worn, crushed, smashed and fatigued, including contact, bending and corrosion fatigue. At the stage of operation up to a tonnage of 150-250 million gross tons, cracks and spalling on the rolling surface accumulate due to the presence of metallurgical origin defects (hairline, laps, scabs, bainite areas in rare cases). In the late stages of operation, after passing more than 150-250 million gross tons, cracks and spalling on the rolling surface accumulate as a result of multiple exposure to high contact tension. Longitudinal horizontal cracks with a depth of up to 8.0 mm should be attributed to the Defect 10.1-2. The rail defect has deviations from the prescribed geometric parameters or strength norms, compliance with which provides rail performance in accordance with operating conditions.

Defective rail (X)

A rail which service properties gradually decrease below the standard level during operation, but which still ensures the safe passage of trains, although in some cases the introduction of a speed limit is required. Such rails are to be replaced during routine maintenance. In our case, we will talk about a defect under the code X 10.1 [1]. The defect under the code (X 10.) stands for delamination and spalling of the metal on the rail head rolling surface, number 1 indicates that the defect is located in the rail joint area [1]. The purpose of this study is to establish the maximum and minimum parameters of the rail at which a break of the rail part is possible. The results obtained will be tabulated and analyzed in detail, as well as compared with similar studies conducted in such countries as Belarus and Russia. The primary objective of our study was to identify this type of defect on the Latvian railways. Using a modern ultrasonic flaw detector RDM - 24 with an angle of entry of the detector RS at cahibage 221,6 of the Jelgava-Krustpils line Vecumnieki – Lāčplesis section, this type of defect was detected in an isolated joint of the 60 E1 rail. This rail was installed in 2010. The tonnage passed in this section amounted to 302 million gross tons with an average cargo density of 35 million gross tons per year. Figure 1 shows the decoded diagram of the defect, from which follows the depth of the defect $H = 4$ mm, length $L = 36$ mm [1]. After determining the parameters of the defective rail, a fragment of the defective rail was cut out using a rail saw. This peace was used for a part of the study for determining the hardness, chemical composition and determination of the microstructure of the metal.

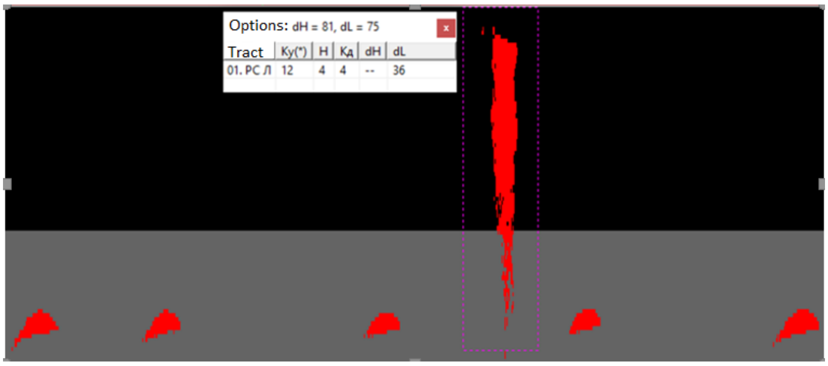

Fig. 1. **Decryption of a defect under the code X10.1 using a specialized flaw detection program model 1.4.8,** note: In 2011, the primary grinding of the rails was carried out by the "Speno" rail grinding train.

According to the data of the Latvian infrastructure maintenance company, the statistics of defects on the Latvian Railway was analyzed and compared with foreign statistics of rail defects [2] (corrected statistics graph).

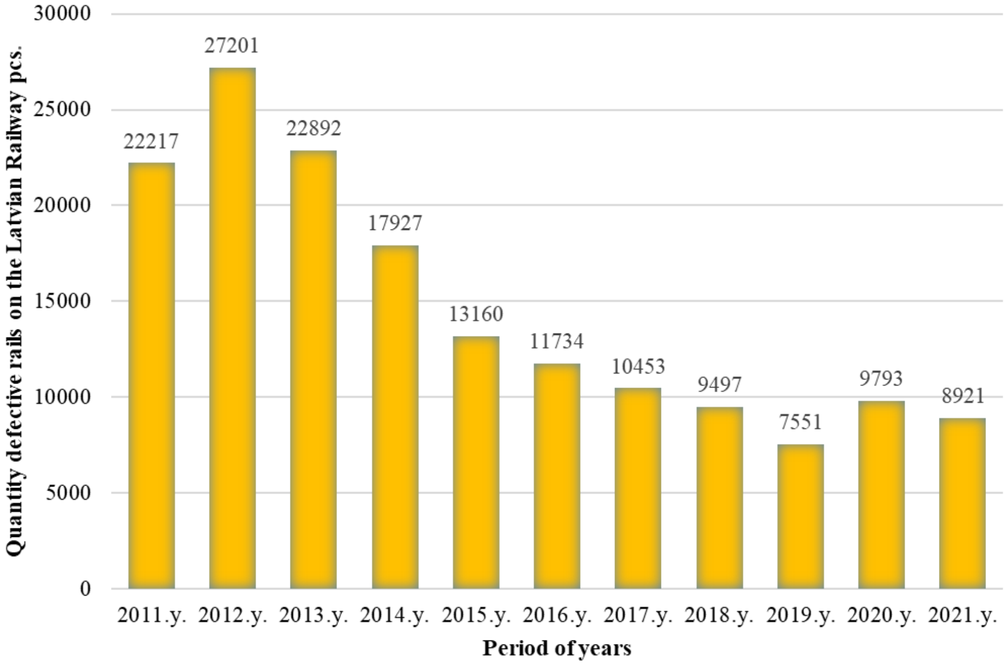

Fig. 2. **Statistics of the total number of defective rails on the Latvian Railway from 2011 to 2021**

From the provided analysis of defective rails shown in Fig. 2 in the period from 2012 to 2019, the number of defective rails on the Latvian Railway noticeably decreased from 27201 to 7551 [2]. The largest number of rail defects in the amount of 27201 was in 2012. In 2013 the number of defects decreased to 22892 cases. From 2014 to 2019, the number of defects has significantly decreased from 17927 to 7551, indicating that the first priority of the Latvian Railway is the safe and uninterrupted movement of trains at the established speeds. However, in 2020 the number of defective rails increased to 9793 and decreased slightly in 2021 to 8921 cases [2].

Despite the decrease in freight traffic, the problem of defective rails remains relevant for the Latvian Railway. According to the statistics of the amount of freight transported by rail in Lithuania from 2007 to 2021, [3] the amount of cargo transported amounted to 218.088 or an average of 14.539 gross million tons per year. Based on the statistics on the amount of freight transported by rail in Latvia from 2007 to 2021, the number of transported cargo amounted to 254.064 or an average of 16.937 gross million tons per year [4]. From the collected and analysed data on defects and freight traffic on railways, in particular Lithuanian and Latvian, it can be concluded that with an increase in the missed tonnage, the number of defects in rail steel also increases [5]. The main defects of group I are: delamination and spalling of metal on the rolling surface.

Next, consider the statistics on the Ukraine railways. Figure 3 shows the defect percentage chart.

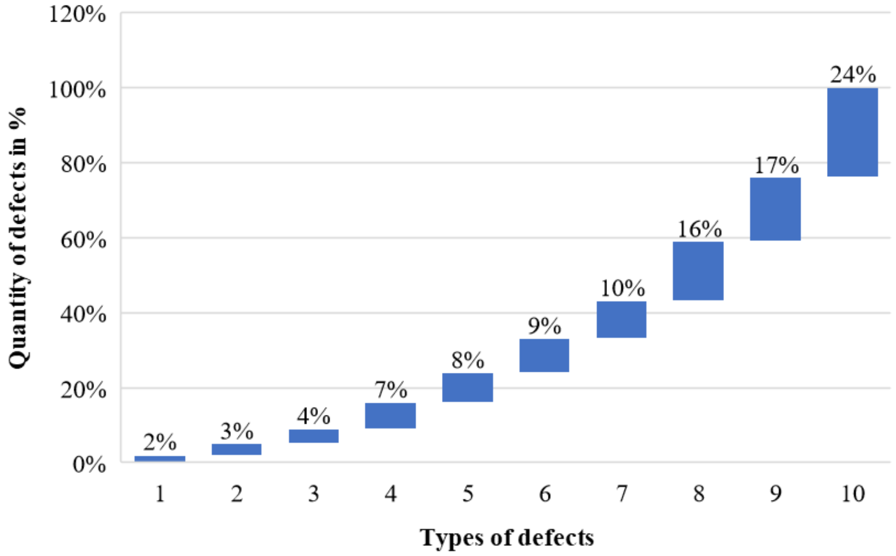

Fig. 3. **Statistics of defective rails on the Ukraine Railways in 2021:** 2% – defective rails under code X 43.1; 3% – defective rails under code X 99.0; 4% – defective rails under code X 18.1-2; 7% – defective rails under code X 11.1-2; 8% – defective rails under code X 17.1-2; 9% – defective rails under code X 44.0; 10% – defective rails under code X 41.0-1-2; 16% – defective rails under code X 10.1-2; 17% – defective rails under code X 14.0-1-2; 24% – defective rails under code X 46.3-4

From the statistics of defects for 2021 on the Ukraine railways, the main defects are defects under the codes X 46.3-4 smashing and vertical wear of the rail head in the welded joint area (24%), X 14.0-1-2 wheel slip impact in the form of local wear and spalling of metal in places of the more mechanical damage to the rail head (17%) and X 10.1-2 cracks and spalling of metal on the surface of the head tread (16%). 10% of defects under the X 41.0-1-2 code are smashing and vertical wear of the rail head [6]. One of the most common defects on the railways of the world is a defect under the code X 44.0 lateral wear of the railhead exceeding the permissible norms, which makes up 9% of the total number of defective rails on the Ukraine railways. No less important is the defect under the code X 17.1-2 of metal spalling on the head rolling surface, which is 8%. The defect code X 11.1-2 cracks and metal spalling on the side working fillet on the middle part of the rail head is 7%. Defects - spalling of the deposited metal layer in the places of surfacing under the code X 18.1-2 make up 4% of the total statistics, and other than listed above defects under the code X 99.0 are relevant on Ukraine railways. 2% – defective rails under the code X 43.1, smashing of the head in the form of a saddle in the area of the bolted joint [7], are detected on the Ukraine railways. This statistic once again confirms the actuality of the problem of defective rails in the head and on the rolling surface both on the Latvian railway and on foreign railways [8].

Hardness in the rail head of steel R350HT

During operation, this defect was cut out and a fragment with a defective place was delivered to the metallographic laboratory of the Riga Technical University. Further, in the laboratory, a detailed sawing and grinding of the defective fragment was carried out. Then, for a more detailed study of this type of defect using the modern device “Tinius O Olsen” Firmware Version 1.07, FH - 31 Series in accordance with the standards (ISO 6508, ISO 2039/1, ASTM E18, ASTM B254, JIS Z2245) the defective rail was checked for hardness on the Brinell scale (HB). Fig. 4 shows the tested defective rail points [7].

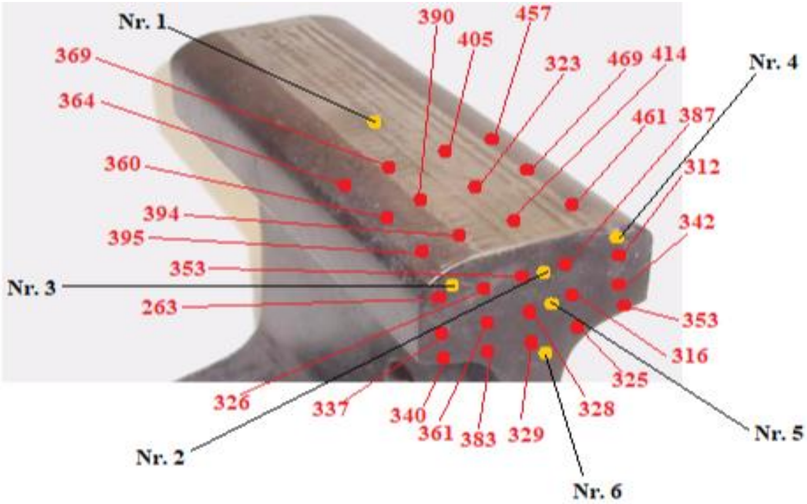

Fig. 4. **Determination of the hardness of rail steel with rail type 60 E1T**

On the head rolling surface (point 1) HB: 364, 360, 395, 394, 390, 369, 405, 323, 414, 461, 469, 457. At a depth of 10 mm from the head rolling surface (point 2), not less than HB: 326, 353, 387. At a depth of 10 mm from the surface of the rail fillet (points 3 and 4), in HB: 263, 312. At a depth of 22 mm from the rail head rolling surface (point 5) HB: 337, 361, 328, 316, 342. At a depth of 35 mm in the transition of the rail head to the web at (point 6) HB: 340, 383, 329, 325, 353.

Further, on the basis of the obtained data, Table 1 was compiled in which the average hardness values are shown at the place of determination (points 1-6).

Table 1

Table of average set hardness values with manufacturer's plant

Place of hardness test	Determination of rail hardness R350HT	
	Factory indicated hardness (HB)	Medium measured hardness (HB)
On head rolling surface (point 1) HB	350-390	400
At a depth of 10 mm from the head rolling surface (point 2), not less than HB	341	328
At a depth of 10 mm from the surface of the rail fillet (points 3 and 4), not less than		
At a depthof 22 mm from the rolling surface of the rail head (point 5), not less than	321	336
At a depth of 35 mm at the rail head-to-web transition (point 6) in HB:	362	346

The study on the hardness of a defective rail had the following results: the average hardness on the rolling surface of the rail head (point 1) was 400 HB, which is 10 HB higher than the required value. Such hardness is typical for the joint area, due to hardening caused by rolling stock wheel impact at the rail gap [9]. At a depth of 10 mm from the rolling surface and the fillet of the rail head (point 2 - 3 - 4) the average hardness was 328 HB, which is 13 HB less than the required one. It is within this depth that the surface defects of delamination and spalling develop; in our case, the defect was located within this depth. At a depth of 22 mm from the rolling surface of the rail head (point 5), the hardness of the rail steel was 336 HB, which is 15 HB higher than the required value. The hardness of the defective rail at a depth of 35 mm at the transition of the rail head to the web (point 6) was 346 HB, which is 16 HB less than the require done. A carried out study on the hardness of a defective rail showed a decrease in the hardness of the metal at a depths of 10 mm and 35 mm.

Determination of mass fractions of the chemical composition of rail steel

The chemical composition of rail steel is the main criterion in the production of all types of rail steel and steel R350HT in particular. To determine the mass fractions of chemical elements, a modern chemical analyzer PMI - Master PRO was used, which operates on the principle of local burning of the sample surface, followed by determination of the chemical composition and output of the obtained data to a printing device. Before determining the chemical composition on the standard, the instrument was calibrated in accordance with the manufacturer’s passport data. The determination of the chemical composition was carried out in three elements of the rail head. Table 2 summarizes the average allowable values for the chemical composition of a defective rail under code x 10.1 [10]. Further, using the chemical analyzer “PMI – Master PRO”, the complete chemical composition of R350HT rail steel [11] was determined. The results of the chemical composition are given in Table 2.

Table 2

Table of the chemical composition of the investigated defect under the code X10.1

Values	Fe	C	Si	Mn	P	S	Cr	Mo	Ni
Max/Min	-	0.570 0.650	1.00 1.30	0,700 1,10	0.0000 0.0600	0.180 0.250	0.0000 0.200	0.0000 0.100	0.0000 0.200
Head%	97.6	0.707	0.359	0.896	0.0600	0.0193	0.0190	0.0030	0.0439
Values	**Al**	**Co**	**Cu**	**Nb**	**Ti**	**V**	**W**	**Pb**	**Zr**
Max/Min	0.0000 0.100	0.0000 0.100	0.0000 0.400	0,0000 0,0700	0.0000 0.0500	0.0000 0.100	0.0000 0.100	0.150 0.350	-
Head%	0.0020	0.0395	0.0077	0.0056	0.0023	0.0396	0.0250	0.0100	0.0030

In Table 3 the main indicators of the values of the chemical composition of type 60 E1 T rails produced at the Nizhny Tagil Metallurgical Plant are given.

Table 3

Table of average values (in percent) of the chemical composition of type 60 E1 T rails produced at the Nizhny Tagil Metallurgical Plant

Values	C	Mn	Si	P	S	Cr	Ni	Cu	Al
Max/Min	± 0.02	± 0.05	± 0.02	+ 0.005	+ 0.005	± 0.02	-	-	+ 0.001
Average%	0.766	0.963	0.360	0.011	0.010	0.0367	0.0483	0.0083	0.0026
Values	**V**	**N**	**H, ppm**	**O2**					
Max/Min	+ 0.02	± 0.005	-	-					
Average%	0.0393	0.00457	1.3	0.0012					

In the process of determining the chemical composition of the steel of the rail [12] fragment with defect code X10.1 [13] in the the railway engineering department laboratory of the Riga Technical University, the following discrepancies were identified. In the declared passport data of the manufacturer according to the EN 13674-1:2011 standard, the following chemical elements were not indicated: (Mo) molybdenum - increases red hardness, elasticity, tensile strength, anti-corrosion and oxidation resistance at high temperatures, (Co) cobalt - increases heat resistance, magnetic properties, increases impact resistance, (Nb) niobium - improves acid resistance and helps reduce corrosion in welded structures, (Ti) titanium - increases strength and density of steel, promotes grain refinement, is a good deoxidizer, improves machinability and corrosion resistance, (W) tungsten - forms very hard chemical compounds in steel - carbides, which sharply increase hardness and red hardness, tungsten prevents grain growth during heating, helps eliminate brittleness during tempering, (Pb) lead - an accidental impurity in steel, has a noticeable effect on its mechanical and physical properties, as well as on corrosion resistance, (Zr) zirconium - has a special effect on the size and growth of grain in steel, refines the grain and allows to get steel with a predetermined given grain size [14]. The content of (Al) aluminum is reduced by 0.0006% and is 0.0020%. The (Cr) chromium content complies with EN 13674-1:2011 standard [15] and is 0.0190%. The percentage value of such a chemical element as (N) nitrogen was not revealed during the studies. (V) vanadium - increases hardness and strength, grinds grain, increases the density of steel [16], as it is a good deoxidizer in acceptable values and is equal to 0.0396%. Let us compare the main obtained average statistical data of the chemical composition with the data of the manufacturer [17]. The comparison is shown in Table 4.

Table 4

Comparison of obtained data on the main elements of the chemical composition with the standard EN-13674-1:2011

Values	C	Si	Mn	P	S
EN-13674-1: 2011 standard	0.746-0.786	0.34-0.38	0.913-1.013	0.016	0.015
Mean obtained values	0.707	0.359	0.896	0.060	0.0193
Difference%	< 0.039	corresponds	< 0.0017	> 0.044	> 0.0043

Comparing the main values of the chemical composition, we can conclude: the carbon content is reduced by 0.039%, the chemical element silicon complies with the EN 13674-1:2011 standard [15], the manganese content is reduced by 0.0017%, the phosphorus content is also increased by 0.044% as well as the sulfur content is increased by 0.0043%. It is known that the content of (C) carbon increases the hardness and wear resistance of rail steel, (Mn) manganese - increases the hardness and wear resistance of steel, providing sufficient toughness, (P, S) phosphorus and sulfur are harmful impurities, they make the steel brittle: with a high content of phosphorus, the rails are cold-brittle, with a high sulfur content, they are red-brittle.

After studying the chemical composition using a stationary oil-cooled cutting machine "MECATOME T 255/300", the defective fragment of the rail head was sawn into three parts.

Then these rail fragments were placed in a hot pressing section using a modern press "Mecapress II".

Then, after pressing out the finished sample, using a grinding and polishing machine of the "Mecatech 334" system with water cooling, the template was ground and polished.

After grinding and polishing the template using a digital microscope "Carl Zeiss Axiovert 40 MAT" at x50 magnification, the structure of the metal of the defective place of the rail head was determined, Fig. 5.

At x50 magnification, the delamination of the rail head in the form of black stripes is clearly visible. The presence of such a branching can lead to a more dangerous acute defect under the code XX30.1 to the horizontal delamination of the rail head [18]. The presence of such cracks in the rail head and the increased dynamic impact from the rolling stock can lead to the puncture of a part of the rail head, which can lead to the derailment of the rolling stock wheelsets. Let us look at the microstructure of the rail. To do this, a defective sample template was etched using a 5% solution of nitric acid HNO3 [19]. Then this sample was examined under a microscope at x200 magnification, Fig. 6.

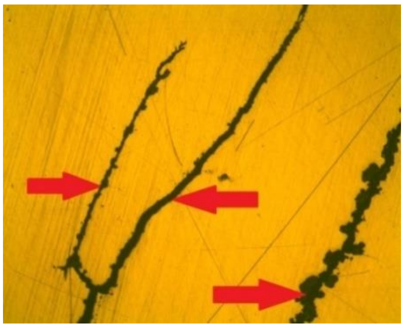

Fig. 5. **Metal structure of a defective rail T VI 08 60E1 at x50 magnification**

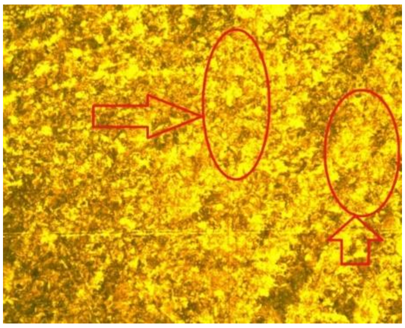

Fig. 6. **Microstructure of X10.1 defect at x200 magnification**

The microstructure of steel R350HT is ferrite – pearlitic. In Fig. 6 a large accumulation of perlite (red arrows show their accumulation) is vissible, which occupies more than half of the total volume. To determine the measurement accuracy and study a defective rail [20] sample under code X 10.1, it was decided to carry out an independent examination at the certified laboratory KIWA JSC "Inspecta Latvia". According to the results of the examination of the studies carried out in the certified laboratory KIWA JSC "Inspecta Latvia" [15], it can be concluded that the results of the studies carried out in the metallographic laboratory of the Riga Technical University are valid. This confirmation of the results will allow us to draw accurate conclusions and give recommendations on extending the service life of the railhead.

Results and discussion

The data for determining the hardness of defective rail steel showed a decrease in the hardness of the metal at a depth of 10 mm and 35 mm from the head rolling surface with 341-328 HB at a depth of 10 mm and from 362-346 HB at a depth of 35 mm. The chemical composition data showed non-compliance of the chemical elements (Mn, C, P, S) quantity according to the EN 13674-1:2011[15] standard. The manganese content is reduced by 0.017%, the percentage of carbon is reduced by 0.039%, it is known that (Mn) manganese increases the hardness and wear resistance of steel, providing sufficient toughness, (C) carbon increases the hardness and wear resistance of rail steel. The phosphorus content is increased by 0.044% as well, and the sulfur content is increased by 0.0043%, with a high content of phosphorus, the rails are cold-brittle, with a high sulfur content, they are red-brittle. Examination of a defective rail under the code X10.1 at the Riga Technical University laboratory is confirmed with the test results of the certified laboratory KIWA A/S "Inspecta Latvia", which proves the accuracy of the studies.

In the article by Zengzhen, M.; Ren, C.; Shanshan, Z. [16] the detection algorithm for rail surface defects is proposed. The improved YOLOv4 defects detection algorithm not only inherits the feature fusion effect of the original structure, but also can obtain more shallow features while reducing the network parameters and improving the feature extraction capability of small targets. The average processing speed of a single image is only 13 ms higher than YOLOv4, which is also very close to the detection speed of YOLOv6. Efficient and accurate detection of rail defects is achieved, where the recognition accuracy of 4 defects, namely, cracks, scars, wear and peeling, reaches 94.8, 94.0, 89.7, and 92.2%, respectively. Various modifications of defectoscopes (RDM-23, 24) of the Moldavian manufacturer are widely used on the Latvian Railway, which are also able to accurately determine the location of defects in the rail [21]. However, the proposed method and algorithm for detecting defects in the rail in this article differs from the method at the Latvian Railway which also requires accurate access to real-time information.

In the publication by Ivanov I.A., Kushner V.S. [22] the question of the prospects for the use of shroud wheelsets of increased hardness is considered. To assess the wear resistance of the material, the authors took into account both characteristics – hardness and ductility.

Experimental studies to assess the wear intensity of the wheel and rail metals showed that an increase in the hardness of wheel steel from 280 HB to 360 HB leads to a decrease in wear. An increase in the hardness per unit of HB reduces wear by one percent. Yes, indeed, the hardness of the metal on the surface of the wheel and the rail is of great importance in the interaction between the wheel and the rail. In our study, it was also scientifically proven that reduced hardness on the tread surface contributes to rapid development of defects.

Conclusions

1. The main reason for the appearance of a defect under the code X 10.1 is the shortcomings in the manufacturing technology, due to which small cracks and hairlines form on the rail, which, in the further process of operation, under the impact of the rolling stock and during further operations until the tonnage of 302 million gross tons, leads to the formation of delaminations and metal spalling on the rolling surface of the rail head. Parameters of the defect exceeding the length of more than 25 mm and depth of more than 8 mm require reduction of train speed to 25 $km \cdot h^{-1}$.
2. Reduction of the chemical elements manganese (0.8960%) and chromium (0.0190%) identified during the study entails a decrease in impact toughness, overall strength and hardness of rail steel at a depth of 10 mm from the surface of the rolling head, hardness of rail steel must be at least 341HB, in our study it was established 328 HB.
3. According to the research results, an increased content of phosphorus (0.0600%) and sulfur (0.0193%) increases the brittleness of rail steel and the tendency to crack.
4. The microstructure of the metal under the microscope confirms the presence of cracks and hairlines in the head of the defective rail, which adversely affect the surface condition of the rail head, which can cause surface defects and their development.

5. As a recommendation for extending the service life of the rail head, periodic continuous grinding of the head surface using rail grinding trains can help. Grinding the surface of the rail head will remove surface defects and remove the decarburized metal layer, as well as improve the smoothness of the train ride, extend the life of the track structure and rolling stock wheelsets.

Acknowledgements

From a foreseen study of a defective rail under code X 10.1, it can be argued that a significant part of the hairline defects, cracks and laps are formed in small sizes from 0.05 - 1 mm during the manufacture of rail steel. And certain passed million tons gross tonnage and depending on the location of this rail (curve, joint, welded places), the process of development of the defect and its release to the rolling surface occurs. If the damage is deeper than 8 mm, the rails are replaced as a matter of priority.

Author contributions

Defectoscopy of rails V.I.; Preparation of the object for the research process (cutting out the railway track and cutting into templates) V.I. Research in the metallographic laboratory of RTU (hardness, chemical composition, metal structure) P.G. and V.I.; Statistics, EN standards, analysis and data curation, V.I. and P.G.; writing, translating – review and editing, P.G. and V.I.; visualization, V.I., project administration, V.I. and P.G.; funding acquisition, P.G. All authors have read and agreed to the published version of the manuscript.

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