RIGA TECHNICAL UNIVERSITY
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ANALYSIS OF THE IMPACT OF RAIL GRINDING ON THEIR CONDITION

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 2 September 2021 at 14.00 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Ķīpsalas Street, Room 204.

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I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Viktors Ivanovs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 5 Chapters; Conclusions; 92 figures; 17 tables; 3 appendices; the total number of pages is 140. The Bibliography contains 65 titles.

ABBREVIATIONS

60 E1, R65 – types of rail profiles;
C – carbon;
Mn – manganese;
Si – silicon;
V – vanadium;
Cr – chrome;
P – phosphorus;
S – sulphur;
Al – aluminium;
Cu – copper;
Ni – nickel;
Ti – titanium;
W – tungsten;
Mo – molybdenum;
Co – cobalt;
Pb – lead;
Zr – zirconium;
HNO_3 – nitric acid liquid;
R350HT, R350LHT, R260 – steel brand;
HB, HBW – hardness values by Brinell scale;
X 10, 11, 17, 1-2 – defect codes of rail head running surface;
R – curve radius, m;
h – depth, mm;
a – width, mm;
l – length, mm;
mil. t. gross – transmitted tonnage;
E – elasticity module;
M – scale;
PŠV (TU 3933-002-060632410-2012) – verniercalibre of road;
H_p – shown wear of the rail;
D – diameter of rolling rim;
D_a – diameter of inner surface of rim from the outside of the wheel;
D_i – diameter of inner surface of rim from the inside of the wheel;
B – width of wheel rim;
hu – flange height;
D_{ra} – outer surface diameter of the hub from the outside of the wheel;
D_{ri} – outer surface diameter of the hub from the inside of the wheel;
d – diameter of the whole in the hub of a wheel;
B_r – length of the hub of the wheel;
r – distance from end surface of the hub till side surface of the rim from the inside of the wheel;

B_{dl} – thickness of disc by the rim of the wheels;
B_{dr} – thickness of disc by the hub of the wheels;
h – elevation of outer rail, mm;
V – movement speed of freight wagon, km/h;
T – temperature;
R_I - wheel radius in contact with the inner edge of the rail;
ΔR_o – deviation of wheel radius in two contact places of outer profile;
[kus] – allowable value of stability ratio for freight wagons;
b – slant angle of wheel flange and horizontal axis;
μ – slip friction ration for non-rolling wheel to the head of the rail;
P_{v1} – vertical component of reaction forces of on-rolling wheel on the rail head, tf, MPa;
P_{v2} – vertical component of reaction forces of non-rolling wheel on the rail head, tf, MPa;
P_h – horizontal component of reaction force of on-rolling wheel on the rail head, tf, MPa;
$P_{st}(m)$ – vertical static load acting on the neck of the axis, tf, MPa;
$kd.s.\check{s} = 0.25\overline{Kd.v.}$ – average value of lateral swinging dynamic ratio;
$H_{\mathrm{r}} = p_{\mathrm{a}}\overline{Kd.h.}$ – average value of frame force;
p_a – load of axis;
$qr.p.$ – force of gravitation of wheelset with acle box;
b – ratio of number of axis in bogies;
δ – ratio depending on suspension elasticity of freight wagons;
v – movement speed of wagon, m/s;
$2B_2$ – distance between the middle part of necks on wheelset axis;
a_1, a_2 – distance between contact points of wheels and middle of the axis neck;
r – radius of the wheel;
l – distance between contact points of the wheel and the rail;
TMP – technical maintenance point.

ANNOTATION

The Doctoral Thesis “Analysis of the impact of rail grinding on their condition” is developed by Viktors Ivanovs to obtain a Doctoral Degree in Engineering. The scientific supervisor is Assoc. Professor Dr. sc. ing. Pāvels Gavrilovs.

In this Doctoral Thesis rail steels are considered according to standards EN 13674-1:2011 and GOST R 51685-2013. Rail steel defects and reasons for their causes are reviewed. The statistics of damaged and heavily damaged rails in the network “Latvijas dzelzceļš” in the period 2011–2019 is studied and analysed in detail. The statistics of rail grinding train operation in “Latvijas dzelzceļš” within the year period 2011–2019 is gathered and analysed. A research of hardness of 60 E1 type rail running surface, of metal chemical composition of the damaged rail with code X 10.1., and structure analysis was performed. Likewise, statistics of wheelset rejection in the network “Latvijas dzelzceļš” in the period 2016–2019 are gathered and analysed, as well as the number of wheel rim defects in the railway of Russian Federation. The main defects of wheelsets are reviewed. The actual wear of wheels and rails in Latvia and the stated wear in the railway of Russia are modelled. Repair profiles of rail head grinding for Latvian rail ways are modelled and their influence on side wear determined due to the rail and wheel surface interaction. Calculations regarding the wheels with flange angle of 66.8° from worn out profile durability coefficient were performed for Latvian railway according to the entry conditions on rail profiles, developed in this dissertation. A rail grinding method was developed. The wheelset repair and wheel grinding economic expenses were calculated.

Recommendations for wheel and rail side wear reduction are presented.

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INTRODUCTION

Topicality of the Subject

The most expensive and responsible elements of railroad rails, whose condition firstly determine the continuous and safe movement of trains, are rails and wheelsets. To maintain the management of rails and wagons in workable condition, more than 3020 tons of new rails and 700 wheelsets are needed annually. On average, in 8 defectoscopy workshops of “Latvijas dzelzceļš” more than 15 848 damaged and 277 highly damaged rails are detected every year. In maintenance point or wagon depos on average more than 521 damaged wheelsets are detected annually. Timely undetected damage of a wheelset and highly damaged rails can lead to breakage of wheels or rails, resulting in running off of the wheelset (bogies) of rolling stock. A promising direction to address this problem is rail grinding technology using rail grinding trains, allowing a mechanical treatment of the rail head without dismantling from the rail road conditions. The list of rail defects that have to be eliminated by using this grinding technology is extensive and includes the following: wave type wear, mechanical damages, flattening and delamination of metal. In addition, one of the main goals of the grinding is the creation of rail cross-profile. Periodic harmonized wheel and rail profile grinding will provide the best possible wheel contact with the rail, evenly distributing inner tension on the surface of wheel and rail, thereby extending operational resources by 15 % … 20 %. The performance properties of rails are determined by counteracting the formation and development of cracks, contact fatigue and wear, the occurrence of which depends to a significant extent on the quality of profiling of the rail head and wheel rolling surface.

Goals and Objectives

Goal

60 E1 and R65 type rail grinding with research of rail grinding rail effectivity in “Latvijas dzelzceļš” rail road curvilinear and straight stations. To develop a harmonized method for rail repair and grinding of asymmetric profiles to reduce the vertical side wear of rail head, as well as to reduce the number of grinded wheels in “Latvijas dzelzceļš” network.

Tasks

1) to examine technical parameters of rail iron by their importance, chemical consistency and hardness;
2) to research and analyse rail steel defects;
3) to gather and analyse the statistics of rail damages in “Latvijas dzelzceļš” network in the past nine years, determine the most often found defects in the defectoscopy warehouses, prevent them and decrypt them by their defect codes;
4) to gather and analyse the statistics of train performance of rail grinding in “Latvijas dzelzceļš” network in the past nine years;

5) to carry out a research on hardness of 60 E1 type rail running surface and damaged rail with code X 10.1. and compare the testing results;
6) to research the interaction effects pf railway wheels and rails, ultimately performing a 3D modelling of the elements;
7) to perform research of wheel and rail profile actual wear in "Latvijas dzelzceļš" network;
8) to develop grinding profiles for preventive recurrent rail head grinding;
9) to make an assessment of profile grinding effect on rail and wheel connection in tensioned state;
10) to perform a performance safety test on the requirements on offered grinding profile after rolling on the flange on the rail;
11) to calculate the economic comparison between rail grinding and wheelset restoration repair works or replacement.

Recommendations to be developed

1) to develop a rail grinding method to reduce rail side wear in "Latvijas dzelzceļš" network.

Research Methods and Methodology

In the research work, experimental and analytical methods to determine the hardness, chemical composition and material structure of damaged and heavily damaged rails are used. Ultimately, performing a 3D modelling of the elements in program Solid Works Simulation Professional using materials and operation requirements used in "Latvijas dzelzceļš", models are projected by applying the interaction of wheelsets: new rail with a new wheel, new rail with a worn-out wheel, worn-out rail with a new wheel, worn-out rail with a worn-out wheel, grinded rail with a new wheel and a grinded rail with a worn-out wheel. The needed information was acquired in the research of the actual data, from the analysis of the production documentation, and literature source of other authors, using analysis and comparison method, as well as based on reports, technological maps, tables and graphs.

Scientific Novelty and Main Results of the Research

1. The Study Programme.
2. A three-dimension modelling of wheel interaction with the rail was performed using the developed rail profile, allowing to determine the rail grinding effect on the tension level of the pair wheel-rail.
3. The rail asymmetric profiles with the least interaction with rail and the smallest number of grinding times are developed as the recommended profiles for rail grinding. The base angles of grinding for asymmetric profile surfaces can reach from 2.68° up to 2.41° for the outer rail and from 2.36° up to 4.61° for the inner rail.

4. The changes of rail grinding level allowed to increase the contact zone, thus reducing the tension on the outer rail in a curve by up to 18 % and divert part of the tension from the wear zone of the side of the wheels on the base of the wheel flanges. The offset reached from 5 mm to 30 mm, the wheel radius difference reaches 5.60 mm in one wheelset, improving the integration of the wheelsets by 4 times.
5. The economic analysis confirms the necessity to use the developed new and repair rail profiles by performing grinding to avoid the repair expenses of the damaged wheelsets.

Practical Application of the Work

On the basis of the proposed recommendation and the research of the performed method, the operational lifetime is significantly extended, the number of uncoupling of carriages from the train is reduced. Ultimately, it will be possible to reduce part of top and inner defects of the rail head, to improve the ability of the rolling stock to fit into the curve, to prevent damages of the inner rail thread of the curves in case of a wheel with a misleading flange passing through, which will improve the train movement smoothness but increase the train movement speed in rail high-speed road stations. Likewise, it will improve the lifetime of the rail road upper elements and rolling stock part.

Work Approbation

The results of the research have been reported and discussed in Latvia

1. 16th International Scientific Conference "Engineering for Rural Development". 24/05/2017–26/05/2017, Latvia, Jelgava. Latvia University of Agriculture.
2. 17th International Scientific Conference "Engineering for Rural Development". 23/05/2018–25/05/2018, Latvia, Jelgava. Latvia University of Life Sciences and Technologies.
3. ICTE in Transportation and Logistics 2018 (ICTE 2018). 14/01/2019–14/01/2019, Procedia Computer Science.
4. 18th International Scientific Conference "Engineering for Rural Development". 22/05/2019–24/05/2019, Latvia, Jelgava. Latvia University of Agriculture.
5. ICTE in Transportation and Logistics 2019. 26/01/2020–26/01/2020, Springer, Cham. Online.
6. 19th International Scientific Conference "Economic Science for Rural Development". 20/05/2020–22/05/2020, Latvia, Jelgava. Latvia University of Life Sciences and Technologies.

The results of the research have been reported and discussed abroad

1. IX International Scientific Conference TRANSPORT PROBLEMS. 28/06/2017–30/06/2017, Poland, Katowice-Sulejów. Faculty of Transport of Silesian University of Technology.
2. Международную научно-практическую конференцию “IX Торайгыровские чтения”. 17/11/2017–17/11/2017, Казахстан, Павлодор. Павлодарский государственный университет им. С. Торайгырова.
3. 8th International Scientific Conference “Rural Development 2017: Bioeconomy Challenges”.23/11/2017–24/11/2017, Lithuania, Kaunas. Aleksandras Stulginskis University.
4. Международная междисциплинарная конференция “Инновационное развитие и современные образовательные технологии в системе физико-математического образования”. 19/04/2018–20/04/2018, Russia, Moscow. ИИУ МГОУ.
5. Transport Means 2019. 02/10/2019–04/10/2019, Lithuania, Palanga. Kaunas University of Technology.

Publications

Recommendations and conclusions of the Thesis are reflected in the following scientific publications indexed in Scopus.

1. P. Gavrilovs, V. Ivanovs. Defect Analysis on Latvian Railway, Research on Defective Rail. 16th International Scientific Conference “Engineering for Rural Development”, ISSN 1691-5976. 24–26 May, Latvia, Jelgava2017. Pp. 1377–1382.
2. P. Gavrilovs, V. Ivanovs. Research of the Defective Frog Wing of 1/11 Mark. Transport Problems, ISSN 1896-0596. e-ISSN 2300-861X. Poland, Katowice 2017. pp. 119–126.
3. П. Гаврилов, В. Иванов, Р. Зарипов. Анализ твердости металла рельса 60 E1. Вестник КазАТК No.1, ISSN 1609-1817. Республика Казахстан, г. Алматы 2017. 23–29 стр.
4. P. Gavrilovs, V. Ivanovs. Research of a Highly Defective Frog Core of Grade 1/9. Rural Development 2017: Bioeconomy Challenges: The 8th International Scientific Conference: Conference Proceedings. e-ISBN 978-609-449-128-3. ISSN 1822-3230. e-ISSN 2345-0916. 23–24 November 2017. Aleksandras Stulginskis University, Lietuva, Kaunas 2018. pp. 266–271.
5. Иванов В.Р., Гаврилов П.Л. Исследование свариваемости рельсов Р65 Тагильского и Азовскгого завода машиной ПРСМ. Сборник научных статей по итогам Международной междисциплинарной конференции. Инновационное развитие и современные образовательные технологии в системе физико-математического образования: актуальные вопросы теории, методики и практики, Москва: ИИУ МГОУ, 19.–20. апреля, 2018. ISBN 978-5-7017-2945-0. Россия, Москва 2018. 29–33 стр.

6. P. Gavrilovs, V. Ivanovs. Analysis of Rail Profile 60 E1 Joints Welded by Means of a Mobile Rail Welding Machine. 17th International Scientific Conference “Engineering for Rural Development” Proceedings, ISSN 1691-5976.23–25 May 2018. Latvia University of Life Sciences and Technologies, Latvia, Jelgava 2018. pp. 1969–1977.
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9. P. Gavrilovs, V. Ivanovs. Study of exothermic welded joint grinding by “Speno” rail grinders. 18th International Scientific Conference “Engineering for Rural Development”, Vol.18. ISSN 1691-5976. Latvia, Jelgava 2019. pp. 1013–1021.
10. P. Gavrilovs, V. Ivanovs. Research of Weldability of Rail Profile 60 E1 Manufactured in Factory “Arcelor Mittal”. Transport Means 2019. ISSN 2351-7034. 2–4.10.2019. Kaunas University of Technology. Lithuania, Palanga 2019. pp. 945–949.
11. P. Gavrilovs, V. Ivanovs, P. Stankevics, F. Mihailovs. Analysis of Highly Defective Rails with Horizontal Splitting in the Head. ICTE in Transportation and Logistics 2019. 26.01.2020 Springer, Cham. Online ISBN978-3-030-39688-6. 2020. pp. 196–202.
12. V. Ivanovs, P. Gavrilovs, A. Boiko, I. Vaicis. Estimating Influence of Rail Profile Shapeon Lateral Wear of Railand Wheel after Grinding of 60e1 and R65 Rails.19th International Scientific Conference “Economic Science for Rural Development”. DOI:10.22616/ERDev.2020.19.TF137. 2005.2020.–22.05.2020. Latvia University of Life Sciences and Technologies. Latvia, Jelgava 2020. pp. 614–624.

1. TASKS, REQUIREMENTS OF RAILS

The load bearing element of the rail road superstructure is the rails. A rail consists of steel beams of specific cross-section, on which the rolling stock moves upon. The standard and conventional rails for all rail roads in the world are broad-gauge railway rails. In “Latvijas dzelzceļš” and in Europe the standard EN 13674-1:2011 [6] relates to the rails of sections and seamless railway roads, as well as the level-crossing transmission production. In the railways of Russian Federation, standard GOST R 51685-2013 is used that is also used in Latvia (for acceptance and receiving roads, partially for main roads), in Kazakhstan, Belarus, Ukraine, and other countries.

Rails are main elements of the railroad superstructure and their functions are:

- to create a surface with the least possible resistance for the movement of the rolling stock;
- to directly absorb and flexibly transfer the force effect from the wheel to the supports (cross-ties/sleepers, baulks);
- to divert wheels of the rolling stock in motion;
- to rail threads with automatic blocking located in the stations work as signalling current conductor;
- in stations with electric thrust – counter current.

Likewise, rails must have the following characteristics:

- resistance against wear;
- fatigue strength;
- high resistance against brittle breakage;
- good weldability;
- high cleanliness of steel;
- good processability;
- low thermal tension;
- precise geometry and straightness;
- long lifetime of operation.

Rail is one of the integral parts of railway superstructure, the high requirements set for them prove their significance in the process of safe transportation of rail road running stock.

Material, chemical composition and steel hardness of rails

Rail steel is a carbon alloy steel that is alloyed with silicon and manganese. Expanded perlite is the base of the alloy phase. Martensite steel furnaces, converter, and electrical furnaces are used for metal melting.

Rail steel brands are divided in 2 groups depending on the type of used deoxidant

The first group includes steel deoxidated with ferromanganese or ferrosilicon. The second group includes steel with deoxidant on the base of aluminium.

The metal of the second group is preferred due to a smaller percentage of non-metal admixture.

The chemical composition of rails is fully regulated by the Russian Federation's standard GOST R 51685-2013 [61].

Nowadays, rails are rolled only from steel ingots. Steel is produced in convertors according to the Bessemer process or in martensite furnaces. Bessemer steel is obtained as the result of blowing-through the melted cast iron (15–18 min). It results in burn-out of carbon and part of its admixture. The steel produced in martensite furnace is boiled from cast iron and steel scraps in large furnaces with a capacity from 200 tons up to 1500 tons in a few hours. This steel is purer and consists of less cold fractures than Bessemer steel. Heavy type (R65 and R75) rails are rolled only from martensite steel. The rail steel quality is stated by its chemical composition, micro and macro structures [19].

According to the data of Europe and standard EN 13674-1:2011, 60 E1 type rail steel chemical composition is shown in Table 1.1 [7].

Table 1.1

Main Indicator Values of 60 E1 Type Rail Steel Chemical Composition According to European Standard EN 13674-1:2011

Steel brand	**Element mass fractions, %**				
	C	**Si**	**Mn**	**P**	**S**
R350HT, R350LHT	0.72–0.80	0.15–0.58	0.70–1.20	0.020	0.025
R260	0.62–0.80	0.15–0.58	0.70–1.20	0.025	0.025

Comments: R350HT–rails made of carbon manganese (C-Mn) steel; thermally treated; R350LHT, R260 –rails made of low alloy steel, not thermally treated.

The steel hardness value of thermally reinforced R50, R65 and R75 type rail headshould correspond to the norms of standard GOST R 51685-2013[61], but 60 E1 type rails should correspond to the norms of European standard EN 13674-1:2011 [6], as shown in Table 1.2.

In the railways of Russian Federation various steel brands are used according to their characteristics and importance (GOST R 51685-2013). However, by their chemical composition, the hardness is similar to the European standard EN 13674-1:2011.

Table 1.2

Hardness Values of 60 E1 Type Thermally Reinforced Rails According to the European Standard EN 13674-1:2011

Steel brand	Hardness range, HB
R350HT, R350LHT	350–390
R260	260–300

Rail steel defects

Pre-rolling heating and rolling are as significant technological procedure in forming the quality as melting and steel casting. In the heating stage, under the influence of metallurgical factors the needed plasticity is created (ability to deform without disintegrating) and the steel resistance to the plastic deformation is reduced. The main negative factors of heating are intensive exposure to heat from the heated furnace gasses on the cold half-finished product when loading it in the furnace and the duration of the steel being located in the zone of high temperatures (900–1250 °C) in the methodical furnace with oxidizing atmosphere. During the rolling process, the plasticity deformation of metal takes place. Temperature, compression regime, and roller calibration plays a significant role in this process. The rational choice of the aforementioned aspects affects the evolution of most defects created as the result of steel casting. Especially the inner cracks can develop, be seen on the outside, oxidize and eventually lead to a defect of rail surface or even plastic deformity, preserving high mechanical characteristics of metal in the former defect zone. Without the transformation of existing defects, the rolling process is the source of the defects themselves, of which many relate to the category of surfaces.

Heating defects include such defects as cracks, oxidation, pits and scaling [22]. The most significant rail steel defects are due to the rolling process: deformations, indents, peel-off of rolling, protrusion, closed rolling, indentation (scratch), imprint (dent), wrinkle, strain crack, small cracks, cavity, air bubble.

The basic defects in metal structure relating to the rail head running surface are pitting of surface and mechanical damages.

2. ANALYSIS OF RAIL DEFECTS IN “LATVIJAS DZELZCEĻŠ” NETWORK

A statistical analysis was performed on the acquired information of damaged rails in “Latvijas dzelzceļš” network during the period from 2011 up until 2019 (Fig. 2.1) [1].

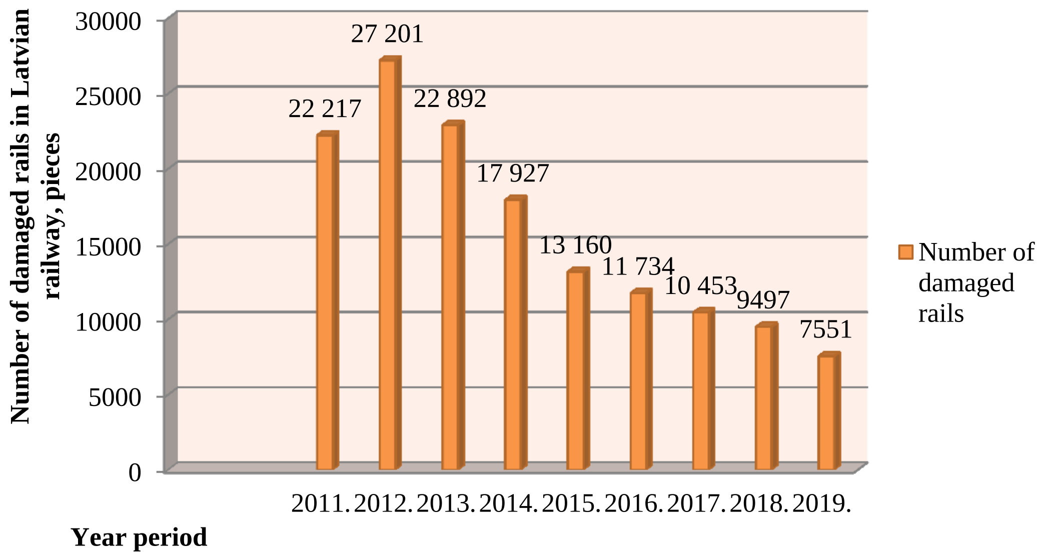


Fig. 2.1. Statistics of damaged rails in “Latvijas dzelzceļš” network in the time period from 2011 up to 2019.

According to the performed analysis on damaged rails (Fig. 2.1) in the time period from 2011 up to 2019, the number of damaged rails in “Latvijas dzelzceļš” network has reduced from 27 201 to7551. In this period, the highest number of damaged rails was 27 201 in year 2012. In the time period 2014–2019, the number of defects has significantly decreased from 17 927 to 7551, demonstrating that the priority of “Latvijas dzelzceļš” is safe and continuous train movement with the set movement speed. However, despite the reduction in the number of damaged rails, the issue is topical in “Latvijas dzelzceļš”. The main defects of Group 1 are metal delamination and pitting on the running surface [1].

The most common defects on the rail head running surface are the following:

- X 10.1-2 metal delamination and pitting on the running surface;
- X 11.1-2 pitting in the work cut-out of the head due to insufficient fatigue strength of metal contact;
- X 17.1-2 pitting and delamination of metal on the hardened layer surface of rail head.

Pitting of metal and delamination cracks on the running surface with code X 10.1-2 usually occur due to violation of rail production technology (closed rolling, small cracks, peeling, etc.) [2]. Such defects can be easily seen in visual inspection, see Fig. 2.2.

Fig. 2.2. A defect found in rail road section Menta–Daudzeva 256 km 6 pk.

This defect is also monitored by measurement instruments – ruler, calliper with depth measurement, as well as ultrasound defectoscopy that is the main perspective method for detecting and monitoring this defect.

Defect with code X 11.1-2 are metal cracks and pitting on the side work cut-out of the head or middle part, created from the inside due to accumulation of local non-metallic inclusions that are stretched along the rolling direction of the track in the form of a line, or created due to insufficient fatigue strength of metal contact on the outer edge of rail surface after the release of the guaranteed tonnage [2]. It is the main problematic defect both in "Latvijas dzelzceļš" and in the railway transport all around the World.

Reasons for emergence and development

Flaws in metallurgical quality of rail steel (accumulation of local non-metallic inclusions, stretched along the direction of rolling) determine the insufficient contact fatigue strength. Most often the work edge of outer threads in rail road curve stations (R = 400–1000 m) are damaged, see Fig. 2.3. Pitting begins with the formation of inner longitudinal cracks of contact fatigue and development in the work cut-out zone of the real head. Contact fatigue cracks can also develop from rolling stock on the middle part of the rail head, gradually reaching under the rolling stock and creating elongated horizontal contact fatigue cracks. Usually, the defect is created on the outer rail work edge in the form of cut-out curves with a small radius, it can be accompanied by side wear. In some cases, a longitudinal crack can appear due to shallow upper contact fatigue cracks that are parallel and can develop even deeper [23].

Fig. 2.3. A defect found in curve R = 708 m in Vecumnieki station 1, on the main road.

To defect 11.1-2 belong longitudinal cracks with location depth of up to 8.00 mm. The contact fatigue longitudinal crack development leads to formation of pitting. Greater hazards are caused by possible crossed fatigue crack formation (defect 21.1.-2) in defect 11 (longitudinal crack).

Defect with code X 17.1-2 is decoded as pitting and metal delamination on the hardened layer of the metal surface of rail head, the defects are caused and developed due to the unsatisfying quality of rail hardening [2].

Main reasons for emergence and development

If the technology of rail hardening is not followed properly, zones of martensite or zones of local uneven hardness transition from the hardened to the unhardened metal layer can form in the hardened layer. During operation, metal delamination and pitting can occur in these zones due to the effect of the rolling stock, see Fig. 2.4. The acceleration of the defect appearance is stimulated by the curvature of the rail ends.

Fig. 2.4. Pitting on rail head surface in Vecumnieki station.

The main techniques for detecting this defect are analogous to those of the aforementioned defects, i.e. outer examination, control with measurement instruments, ultrasound defectoscopy.

The road administration of "Latvijas dzelzceļš" uses various methods for reducing of damaged places. One of these methods is a periodic rail grinding with a rail grinding train.

2.1. Analysis of Heavily Damaged Rails in the Network of Latvian Railways

A research of statistical analysis regarding heavily damaged rails was carried out from 2011 up to 2019. First of all, every detected heavily damaged rail is a threat to the safety of the rolling stock. Therefore, according to the existing manual C-010 [2], this heavily damaged rail must be replaced within 5 hours of detection. Figure 2.5 presents a chart of heavily damaged rails in the network of Latvian railways.

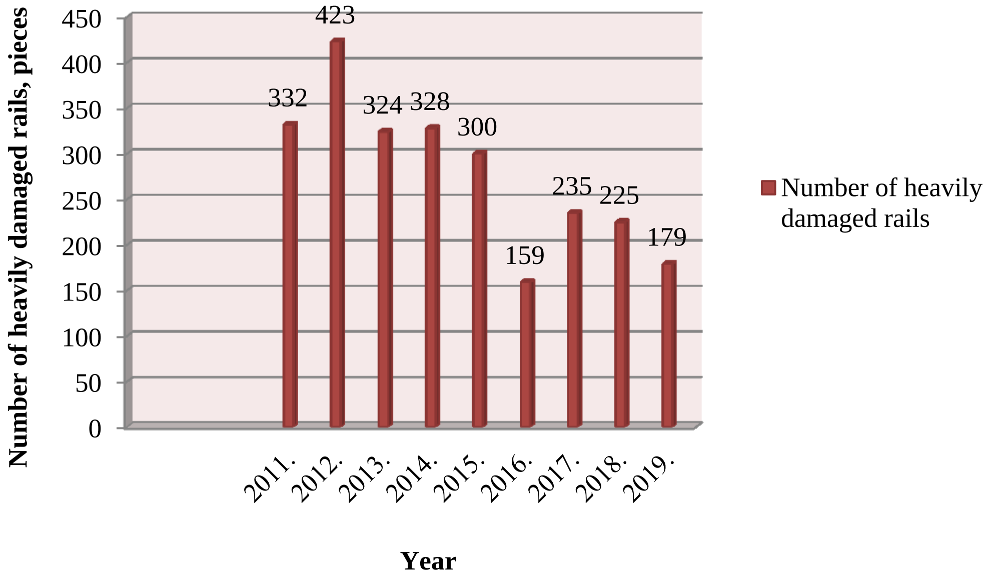


Fig. 2.5. Statistics of heavily damaged rails in the railway network of Latvia in the time period from 2011 up to 2019.

Statistical chart of the time period from year 2011 up to 2019 revealed 2495 heavily damaged rails endangering the movement of rolling stock [1], of which the largest number of were found in 2012 – 432 pieces. In 2013, the number of heavily damaged rails was 324 pieces, however, in 2014, this number increased again and reached 328 pieces. In the time period 2015–2016, the number of detected heavily damaged rails fell sharply from 300 to 159 defects. In 2017, the number of heavily damaged rails reached 235 pieces in comparison with 2016. The number of heavily damaged rails detected in defectoscopy warehouses in 2018 was 225 pieces, which is 10 pieces less of heavily damaged rails than in 2017. The number of heavily damaged rails in 2019 decreased to 179 pieces.

This statistical analysis on heavily damaged rails proves the topical issue of heavily damaged rails in "Latvijas dzelzceļš" network.

2.2. Analysis of Heavily Damaged Rail Heads in the Railway Network of Latvia

Rail head is one of the most important construction elements the upper part of which absorbs the pressure of the wheelset on the rolling stock. Also, the rail head guides the movement of wheels that has a retaining ring with a specific sleeve from the inner work side of the rail head. The detection of heavily damaged rail heads is the main task of defectoscopy warehouse workers. Figure 2.6 shows a chart of heavily damaged rail heads in the time period from 2011 up to 2019 [1].

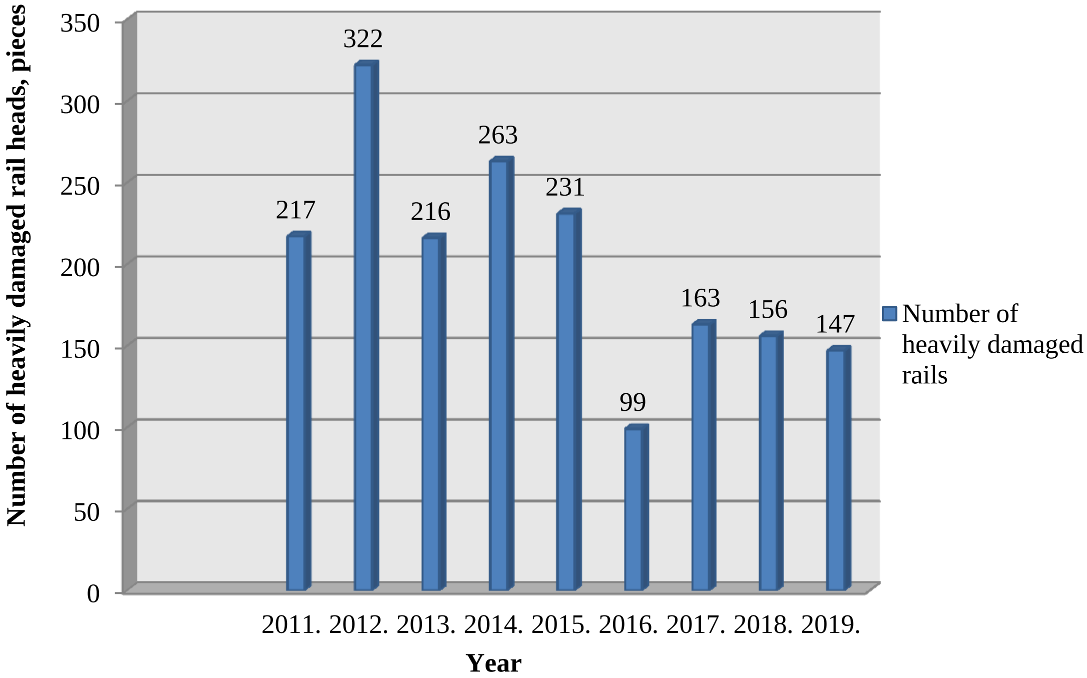


Fig. 2.6. Statistics of heavily damaged rails in “Latvijas dzelzceļš” network from 2011 to 2019.

More than 21 defect develops in the rail head thus taking the first place in detection of heavily damaged rails. As presented in the chart in Fig. 2.6, the number of detected heavily damaged heads in the time period from 2011 to 2019 was 1814 pieces [1], which makes 68.10 % of the total number of heavily damaged rail heads detected. The largest number of heavily damaged rail heads was in 2012 with a total of 322 pieces. In year 2013, the number of heavily damaged rails decreased to 216 pieces. However, in 2014, the number of detected heavily damaged rail heads increased by 47 cases and was 263 heavily damaged rail heads in total. In the time period 2015–2016, the number of detected heavily damaged rails significantly decreased from 231 to 99 cases, a difference of more than 132 cases. The number of detected heavily damaged rails increased again in the time period 2016–2017 by 54 pieces, and it was 163 heavily damaged rail heads. In 2018, the number of heavily damaged rails fell to 156 pieces. In 2019, the number of heavily damaged rails was 147 pieces.

The research of statistics on heavily damaged rail heads proves the large amount of detected heavily damaged rail heads, affirming the necessity to perform additional control (visual inspection, defectoscopy) of the condition of rail heads. Similarly, the planned precaution events for prolonging the operation lifetime of rail heads can benefit by rail milling or grinding with a rail grinding train. Let us look at the main defects of heavily damaged rails that are topical in the railway network of Latvia.

2.3. Statistical Analysis of Company "Speno" Regarding the Rail Grinding Train Operation in "Latvijas dzelzceļš" Network

To prolong the operational lifetime of rail head as well as to prevent wave-type wear, mechanical damages, metal compression and delamination, "Latvijas dzelzceļš" uses a rail grinding train of company "Speno". Besides, one of the main aims of grinding is the creation of rail cross-profile. Periodic correction of profile with grinding provides the best contact between a wheel and the rail evenly distributing the internal stresses on the rail surface and thus extending its operational resources by 15 % … 20 %. Figure 2.7 presents a statistical chart on the work of the rail grinding train of company "Speno" in "Latvijas dzelzceļš" network [8].

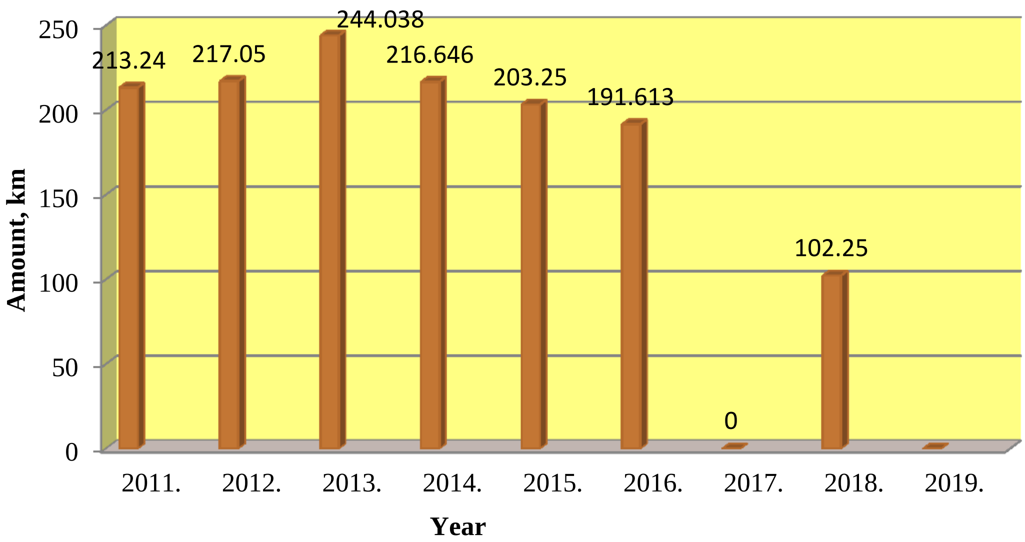


Fig. 2.7. Statistics of quantity (km) of the work of rail grinding train of company "Speno" on Latvian railways in time period 2011–2019.

As shown in the chart of Fig. 2.7, the total number of grinded rails in the time period 2011–2019 is 1388.087 km/railway. In the time period 2011–2013 in the railways of Latvia the number of grinded rails increased gradually from 213.24 to 244.038 km/railway. However, in the time period 2014–2016, the rail grinding gradually decreased from 216.646 km/railway to 191.613 km/railway. In 2017 rail grinding in "Latvijas dzelzceļš" was not performed. And in 2018 only 102.25 km/railway were grinded. In 2019 rail grinding was not performed.

These statistics indicate the relevance of the use of rail grinding train in "Latvijas dzelzceļš" as a way to maintain the lifetime of rails [9].

3. RESEARCH OF HARDNESS OF 60 E1 TYPE RAIL RUNNING SURFACE ANDOF DAMAGED RAIL CODED X10.1

3.1. Research of Hardness of 60 E1 Type Rail Running Surface

Since 2013, “Latvijas dzelzceļš” widely used rails with steel brand R350HT and tail type ENSIDESA 60 E1 of English company “Arcelor Mittal” (Fig. 3.1). These rails are mounted both on main and acceptance and dispatchment rail roads. The rails must conform to European standard EN 13674-1 2011 (XA) [6].

As a general knowledge, mechanical characteristics involve hardness, strength, impact strength, and plasticity.

Hardness of metals and alloys – a primary type characteristic of a construction – is a quality of a material to create resistance when a foreign substance gets into its top layers that does not deform and does not break apart due to additional loads (indentor).

To determine the hardness of rail head metal, railroad section Vecumnieki–Misa of “Latvijas dzelzceļš” network was chosen. In this rail section an overhaul repair work was performed by putting rails ENSIDESA 02 14 60 E1 of English company “Arcelor Mittal”, which means: ENSIDESA producing company, 02 – month of release, 14 – year of release, and 60 E1 – rail type.

After putting the new long rails, a grinding of rail head running surface was performed using rail grinding train URR-112 of Swiss company “Speno”.

In 2017, the tonnage passed through on this section of rails was 47.4 mil. t. gross. The hardness measurement was performed using portable hardness measurement tool Krautkramer. Figure 3.1 presents metal hardness measurements on a grinded rail running surface in curve R = 1307 m. Figure 3.2 presents metal hardness measurements on a grinded rail running surface of a straight rail section. At the moment of measurement, the work side wear of head was 3 mm and vertical wear 1 mm.

For the comparison, running surface hardness measurements were performed on the new rails without tonnage transit, which were laid in routine maintenance process in railroad section Vecumnieki–Lāčplēsis, 1st picket of the 219th kilometer on 12 September 2017. The new rails ENSIDESA 02 13 60 E1 and 01 16 60 E1 are produced by English company “Arcelor Mittal”. Figure 3.3 presents metal hardness measurements on the running surface of the new rail ENSIDESA 01 16 60 E1 in a straight railroad station.

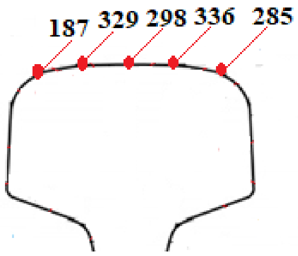


Fig. 3.1. Metal hardness measurements on grinded rail ENSIDESA 02 14 60 E1.

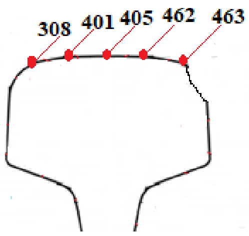


Fig. 3.2. Metal hardness measurements on the running surface of the grinded rail (in curve *R* = 1307 m) ENSIDESA 02 14 60 E1.

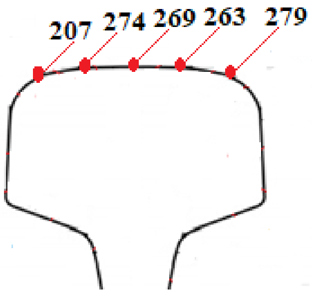


Fig. 3.3. Metal hardness measurements on the running surface of the new rail ENSIDESA 01 16 60 E1.

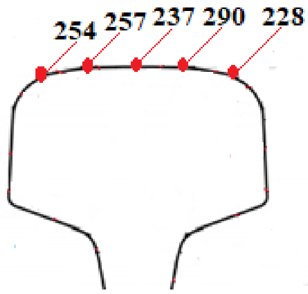


Fig. 3.4. Metal hardness measurements (in curve *R* = 956 m) on the new rail ENSIDESA 05 13 60 E1.

Figure 3.4 presents metal hardness measurements on the running surface of the new rail in curved rail road station *R* = 956 m.

According to the acquired data, a table was developed and a comparison was done using the data of the producing factory passport. The data obtained are compiled in Table 3.1.

Table 3.1

Comparison of Steel of Running Surface of Rail Type 60 E1 ENSIDESA, Brand R350HT with the Data of the Producing Factory

Place of hardness determi-nation	**Hardness brand of rail R350HT**				
	Hardness of the producing factory, HB	**Average hardness (60 E1 ENSIDESA rails), HB**			
		Grinded rail ENSIDESA 02 14 60 E1, HB	**New rail ENSIDESA 01 16 60 E1, HB**	**Grinded rail in curve ENSIDESA 02 14 60 E1, HB**	**New rail in curve ENSIDESA 05 13 60 E1, HB**
1	2	3	4	5	6
Running surface of head, HB	357	287	258	408	253

The average hardness of rail head running surface 60 E1 ENSIDESA does not correspond to the passport data of producing factory, except for the grinded rail in a curve with radius *R* = 1307 m. According to the results of hardness assessment, it is 408 HB which is 51 HB higher than the value in the passport. The hardness increase on the running stock in the curved section can explain the increased interaction between the wheelset retaining ring and rail head running surface.

According to the results of the research, conclusions can be made that the metal hardness of the grinded rail turned out to be 29 HB higher than the non-grinded rail. Comparing the acquired metal hardness of the new rail with the passport data of producing factory, anyways there is a non-compliance, rail head metal hardness is lower by 104 HB. Lowered hardness on rail running surface can lead to intensive vertical and side wear of rail head in railroad curved sections and a rapid development of defects on rail head in straight sections.

3.2. Research of the Damaged Rail with Code X10.1

One of the most popular defects in "Latvijas dzelzceļš" network is the defect with code X 10.1-2. This defect includes metal cracks and pitting on the running surface of head due to non-compliance with the manufacturing technology (closed rolling, small cracks, peeling, etc.) [2], see Fig. 3.5. The defect location designation with a number (third number in the defect code) is assumed as follows:

0 – along the entire length of the rail;

1 – overlay connection of a threaded bolt is 750 mm apart and less from the end of the rail;

2 – outside the overlay connection of a threaded bolt is more than 750 mm apart from the end of the rail.

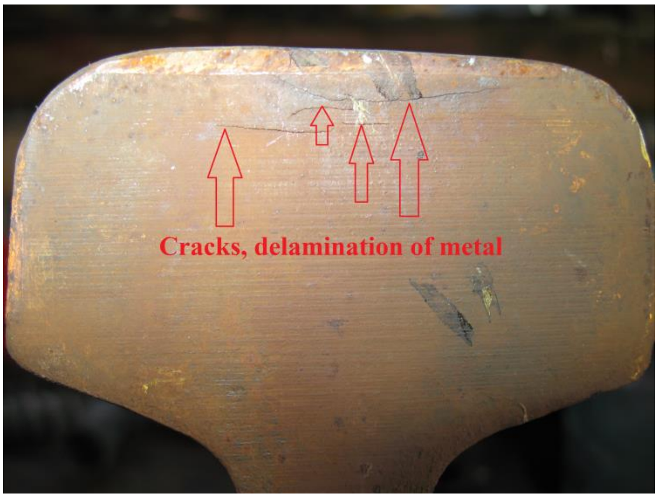


Fig. 3.5. Defect with code X10.1 found in railroad section Vecumnieki–Lāčplēsis.

Research of the damaged rail

The defect of the damaged rail with code 10.1 found in section Vecumnieki–Lāčplēsis, 221 km 6 pk, served as a sample for research using a contemporary RDM-24 type ultrasound defectoscopy, see Fig. 3.6.

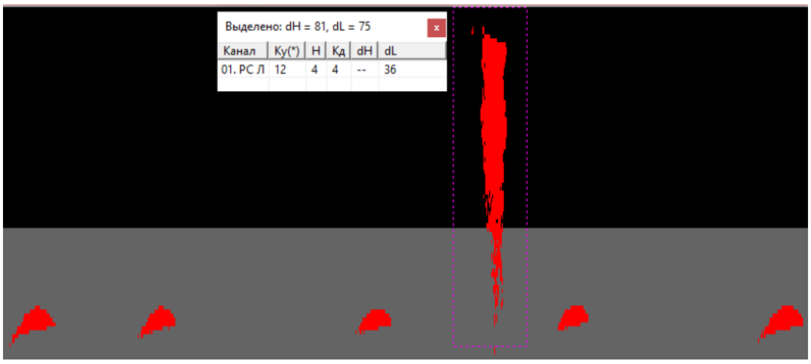


Fig. 3.6. The deciphering of the defect with code X 10.1 using a specialized defectoscopy program of model 1.4.8.

Comments: In 2011, the initial rail grinding was performed using the rail grinding train of company “Speno”. Until the moment of detecting the defect, the passed through tonnage was 302 mil. t., gross, with an average load stress in this station 35 mil. t., gross, annually.

During operation, this defect was cut out and the fragment with the defect location was transported to the Metal Processing Laboratory of Riga Technical University Department of Railway Engineering, Institute of Transport, where a detailed sawing and grinding of the defect fragment was performed in the laboratory. Afterwards, using a modern hardness measurement tool Tinius O Olsen Fikrmware Version 1.07, FH-31 Series, the hardness of rail head was stated according to the Brinell scale. Results of the research are shown in Fig. 3.7.

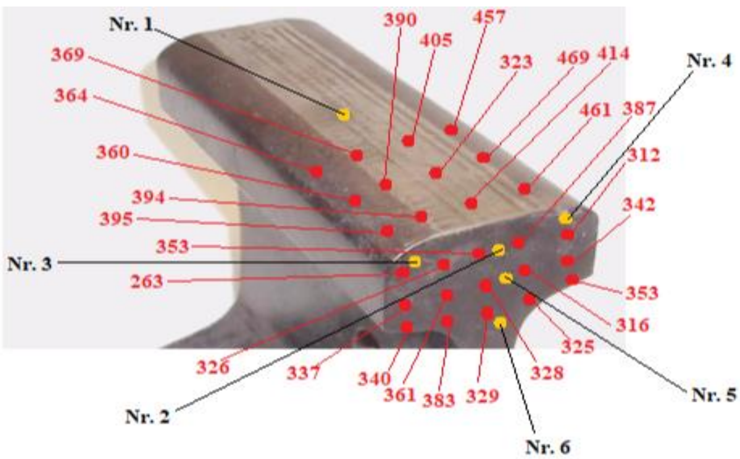


Fig. 3.7. Hardness determination of the damaged Tagila rails T VI 08 by points.

Further on, according to the acquired data, Table 3.2 was created in which the average values were set by hardness according to the location (points 1–5).

Table 3.2

Hardness Values Set by the Producing Factory and Average Measured Values

Location of the hardness determination	**R350HT brand of rail hardness**	
	Hardness of the producing factory, HB	**Average measured hardness, HB**
On running surface of head (point 1), HB	350–390	400
10 mm deep from the running surface of head (point 2), no less than HB	341	**328**
10 mm deep from the rail form cut surface (points 3 and 4), no less than HB		
22 mm deep from the running surface of rail head (point 5), no less than HB	321	336
35 mm deep at the place of transition from the rail head to narrowing (point 6), HB	–	346

The performed research shows a non-compliance at 10 mm depth in points 2, 3, 4 (Fig. 3.7). The average measured hardness in points 2 and 3 is 328 HB, which is by 13 HB less than the hardness stated by the producing factory. The decline in hardness in these points presents the locations of defects, a crack 8.1 mm deep and 7.5 mm long.

Further, using chemical analyser PMI-Master PRO, see Fig. 3.8, a full chemical composition for steel rail R350HT was found [7]. The results of the chemical composition are presented in Table 3.3.

Fig. 3.8. Determination of chemical composition using chemical analyser PMI-Master PRO.

During the determination process of steel defect X10.1 performed in the Railway Department of RTU laboratory, the following differences were found. In the data stated by the producing factory the following elements were not stated: molybdenum (Mo), cobalt (Co), niobium (Nb), Titanium (Ti), tungsten (W), lead (Pb), zirconium (Zr).

The content of aluminium (Al) had reduced by 0.0006 % and is 0.0020. The content of Chrome (Cr) does not conform to the standard and is 0.0190 %. During the research the percentage value of such chemical element as nitrogen (N) was not found. Vanadium (V) increases hardness and strength and grinds the grains. It increases the density of steel, as it is a good deoxidant, and has the allowable values and is equal to 0.0396 %.

Table 3.3

Chemical Composition of the Researched Defect with Code X 10.1

Values	Fe	C	Si	Mn	P	S	Cr	Mo	Ni
Max/Min	–	0.550 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
1	97.70	0.667	0.346	0.948	0.0080	0.0265	0.0218	0.0030	0.0400
2	97.40	0.756	0.346	0.838	0.0050	0.0264	0.0153	0.0030	0.0499
3	97.80	0.698	0.385	0.902	0.0050	0.0050	0.0201	0.0030	0.0419
Average, %	97.60	0.707	0.359	0.896	0.0060	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	–
1	0.0020	0.0362	0.0091	0.0030	0.0020	0.0401	0.0250	0.0100	0.0030
2	0.0020	0.0448	0.0085	0.0110	0.0030	0.0406	0.0250	0.0100	0.0030
3	0.0020	0.0374	0.0055	0.0030	0.0020	0.0380	0.0250	0.0100	0.0030
Average, %	0.0020	0.0395	0.0077	0.0056	0.0023	0.0396	0.0250	0.0100	0.0030

Further, the main researched average statistical data of the chemical composition shall be compared to the producing factory data, see Table 3.4.

Table 3.4

Comparison of the Main Elements of Chemical Composition and European Standard EN 13674-1:2011

Value	C	Si	Mn	P	S
By EN-13674-1:2011 standard	0.746–0.786	0.34–0.38	0.913–1.013	0.016	0.015
Average stated	0.707	0.359	0.896	0.060	0.0193
Difference, %	**<0.039**	Conforms	**<0.017**	**>0.044**	**>0.0043**

Comparing the main values of the chemical composition, the following conclusions can be drawn: the content of carbon is reduced by 0039 %, chemical element silicon corresponds to the standard, the content of manganese is reduced by 0.017 %, the content of phosphorus increased by 0.044 %, and the content of sulphur increased by 00043 %. As it is known, the content of carbon (C) increases the hardness and wear resistance of rails. Manganese (Mn) increases the hardness and wear resistance of steel, providing it with sufficient viscosity.

Phosphorus and sulphur (P, S) are harmful impurities, they make the steel brittle; if there is a large content of phosphorus, cold fractures may appear in the rails, however, if there is a large content of sulphur – red fractures appear.

After performing research on chemical composition using stationary turning machine "MECATOME T 255/300" with oil cooling, the defect fragment of rail head was cut into three pieces.

Afterwards, these rail fragments were put in the hot-pressing section of the contemporary press Mecapress II.

Then, after pressing of the finished template, the template grinding and polishing was performed using Mecatech 334 system’s grinding and polishing machine with water cooling, see Fig. 3.9.

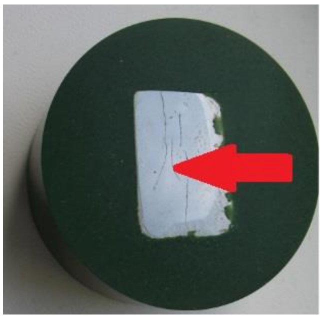


Fig. 3.9. Template of the damaged rail head after grinding.

After grinding and polishing of the template, the metal structure of the rail head defect location was determined using digital microscope Carl Zeiss Axiovert 40 MAT with 50× zoom, see Fig. 3.10.

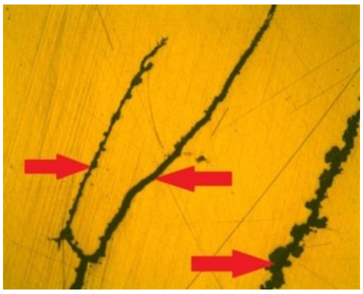
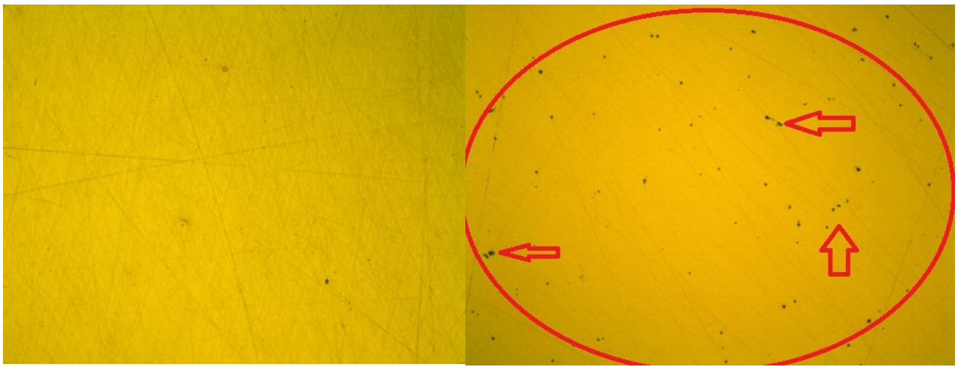


Fig. 3.10. Metal structure of the damaged rail T VI 08 60 E1 with an 50× zoom.

Using 50× zoom, layering in the form of black zones can be seen on the rail head. The presence of such a branched defect can lead to a more dangerous and very severe damage with a code XX 30.1, such as horizontal delamination of the rail head.

To compare metal structure, grinded and non-grinded rails 60 E1 type were researched in of RTU Department of Railway Engineering, Institute of Transport, Metallographic laboratory using microscope with 50× zoom in Fig. 9.11 a, b.

As shown in Fig. 3.11 a, the metal structure of a grinded rail is clean, without inserts and alloys. The metal structure of non-grinded rail as seen in Fig. 3.11 b has a lot of black dots that are marked with red arrows within the red circle. This shows, that the metal structure is not in a good condition, and if no measures for its improvement are taken, for example, continuous rail head grinding with rail grinding train, surface defects can appear that reduce operational lifetime with transmitted tonnage.



a) b)

Fig. 3.11. Metal structure of 60 E1 type rail using 50× zoom: a) grinded with a grinding train; b) non-grinded rail.

The rail micro structure is discussed further. Using 5 % nitric acid solution HNO_3, a defect sample etching was performed [17]. Afterwards, this sample was examined under a microscope with 200× zoom, see Fig. 3.12.

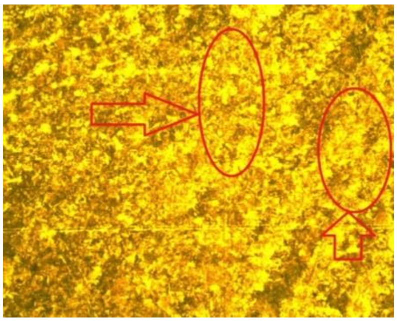


Fig. 3.12. Microstructure of defect X10.1 with 200× zoom.

The microstructure of steel R350HT is of ferrite-perlite, in Fig. 3.12 it can be seen with a large collection of perlite (marked with red arrows) that takes up more than half of the total amount. The increased oxygen content of more than 0.039 % proves it.

The performed research allows to determine the rail steel hardness, steel chemical composition, mass fraction of metal elements, metal structure and micro structure. This also provides answers to questions, for example, in case of rail breakage or creation of cracks. In this research, it was found that the hardness of chemical composition of the damaged rail (X 10.1) had the following non-compliances: 10 mm deep from the running surface of head the hardness was 328 HB, which is 13 HB less than the stated amount. The same relates to the data of chemical composition which had the following on-compliances: carbon content (C) is less than the stated by 0.039 %, manganese (Mn) is reduced by 0.017 %, phosphorus (P) is increased by 0.044 % and sulphur (S) by 0.0043 %. Head delamination as horizontal cracks can be seen in the metal structure. Metal structure is ferrite-perlite. The performed research was verified in a certified testing laboratory of Inspecta Latvia. The testing results correspond to the research performed in the metallographi laboratory of Riga Technical University Department of Railway Engineering, Institute of Transport.

4. STATEMENT OF THE RESEARCH TASK IN REGARD TO THE ASSESSMENT OF IMPACT OF RAILWAY WHEEL AND RAIL INTERACTION. A 3D MODELING OF ELEMENTS PERFORMED AS A RESULT

One of the most significant problems related to the transportation safety of railway stock and its effectivity is an exact description of the mechanical operation of the rail. To extend the service life of wheels and rails, as well as in order to improve the parameters of train movement (speed, economy) it is necessary, with high accuracy, to model and study the heavily deformed state in the system wheel-rail in wheel rim interaction with various profiles: new rail and new wheelset rim, worn-out rail (side and vertical wear), and new wheelset rim, worn-out wheelset rim and new rail, worn-out wheelset rim and worn-out rail (side and vertical wear), new wheelset rim and grinded rail head, worn-out wheelset rim and grinded rail head.

4.1. Wheel and Rail Wear in the Railways of Latvia and Russia

Interaction between rail wheel and rail is one of the problems for wheel movement against the rail. The construction materials must have a sufficient strength to provide resistance to the vertical forces created due to high loads and the dynamic load caused by interaction between wheel and rail that is created with vertical and crossing accelerations of running stock elements, that are relatively created by track roughness and wheel non-roundness.

The interaction in the wheel-rail system is always followed by wear, the problem is its intensity, speed of losing metal off of wheel flange work surface and rail side surface.

The distance of straight railway sections in “Latvijas dzelzceļš” is not long, thus wagon movement takes place on the highway railroad with radius R = 800 m. As a result, the horizontal force impact on the wheel and rail is significant. Wheelset rolling profiles have various transition radiuses from rolling surface by the flange [20]. Almost all R65 rails in “Latvijas dzelzceļš” network are changed to EN 60 E1 [16]. Thus, the radius from rail head side edge by the work surface has changed accordingly from 15 mm to 13 mm. The working time of usable wheels with the rail has been reduced causing the load part transfer to flange (two-point contact). Most common wheel defects in “Latvijas dzelzceļš” network are shown in Table 4.1.

The main problem of wheelsets in “Latvijas dzelzceļš” network is pitting, on-welding, and shears, as well as the thin flange and sharp-edged rolling created in the case of a two-point contact wheel-rail.

Figure 4.1 presents the statistics on wheelset rejection in “Latvijas dzelzceļš” network in 2016–2019 [9]. Based on the data in Table 4.1, a graphic picture shall be created on the main defects of wheelset that impact the rail head wear, see Fig. 4.1.

Table 4.1

Statistics on Wheelset Rejection in "Latvijas dzelzceļš" Network in 2016–2019

Main wheel defects	**2016**	**2017**	**2018**	**2019**
Sharp-edged flange rolling	63	20	8	6
Pitting	155	172	257	249
On-welding and shears	158	145	315	218
Thin flange	51	64	96	109
Total count	427	401	676	582

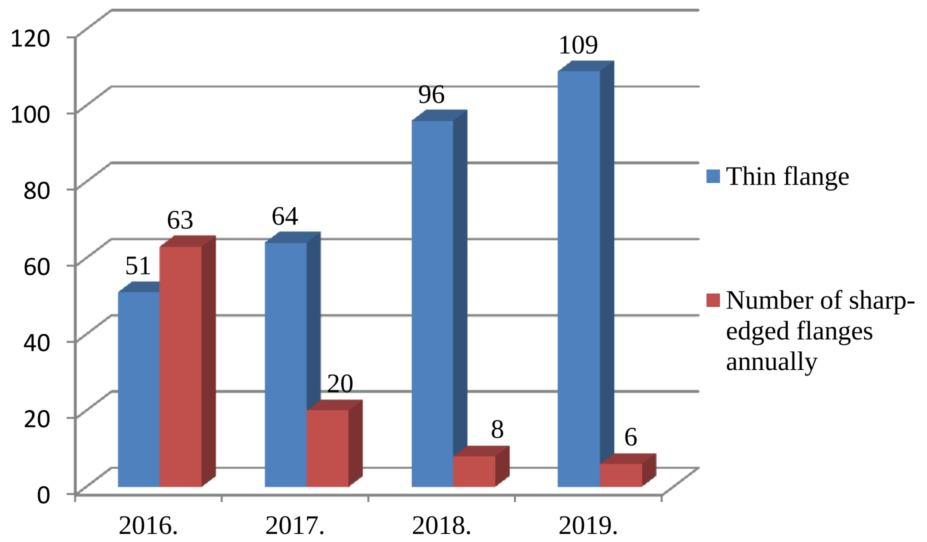


Fig. 4.1. Statistics on sharp-edged and thin flange defects in "Latvijas dzelzceļš" network in 2016–2019.

As seen from Fig. 4.1, the main defect in 2016 was the sharp-edged flange rolling, of which there were 63 defects. In 2017, the number of this type of defect reduced to 20 defects. In the next years, from 2018 to 2019, the number of this type of defect reduced from 8 to 6. However, the amount of thin flange defects increased. Since in 2016 the number of this defect was 51, but in 2017, it was 64. In 2018, the number of thin flange defects increased to 96 defects, and in 2019 there were 109 cases of this defect found.

According to the analysis of literature sources (publications, scientific articles, journals, and books) and the gathered statistical data, one can conclude that this problem regarding wheelset and rail head wear is topical in other countries as well, such as the USA, Ukraine, Belarus, and Russia [9]. The comparison between the wheelset and rail head wear defect statistics in Russian railway can be mentioned as an example. Figure 4.2 presents a numerical diagram on wheelset rim damaged due to various types of defects.

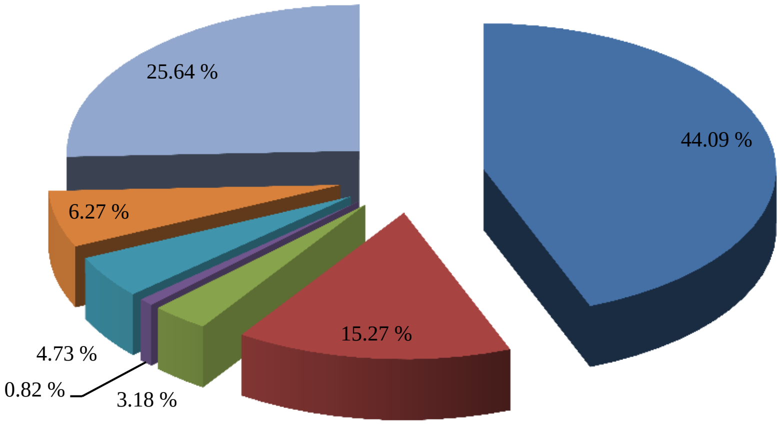


Fig. 4.2. Subdivision of wheelset rim defect count in Russian railways in percentage [9].

As shown in Fig. 4.2, the most common damages of wheelsets are:

- maximum wear of wheelset flange – 44.09 %;
- exceeding the allowable diameter difference of rim – 25.64 %;
- relaxation of retaining ring mounting – 6.27 %;
- vertical cut-off of a flange – 15.27 %;
- metal on-flow on the outer edge – 4.73 %;
- shears – 3.18 %;
- other reasons – 0.82 %.

According to Fig. 4.2, the main wear of wheelset rim in Russian railways is the wheelset flange wear [42]. In Fig. 4.3 a, b, a wheelset rim wear profile is shown that is common in the railways of Russia and Latvia.

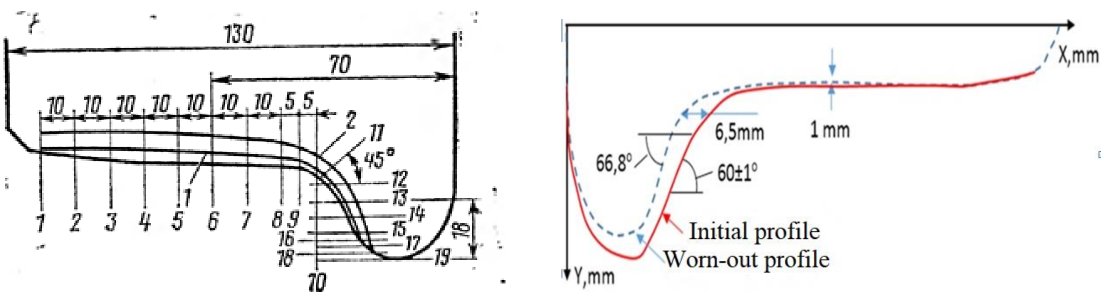


Fig. 4.3. a) Wheelset rim–medium wear 1 and maximal wear 2 – profiles in the network of Russian railways: 1–19 rim cross-sections, can be used for description of a profile [18]; b) typical wheel wear in Latvian railways.

Figure 4.3 b presents the profile tread wear of Latvian railway wheels which reaches only 1–2 mm, but the wheel wear with thin flanges – 6.50 mm, that corresponds to the results shown in Fig. 4.1. This is the reason, why in Latvian railways a thin flange wear of wheels is so important.

4.2. Types and Periodicity of Rail Grinding

One of the methods to increase the operational lifetime of rails is rail grinding using a rail grinding train.

The types of rail grinding are:

- initial rail continuous grinding after rail assembly eliminates metal carbon-free layer on the new rails the surface of which loses carbon and resistance against mechanical damages after its hardening, production roughness and micro cracks are prevented as well;
- preventive – which includes regular removal of the most damaged layer of metal roughness and surface cracks in the slow growth stage, which allows to prevent their accelerated development;
- profile grinding – when rail head is grinded in all perimeter in order to eliminate significant surface defects and restore the specified profiles.

At the moment, profile grinding is one of the priority areas.

4.3. Known Profiles and Methodology of Rail Grinding

Defect prevention is performed as rail grinding according to the technological process with a rail grinding train (Speno), repair profiles tend to replicate the profile of the new rail (Fig. 4.3) taking into account the wear of the grinding rail with 3–4 mm step [26]. The regulatory documentation recommends grinding on asymmetrical profiles of the repair for the inner and outer rail taking into account the side wear of the rail with 5 mm step (Fig. 4.5). Known techniques for a more accurate description of the repair profile, including additional points in the repair profile are shown in Fig. 4.6). Techniques for the dynamic modelling of rolling stock by analysing the wheel-rail contact forces are also known [11]–[13].

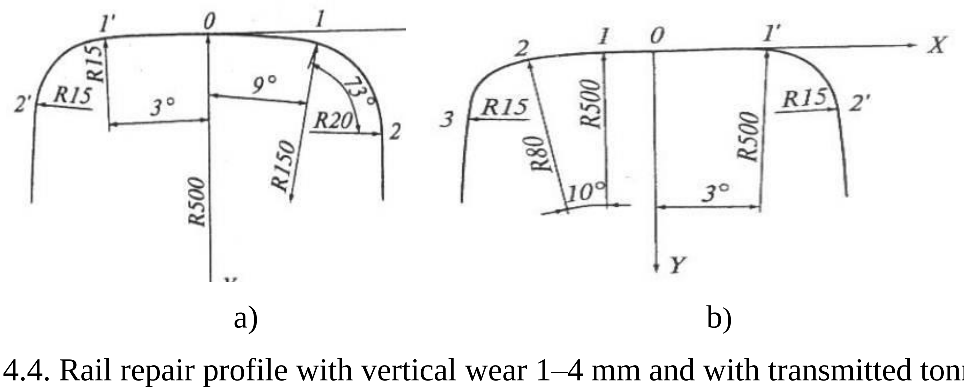
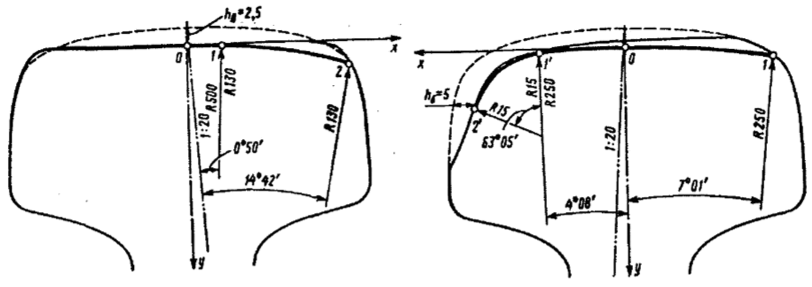
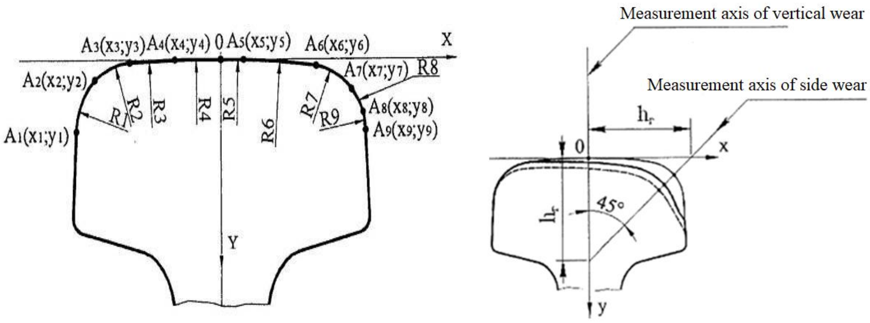


Fig. 4.4. Rail repair profile with vertical wear 1–4 mm and with transmitted tonnage from 150 mil. t. up to 500 mil. t., gross in curves R = 800–1000 m:
a) outer thread; b) inner thread [23].



a) b)

Fig. 4.5. Repair asymmetric profile for rails R65 with wear in curve: a) inner rail with vertical wear 2.50 mm; b) inner rail with outer wear 5 mm [23].



a) b)

Fig. 4.6. Rail repair profile schemes: a) diagram of the location of the characteristic points and radius of the rail repair profile; b) vertical and lateral wear measurement scheme of the rail [23].

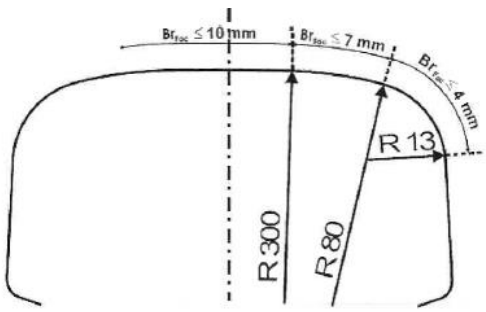


Fig. 4.7. Allowable values of rail 60 E1 type grinding [23].

The aforementioned methods and approaches for renovation of rail head profile using grinding based on repeating the new rail profile. The main criteria for rail 60 E1 type repair profile renovation is presented in Fig. 4.7. When performing the profile grinding of rail 60 E1 type, the removal of the parent metal must not exceed 4 mm on the side surface, 7 mm in the transition zone, and 10 mm on the running surface [3].

5. RESULTS OF THE RESEARCH

5.1. Research on the Actual Wheel and Rail Profile Wear in “Latvijas Dzelzceļš” Network

For the assessment of wheelset rim wear in “Latvijas dzelzceļš” network, factual research information on the most characteristic wear of the wheelset rim of freight wagons was gathered. As a result of the research, reproductions were made from the wear of the wheelset rims, which are typical for the Latvian railway (Fig. 5.1).

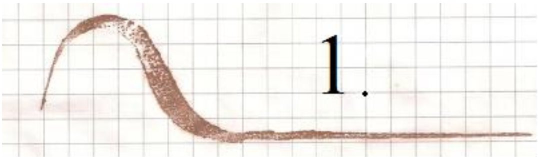


Fig. 5.1. Representation of the characteristic wear of the running surface of a freight train wheel, found in “Latvijas dzelzceļš” network.

After the representation was made, the wear of the wheelset rims of the freight trains were measured and the most common ones in this network of “Latvijas dzelzceļš” were selected. In scale M 1:1 wheelset rim wears were drawn with distribution of freight wagon wheel wear by points (Fig. 5.2).

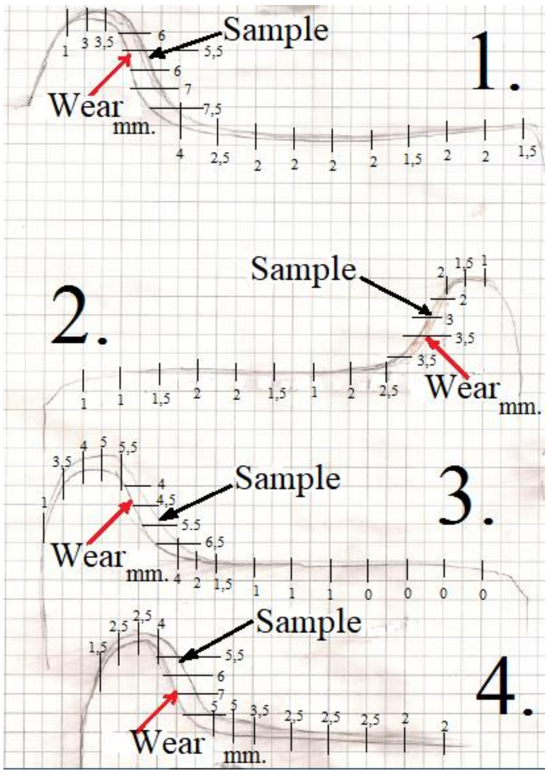


Fig. 5.2. Characteristic wear of freight wagon wheelset rims (1, 2, 3, 4) in “Latvijas dzelzceļš” network.

Fig. 5.2 shows that the heaviest wear of the wheelset rim is on the flange part of the first rim – it is 7.50 mm. However, the wear on the second rim is 3.50 mm. The wear of flange part on the third and fourth rim fluctuates from 7 mm to 550 mm. Wear on the wheel rim is located in zone 1–3.50 mm. Based on the research performed at this stage, it can be said that the wear of the rim of the wheelset of freight wagons is topical in “Latvijas dzelzceļš” network. This is also confirmed by the defect statistics of the sharp-edged rim wheelset and the thin rim.

As a rule of thumb, wear of the wheelset is caused by the rail head wear from the contact between wheel and rail. To determine average statistical rail head wear in the network of Latvian railways, a research was performed using PŠV (TU 3933-002-060632410-2012) type road calliper, the statistics of average indicators were gathered. Figure 5.3 presents one of the fragments of the aforementioned research.

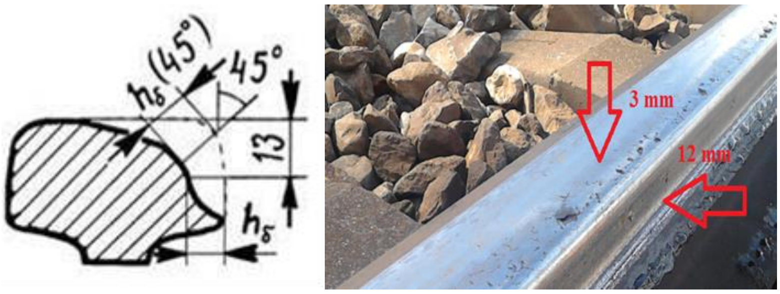


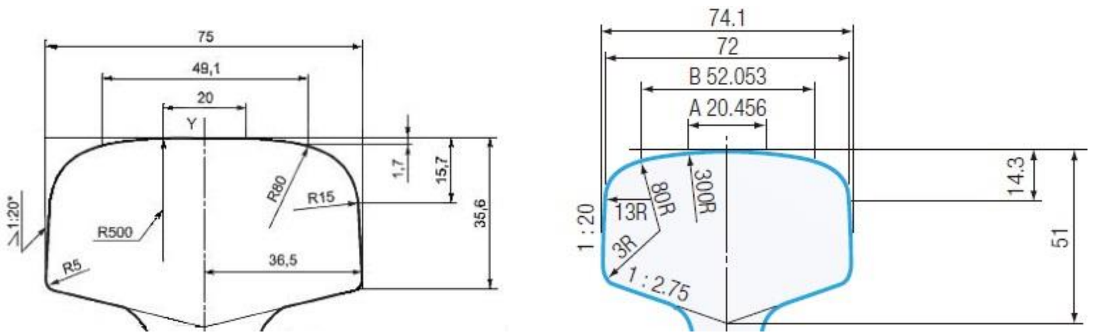
Fig. 5.3. Wear of rail 60 E1 in curve R = 708 m in Vecumnieki station [9].

The vertical wear of rail 60 E1 is 3 mm, the rail head side wear, which develops on the outer rails of railroad curved stations due to the friction between the working edge of the rail and the wheel flange; it is being measured in the level that is 13 mm lower than the pf rail head level, and is 12 mm.

Thus, the wear of wheels and rail influences their interaction.

5.2. Description of Calculation Models, Load Modes of Wheels and Rails

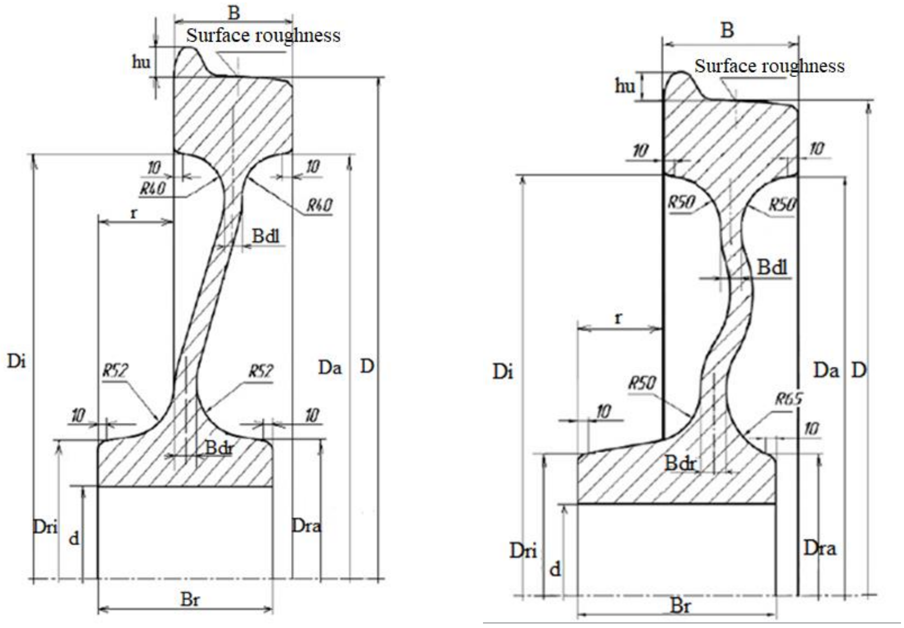
The subjects of research are 60 E1 and R65 (rail profile according to [3], [21], (Fig. 5.4) type rail and freight wagon seamlessly rolled wheels of its wheelset (the wheel profile is a flat conical or curvilinear disc shape [24], (Fig. 5.5).



a) b)

Fig. 5.4. Head profile of a) 60 E1 rail and b) R65 rail [3], [21].

Wheels used in operation under freight wagons are made either of 2 or T brand steel, and the wheel profile is a flat conical or curvilinear disc shape. The structures and main sizes of the wheels are shown in Fig. 5.5 a, b.



a) b)

Fig. 5.5. Structures and main sizes of wheels: a) with flat conical disk;
b) with curvilinear disk (GOST 10791) [24].

According to the stated profiles, a 3D modelling of rail and wheel geometry will be performed in Solidworks program. The assessment of tensed condition rail contact with wheel will be performed in Solidworks Simulation program. To verify the precision of created models, initially a comparison will be made without the appropriate tolerances (friction at contact is not included) with Hertzian contact (friction) theory. Then the assessment of stress distribution level and characterisation calculations for a new rail and a rail with wear characteristic to "Latvijas dzelzceļš" network will be done. To do the assessment of rail grinding impact, calculations of grinded rail with new and worn-out wheel shall be made. Calculations of tensed state will be made for a straight section of railroad and curve done with a radius of 800 m (most common in the main railway road curved turns of "Latvijas dzelzceļš" network) in the following order:

- new rail with new wheel;
- new rail with work-out wheel;
- worn-out rail with new wheel;
- worn-out rail with worn-out wheel;
- grinded rail with new wheel;
- grinded rail with worn-out wheel.

The following initial data are accepted for this.

Materials

Rail steel – R350HT, with high carbon content, with hardened surface. Fluidity limit = 763 MPa, limit of difference = 1210 MPa. Wheel material – steel 2 or T. Flow limit = 990 MPa. Strength limit = 1110 MPa. The material is assumed to be homogenous. Elasticity module and Poisson's ratio is assumed accordingly: E = 210 000 MPa, m = 0.28, rail density p = 7800 kg/m^3.

Conditions for creating a wheel-rail interaction model

- Elevation of outer rail h = 60–65 mm –assumed 60 mm.
- Movement speed of freight wagon V = 90 km/h.
- Road: Swetrak type reinforced concrete cross-ties, ballast –granite rubble.
- Maximal load on wheelset axis is assumed 25 tons (according to [12]). Therefore, for the calculation a freight wagon with mass of 100 tons is chosen.

For the assessment of wheel profile wear influence on tensed condition of rail, in calculations worn-out wheel profiles shall be used that are in operation in "Latvijas dzelzceļš" and "Russian Railways" networks. The maximal side wear of rail head is14 mm and vertical wear of rail is 3 mm.

Assumed tolerances

- Grinding calculations are made for previously found one-point contacts of new and worn-out rails.
- Calculations are made for normal weather T = 0 °C, T = +25 °C, T = –20 °C.
- Changes of cross-ties hardness are not taken into consideration, securing the rail foot firmly in the vertical and horizontal directions.
- Plastic deformations of the material are not taken into account in the calculation models.

Further follows testing of calculation models according to the specified wheel and rail criteria in the modelling program.

5.3. Testing of Calculation Model and Assessment of the Accuracy of the Received Modelling Results

Research subjects are 60 E1 [4] and a seamlessly rolled wheel, GOST-10791, of a wheelset of freight wagon with mass of 100 tons [20], see Fig. 5.5. The model has a symmetric axis, so it is possible to examine a quarter of a wheel. The zone of operational contact is 13–16 mm [14], but the contacting zone with flange, depending on the angle of wheel against rail, on-rolling angle tilts forwards [15]. To reduce the machine time, we removed the wheel hub and disk from the wheel model. For calculations of straight rail road, a wheel model in sections with an angle of 90° and rail length 50 mm is used. For calculations of curved rail road, a rail model of 80 mm in length is used, Fig. 5.6. As a result of optimization, the dimensions of the end elements in the transition zones in the element network model are 1.40 mm for contact surfaces, but in regular zones it is assumed 9 mm, Fig. 5.6 b.

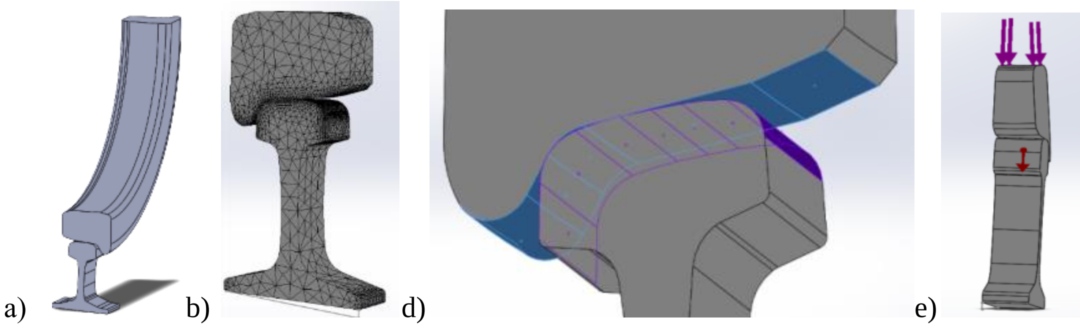


Fig. 5.6. Wheel and rail calculation model: a) on a straight rail road; b) end element network; d) surface contact without initial touch, wheel and rail network separately; e) load application, model fragments.

Restrictions of the model

The base of the rail is firmly fixed. On the cross-sectional surface of the rail, movement in the direction of the longitudinal axis of the rail is restricted. Movement in the perpendicular direction is limited on the wheel cross sections as axle symmetry. On the upper surface of the disc cut and the wheel hub, movement in the horizontal transverse axis of the wheel in the direction of the wheel is restricted. Also, if there is no movement in the curve, the longitudinal movement of the wheel surface on the wheel axle is limited Fig. 5.7.

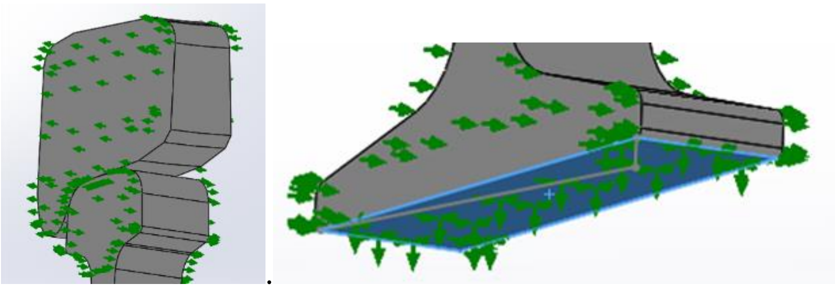


Fig. 5.7. Restrictions of the model.

Loads

A vertical load equal to 1/8 of the wagon weight is added to the model. The load is then re-calculated for the wheel sector with a 90° angle. The uneven load from the weight of the wagon is added to the upper surface of the wheel sector, according to the law on the distribution of the load from the wheelset axle to the wheel hub hole. The density of the wheel and rail materials is taken into account. During the research of the wheel movement in curves with radiuses, the lateral load is also applied in the transverse direction of the wheel to the outer surface of the wheel, Fig. 5.6 e.

In order to evaluate the accuracy of the developed test models, dimensional comparisons of the contact areas were made for wheel GOST-10791 [24] and rail R65, Fig. 5.8.

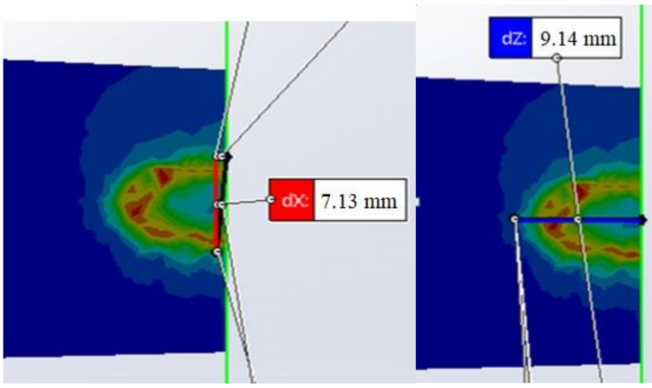


Fig. 5.8. Calculated values of contact area on rail running surface.

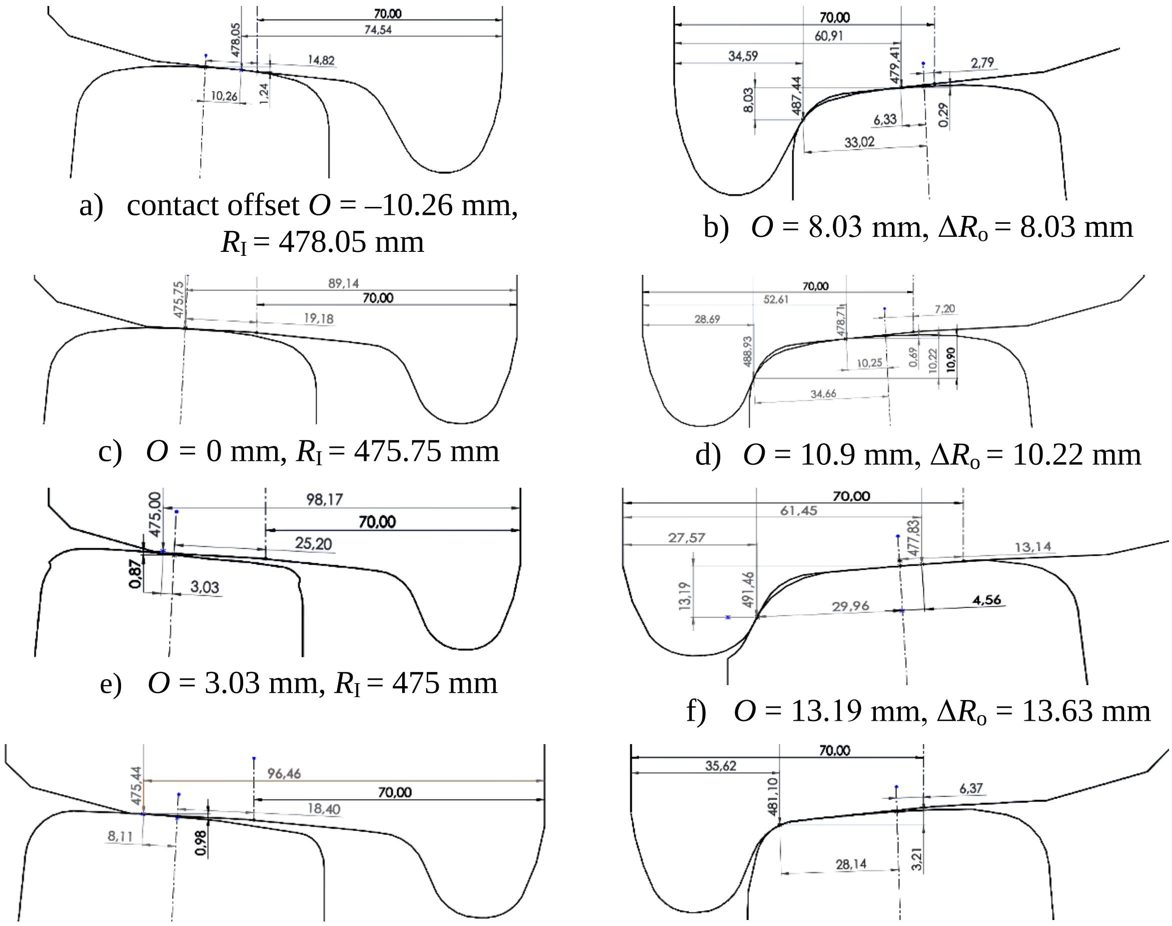
The area dimensions of the contact of calculation model wheel-rail are 14.26–18.28 mm, obtained by modelling and are in agreement with the obtained 14.80 mm according to Hertz's theory [14] and operational data – 13–16 mm [14]. The stress and contact pressure levels in the models of wheel-rail are calculated on the basis of a linear elastic material model and are of a variety from 700 MPa up to 2400 MPa. Also, they are consistent with the results of other authors [10], [14], [16], [25], exceeding the level by 10–12 % relative to the nonlinear model of the material.

However, the main aim of this modelling process is a comparative analysis of grinding influence on relatively new and worn-out rails and wheels that are in operation in "Latvijas dzelzceļš" network.

5.4. Development of Profile Grinding for Preventive Repeated Grinding

According to the gathered data on the wear of wheel (Fig. 5.2) and rail (Fig. 5.3), their contact interaction will be researched from a geometric point of view. A 3D modelling of wheel GOST-10791 [20] and rail 60 E1 [4] will be performed in SolidWorks program. The contact form assessment was modelled for new and worn-out rails in various combinations with wheels. The most dangerous contact types subject to further stress assessment are shown in Fig. 5.9 in straight rail road sections and accordingly curved sections with an 800 meter radius.

The results of geometric modelling of variants revealed that in straight rail road sections there the contact is predominantly in the middle area of wheel and rail, which does not cause edge wear – single point contact. Thus, according to the results of the location zone of the interaction between the wheel and rail contact surfaces, asymmetrical profiles for rail grinding have been developed for tracks with a radius of 800 meters, taking into account the profile of the wheel, which has a characteristic wear in "Latvijas dzelzceļš" network.



a) contact offset O = –10.26 mm, R_I = 478.05 mm

b) O = 8.03 mm, ΔR_o = 8.03 mm

c) O = 0 mm, R_I = 475.75 mm

d) O = 10.9 mm, ΔR_o = 10.22 mm

e) O = 3.03 mm, R_I = 475 mm

f) O = 13.19 mm, ΔR_o = 13.63 mm

g) O = 8.11 mm, R_I = 475.44 mm

h) O = 28.14 mm, R_o = 481.10 mm

Fig. 5.9. Contact types of interaction of 60 E1 type rail and wheelGOST-10791 profiles: a), b) new rail (grinded rail by new) and new wheel; c), d)side wear of 6.50 mm of new rail and wheel; e), f) vertical wear of inner rail – 2.50 mm, side wear of outer rail – 6 mm, vertical – 1.50 mm, and wheel wear – 6.50 mm; g), h) developed rail grinding profile with wheel wear 6.50 mm; a), c), e), g) R_I – the radius of the wheel in contact with the inner edge of the rail; b), d), f), h) ΔR_o – wheel radius deviation at two contacts of the outer rail profile.

The evaluation of the influence of different rail grinding profiles on the pair wheel-rail friction interaction confirmed the efficiency of rail grinding profiles Figs. 5.9 g, h. The wheel-rail contact area is shifted to the track curve centre, wherein the displacement of the inner rail is 5 mm to 18 mm and the wheel radius is reduced by 0.44–2.60 mm, but on the outer rail from 18 mm to 32 mm, and the wheel radius increases from1.69 mm up to 3.27 mm. The difference between the inner and outer radius of the wheel for the profiles used varies from 1.36 mm to 2.96 mm, but the highest value of 5.66 mm is reached for the rail profiles developed in this work [9]. The increase in the radius difference allows to improve the inclusion of the wheelset 4 times, and the single-point contact does not affect the edge area in the modelled curves with a radius of 800 m.

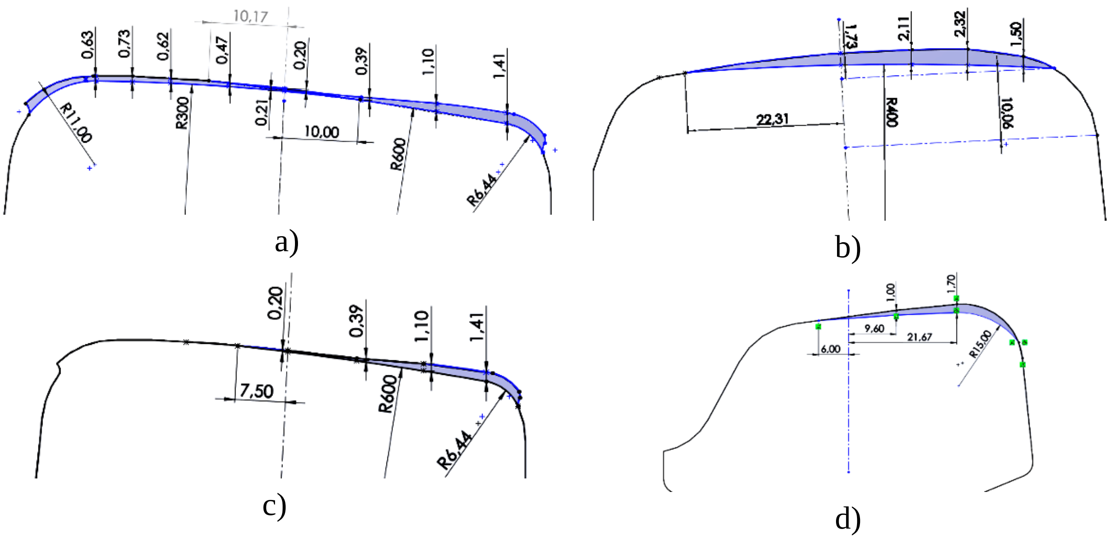
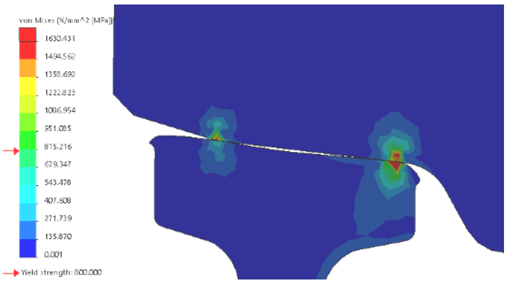


Fig. 5.10. Developed repair profiles for grinding rails in straight lines and curves with a radius of 800 m: a) worn-out railroad track profile in straight railroad section of “Latvijas dzelzceļš” network; b) in curved; d) worn-out profile (Fig. 5.2.(3)) – for outer rail with side wear; c) new and worn profile of 2.50 mm of inner rail.

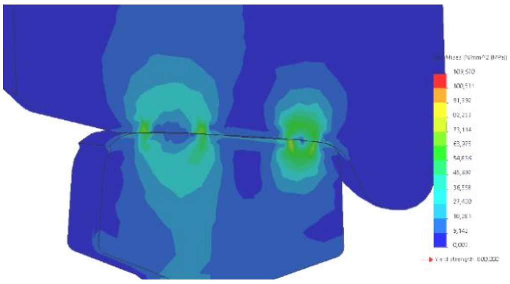
Figure 5.10 presents the designed asymmetric grinding profiles for the inner and outer rail. Among them, a pair of rail asymmetric profiles with less wheel interaction with the rail and a smaller number of grindings were identified as the recommended profiles for rail grinding. Comparing to inner rail profile, the range of outer rail grinding is larger, but its grinding zones are split between the side of the rail and the upper part of rail head. The inner rail profile is basically grinded in the local area at the top of the rail. The main angles of asymmetric profile surface grinding have reached from 2.68° up to 2.41° for outer rail and from 2.36° up to 4.61° for inner rail [9]. The assessment of rail grinding impact will be performed by 3D modelling of the interaction of pair wheel-rail, using the developed rail profile. The contact stress level will be determined using Solidworks Simulation.

5.5. Evaluation of the Effect of Grinding Profiles on the Rail and Wheel Connection from the Tensioned State

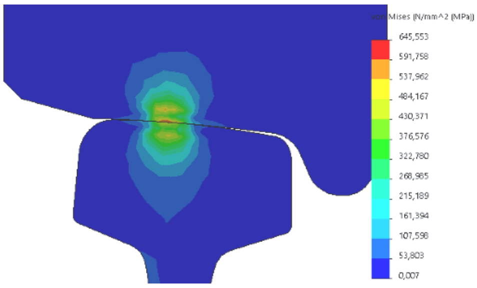
Taking into consideration the results of geometric modelling of contact zone, wheel and rail contact stress will be calculated in straight rail road parts and curves with a radius of 800 m. 60 E1 type rails with new profile, worn-out and newly modelled asymmetric rail repair (grinding) profile, as shown in Fig. 5.10, was chosen. Wheel GOST-10791 [24] with the characteristic wear of “Latvijas dzelzceļš” network, as in Fig. 5.2 (3), was chosen. The results of calculations are shown in Figs. 5.11 and 5.12.



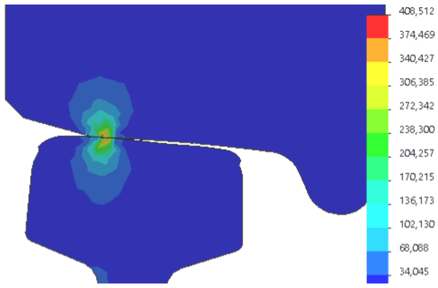
a) Deviation of rail axis – 5 mm



b) Maximal deviation of rail axis –2.50 mm

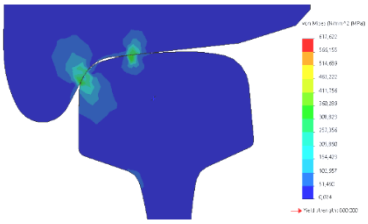


c) Nominal deviation of rail axis – 4 mm

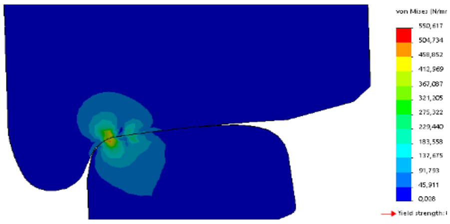


d) Deviation of rail axis – 6.40 mm

Fig. 5.11. Von Mises stress of worn-out wheel on rail profiles in "Latvijas dzelzceļš" network: in straight rail road sections: a) maximal wear of rail profile; b) wear of rail 2.50 mm; c) calculation profile of rail in Fig. 5.10 a; inner rail in curve d) designed rail profile in Fig. 5.10.



a)



b)

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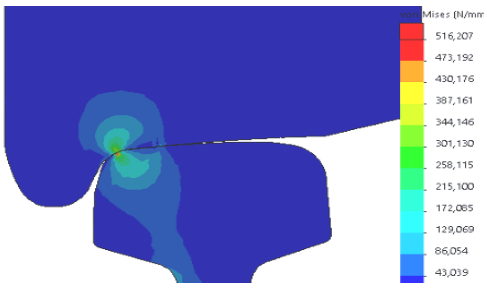

d)

Fig. 5.12. Von Mises stress of worn-out rail profiles in "Latvijas dzelzceļš" network and outer rails in curved rail roads: a) stresses for new rail in outer profile; b) stresses in ridge area for rail wear 2.50 mm; c) designed rail profile, customized for grinding in the zone of radius; d) stress zone deviation from flange, using developed outer rail profile as shown in Figs. 5.10 b and 5.12 c.

On straight rail roads, during the interaction of profiles of the worn-out wheel and rails, the stress level of 1630 MPa exceeds the limit of material flow ability, see Fig. 5.11. Using the developed rail profile shown in Fig. 5.10a), the stress reduced to 640 MPa. The stress level on the outer rail during the wheel and rail interaction on curved rail roads was 1770 MPa in one-point contact, and 620 MPa in the two-point contact (Figs.5.12 a, b). After the corrective grinding of rail, the stresses reduced to 510 MPa in the work radius zone (Figs. 5.12 c, d). In the outer rail, the stresses reach 450 MPa (Fig. 5.11 d), using the developed rail profile (Fig. 5.10 c).

As shown in Fig. 5.11 c, the use of the developed rail (Figs. 5.10 a, c) will allow on rail road to shift the contact area from the outside of the rail road on a straight line to an area with less wheel and rail wear (Figs. 5.2(3) and 5.11 a). This solution will stimulate more even wear of the rail and wheel profiles. As shown in Fig. 5.12 d, the usage of the developed profile (Fig. 5.10 b) and the corrective grinding for profile (Fig. 5.12 c) will allow the outer rails with the contact area of the wheel flange surfaces to be excluded in the curves. Performing grinding along these profiles, a one-point contact can have a larger area than the usable rail grinding profiles. A two-point contact development is possible as well, as can be seen from the example in Fig. 5.12 b, with minimal gaps of 1.00–1.20 mm in the flange base radius zone. After working on the outer rail and wheel surface, the profiles of rails and wheel will have a conformal state with gaps of 0.40–0.60 mm by the flange base.

5.6. Operational Safety Check of the Proposed Profile Grinding after Rolling the Flange on the Rail

When driving on the rail road track, a position of the wheelset is possible, at which one of the wheels drives on the rail with a flange. Being in the movement on curved rail roads, or also often on straight rail road sections, front wheels of a train bogie drive on the rail head side edges with the flange. The drive-on angle can reach 0.573° and even a bit more (in fast curves). Then, the wheel tends to run on the rail in the plane of sliding with the outer surface tangent of the flange creating angle β with horizontal axis (flange slope angle). The location of flange contact with the rail head is in front of the vertical radius of the wheel causing advance into contact.

According to the norms, in order to assess the wheel stability against driving off of rails, the stability ration is calculated, and the following conditions are required:

$$kus = \varepsilon \frac{P_{\mathrm{v1}}}{P_{\mathrm{h}}} \geq [kus], \tag{5.1}$$

where

$[kus] = 1.50$ is the allowable value of the stability factor for freight wagons;

ε is the ratio calculated by formula:

$$\varepsilon = \frac{\tan \beta - 0.25}{1 + 0.25 \tan \beta} = \frac{\tan 66.83° - 0.25}{1 + 0.25 \tan 66.83°} = 1.317, \tag{5.2}$$

where

β – a slope angle, formed by the rim of the wheel with the horizontal axis, which for a standard wheel is 60°, developed by Railway Research Institute of JSC Russian Railways (VNIIZhT, – 65°, for wheels, developed by the Organisation for Cooperation between Railways (OSJD – *OSŽD*) especifically for their railways, – 70° (in addition to the listed wheels, other wheels with special profiles can be used);in this case, the developed slope angle was presumed β = 66.83° = 2.34;

μ – slip friction ratio for wheel not running on the rail head, $\mu = 0.25$;

P_{v1} – vertical component of reaction forces of the wheel running on the rail head, tf, MPa;

P_{v2} – vertical component of reaction forces of the wheel not running on the rail head, tf, MPa;

P_h – horizontal component of reaction forces of the wheel running on the rail head, which operates simultaneously with P_{v1} and P_{v2}, tf, MPa.

Forces P_{v1}, P_{v2}, P_h are determined by the following formulas:

$$P_{v1} = 2P_{st}(m)\left[\frac{b_2 - a_2}{l}(1 - kd.v_1) - \frac{b_2}{l}kd.s.\check{s}\right] + H_r\frac{r}{l} + qr.p.\frac{b_2 - a_2}{l}; \tag{5.3}$$

$$P_{v2} = 2P_{st}(m)\left[\frac{b_2 - a_1}{l}(1 - kd.v_1) - \frac{b_2}{l}kd.s.\check{s}\right] + H_r\frac{r}{l} + qr.p.\frac{b_2 - a_1}{l}; \tag{5.4}$$

$$P_h = H_r + \mu P_{v2}, \tag{5.5}$$

where

$P_{st}(m)$ – vertical static load acting on the neck of axis, tf, MPa;

$kd.s.\check{s} = 0{,}25\overline{Kd.v.}$ – average value of lateral swinging dynamic;

$H_r = p_a\overline{Kd.h.}$ – average value of frame force, calculatable by the average value of horizontal dynamic, where p_a is axis load, $p_a = 25$ tf $= 2452$ MPa;

qr.p. – force of gravitation of wheel set with axle boxes, $qr.p. = 1.4$tf $= 137.30$ MPa;

The average value of wheelset horizontal dynamic ration is calculated by Formula (5.6).

$$\overline{Kd.h.} = b\delta(5 + v), \tag{5.6}$$

where

b – coefficient of number of bogie axis, $b = 1$ [27];

δ – coefficient that depends on the suspension flexibility of freight wagons $\delta = 0.003$ [27];

v – movement speed of wagons, m/s; $v = 25$ m/s;

$$\overline{Kd.h.} = 0.003 \cdot 1(5 + 25) = 0.09;$$

$2B_2$ – distance between the middles of wheelset axis necks, $2B_2 = 2.036$ m;

a_1, a_2 – distance from contact points till the middle of axis necks, $a_1 = 0.217$ m, $a_2 = 0.264$ m;

r – wheel radius;

l – distance between the wheel contact points with the rail, assumed equal to 1.555 m.

By replacing 5.3 and 5.4 in formula

$$2P_{\mathrm{st}}(m) = p_{\mathrm{a}} - qr.p., \quad (5.7)$$

$$2P_{\mathrm{st}}(m) = 25 - 1.4 = 23.50 \text{ tf } = 2305 \text{ MPa},$$

Also, by inserting numerical values in linear quantities and the nominal wheel radius $r = 0.475$ m, after conversion we get the following simplified equations for P_{v1} and P_{v2}:

$$\begin{aligned} P_{\mathrm{v1}} &= p_{\mathrm{a}}\left(0.485 - 0.528\overline{Kd.v.} + 0.289\overline{Kd.h.}\right) + 0.528\overline{Kd.v.}\,qr.p. = \\ &= 23.5(0.485 - 0.528 \cdot 0.23 + 0.289 \cdot 0.09) + 0.528 \cdot 0.165 \cdot 1.4 = \\ &= 9.27 \text{ tf } = 909.10 \text{ MPa}, \end{aligned} \quad (5.8)$$

$$\begin{aligned} P_{\mathrm{v2}} &= p_{\mathrm{a}}\left(0.515 - 0.222\overline{Kd.v.} - 0.289\overline{Kd.h.}\right) + 0.222\overline{Kd.v.}\,qr.p. = \\ &= 25(0.515 - 0.222 \cdot 0.23 - 0.289 \cdot 0.09) + 0.222 \cdot 0.23 \cdot 1.4 = \\ &= 11.01 \text{ tf} = 1089 \text{ MPa}, \end{aligned} \quad (5.9)$$

$$H_{\mathrm{r}} = 23.5 \cdot 0.09 = 2.11 \text{ tf } = 206.90 \text{ MPa}.$$

$$P_{\mathrm{h}} = 2.12 + 0.25 \cdot 11.01 = 4.86 \text{ tf } = 476.60 \text{ MPa}.$$

$$kus = 1.317\frac{9.27}{4.86} = 1.317\frac{909.10}{476.60} = 2.51 > [kus] = 1.50.$$

The calculated coefficient is 2.51, exceeding the minimum allowable value 1.50 for freight wagons and approves the stability and operational safety margins, that is, the sliding of the flange on the rail head is prevented [9].

5.7. Developed Methodology of Rail Grinding

Based on the performed research, a methodology is developed to reduce the wheel and rail wear by performing a coordinated grinding of the wheel and rail. As in the friction pair wheel-rail occurs mutual wear of contact surfaces, it is suggested to look for the repair profile shape for grinding of the rails taking into account the wear profile of the wheel. Of course, the task becomes complicated due to the diverse wheel profiles that have been put into operation. In addition, if the tread wear of the wheel profiles is 1–2 mm, the inclination of the wheel tread changes, the contact points shift horizontally relative to the rail, the type of contact and the nature of the wear change accordingly. Similarly, with such an unobserved wheel profile, the wheel radius per wheelset tends to become the same, which is especially not acceptable in the sections of track curves.

It is, therefore, proposed to collect statistics on the total number of new wheel profiles, as well as to take into account the main wear patterns of wheel profiles. The information must be sorted according to the shape of the wheel profiles and the nature of the wear in general or in movement type of sections in “Latvijas dzelzceļš” network. In this way, separate sections with similar track wear will be separated. In the future, it will be possible to solve the task of creating a rail profile for coordinated grinding with a wheel profile. Development of a large number of track profiles for preventive and repair grinding with less discretion for vertical and horizontal wheel-rail wear will reduce the amount of metal removed from the track and reduce the grinding time.

5.8. Economic Comparison of Rail Grinding and Wheelset Restoration Works and the Replacement

Further, the economic costs will be compared with the annual costs of grinding the tracks with the costs of repairs to renew or replace the wheelsets.

Currently, according to the accounting data of "Latvijas dzelzceļš", about EUR 2500 are needed to grind 1 km of track in Latvia. Thus the collection of rail maintenance statistics (on rail wear) and the processing and analysis of the condition of the rail maintenance is the first level task for the Road Administration. Expenditure on the collection of track condition statistics, when creating the economic comparative schedule, is not accounted for, therefore EUR 2500 is accepted for 1 km of track grinding.

According to the accounting data of the repair shops, at the technical maintenance points (TMP) of rolling stock, the price of one pair of wheelsets in a set is EUR 2500–2700. By contrast, the price of a new or by a repair company repaired wheelset is EUR 3100–3200 (including rolling, dismantling, turning, full audit, assembly, tightening). According to the statistical data regarding the wheelset defects (Fig. 4.1) sharp edged on-welding and thin flanges are the main defects in the interaction of wheel and rail in "Latvijas dzelzceļš" network. The number of these defects will be summed up when drawing up the economic graph. For economic comparison, we will show the statistics of grinded rails and exposed sharp-edged on-welding and thin flange defects in the period of 2016–2019. For this purpose, a graph will be created in Microsoft Excel (Fig. 5.13).

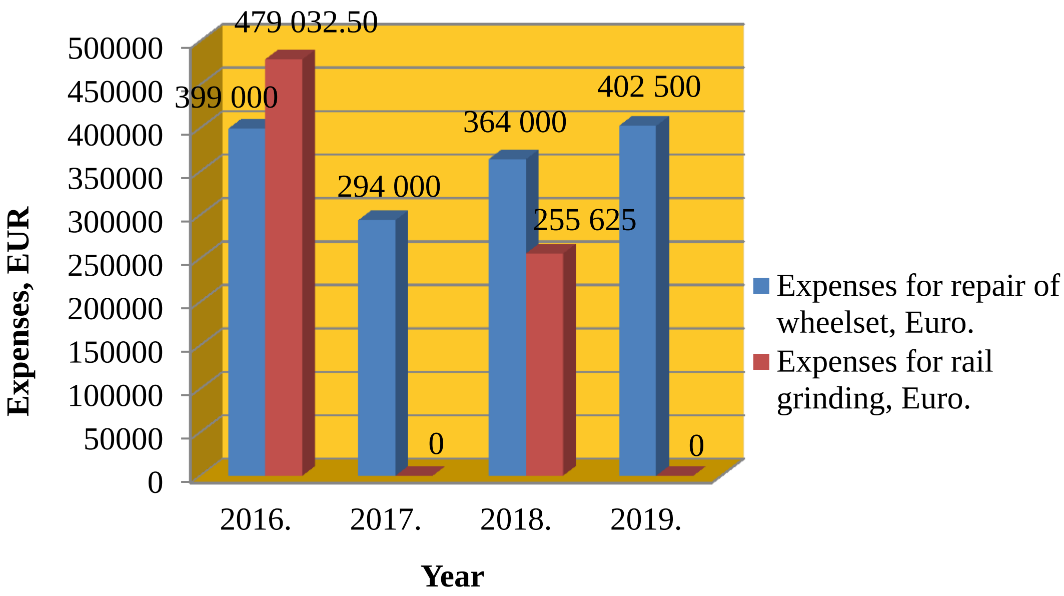

Fig. 5.13. Economic expenses for wheelset defect repair and rail grinding.

As shown in Fig. 5.13, in 2016, "Latvijas dzelzceļš" spent EUR 399 000 for the repair of wheel pair defects, while EUR 479 032.50 were spent for rail grinding. In 2017, the expenses for wheelset defect repair reduced to EUR 294 000. The rail grinding expenses were EUR 0. Expenses in 2018 of unplanned wheelset defect repair were EUR 364 000, but for rail grinding – EUR 255 625. However, in 2019, the expenses of wheelset repair increased up to EUR 402 500. Rail grinding in "Latvijas dzelzceļš" network in 2019 was not performed and, accordingly, the expenses were EUR 0. The economic expenses for wheelset repair and rail grinding are shown in Table 5.1.

Table 5.1

PLC "Latvijas dzelzceļš" Expenses for Wheelset Repair and Rail Grinding

Expenses for wheelset repair in 2016–2019, EUR	**Expenses for rail grinding in 2016–2019, EUR**	**Total expenses of PLC "Latvijas dzelzceļš", 2016–2019 for wheelset repair and rail grinding, EUR**
1 459 500	734 657.50	2 194 157.50

Total expenses of "Latvijas dzelzceļš" for wheelset repair and rail grinding in 2016–2019 were EUR 2 194 157.50, of which for repairing wheel pair defects, incl. also unplanned repairs – EUR 1 459 500 and rail grinding – EUR 734 657.50.

The following conclusions can be drawn from the economic analysis of the resources spent for wheelset repair and rail grinding: non-alignment of the wheel with the rail imposes high economic costs for their elimination.

MAIN RESULTS AND CONCLUSIONS

Summarizing the results of the research work, the following conclusions can be drawn:

1. Rails are an integral part of rail road superstructure; the high requirements, characteristics and properties imposed on them indicate the importance of a safe transport process with railway rolling stock. Rail steel consists of many chemical elements, the main indicators of which are the content of carbon, silicon, manganese and harmful impurities such as phosphorus and sulphur. Rail steel hardness is one of the most essential parameters for the safety of rolling stock driving through on it, and they must correspond to the current standards (EN 13674-1:2011, GOST R 51685-2013) in the country in which they are used.
2. From the analysis of rail steel defects, it can be concluded that the heating defect occurs as a result of high temperatures and rail steel overheating, the rolled stock defects are formed as a result of incorrect rolling, rolling of the metal, as well as incorrect calibration of mechanisms involved in rail steel rolling and rolling processes. Incorrect cleaning (indentations), scratches on the surface of the rolling from the worn-out reinforcement of rolling, worn-out form, insufficient adherence to technologies for heating, melting, and casting ingots in molds, is also a reason for a number of these defects. Defects in the metal structure, as a rule, are associated with non-compliance with welding technology and heat treatment of steel rails after the welding process.
3. The following conclusions can be drawn from the overall analysis of the damaged and heavily damaged rail defects in "Latvijas dzelzceļš" network:
   - the number of heavily damaged rail defects in 2011–2019 was 2495 very severe defects;
   - the number of detected heavily damaged rail head defects in 2011–2019 was 1814 very severe defects;

   These statistics show the necessity to perform technical and planned precautions to save and prolong the rail head operational lifetime. One of such solutions is rail grinding using a rail grinding train.
4. The analysis of usage of the rail grinding train of company "Speno" in "Latvijas dzelzceļš" network proves the topicality of rail grinding train usage on Latvian railways to save and prolong the rail operational lifetime. In the period from 2011 to 2019, a total of 1 388 087 km/roads of Latvian railway were grinded.
5. The assessment of hardness according to Brinell scale (HB) showed that the hardness of grinded rails is higher than of un-grinded rails by 29 HB. The grinding technique increases the surface hardness 1.2 times. It is stimulated by the use of intermittent discs, that reduce the temperature of surface to be treated, additionally deforms material and increases its level of strengthening. Comparing to the acquired metal hardness of the new rail with the data of production passport, there are differences, the rail metal hardness is less than 104 HB. One of the methods to prolong the operational

lifetime of rail head is the initial and periodic grinding of rails, depending on the throughput tonnage and operating modes.

6. The most common defect in "Latvijas dzelzceļš" network is the defect with code X 10.1. In the course of the research, it was determined that the main reason for the occurrence of the defect with the code X 10.1 is deficiencies in the manufacturing technology, due to which small cracks and tiny fractures are formed on the rail, which due to impact of rolling stock and mill.t. gross tonnage in the process of further operation develop into metal peeling and pitting on the rolling surface of the rail head. The data for the determination of the hardness of rail steel defects show a reduced hardness of the metal at a depth of 10 mm and 35 mm from the head surface, from 341 to 328 HB at a depth of 10 mm and 362–346 HB at a depth of 35 mm. Chemical composition data indicate non-compliance of chemical elements (Mn, C, P, S) with EN 13674-1:2011. Manganese content decreased by 0.017 %, carbon content decreased by 0.039 %, phosphorus content increased by 0.044 %, and sulphur content increased by 0.0043 %. The reduced manganese and chromium content results in a reduction in the impact strength, strength, wear resistance and hardness of the rail steel. Increased phosphorus and sulphur content increases the brittleness of the rail steel and the tendency to crack. The metal structure under the microscope also confirms the presence of cracks and fractures in the damaged rail head. The microstructure of non-grinded rails under the microscope showed inclusions and impurities that adversely affected the surface condition of the rail head, which could serve as a cause of surface defects and development. The results of RTU Department of Railway Engineering, Institute of Transport, Metallographic laboratory research on damaged rails with code X 10.1 are confirmed by a certified testing laboratory KIWA of "Inspecta Latvia", which shows the conformity of the test results.
7. Repair profiles for grinding the rail head for the tracks of "Latvijas dzelzceļš" have been modelled and their impact on the side wear of the interaction surfaces of the rails and wheels has been evaluated. The result of this study on the profile of worn wheels was included in the development of a new repair profile for the rail grinding method as a key factor.

According to the research results and 3D modelling, the following was summarized

1. A method has been developed for creating repair profiles for grinding the rail head, which is based on the use of real worn wheel profiles. This allowed to increase the precision of rail repair profile grinding, to model more precisely one-point contact in straight rail road or two-point contact in curved tracks, and thus to reduce the number of wheel flange defects in various sections of railway tracks of "Latvijas dzelzceļš".
2. Three-dimensional modelling of the wheel interaction with the rail was performed using the developed rail profile, which allowed to evaluate the effect of rail grinding on the stress level in the wheel-rail pair.
3. Asymmetric rail profiles with the lowest wheel interaction with the rail and the lowest number of grindings have been developed as the recommended profiles for rail

grinding. The basic grinding angles for asymmetric profile surfaces range from 2.68° to 2.41° for the outer rail and from 2.36° to 4.61° for the inner rail. As an alternative, we offer to reduce the slope of the outer rail to 1.9° and increase the slope angle of the inner rail.

4. Changes in the grinding angle of the rail made it possible to increase the contact area and, as a result, to reduce the stress on the outer rail in the curve by up to 18 % and to shift part of the load from the wheel edge wear area to the wheel flange base. The displacement reached from 5 mm to 30 mm, the difference in wheel radiuses reaches 5.60 mm in one wheel set, which improved the fit of the wheelsets 4 times.
5. The calculation of the stability coefficient for the worn profiles of wheels with a flange angle of 66.8° in "Latvijas dzelzceļš" network has been performed in accordance with the driving conditions on the rail profiles developed in this dissertation. The calculation factor was 2.51, which increases the minimum value 1.50 for freight wagons and confirms the stability and operational safety margins.
6. The economic analysis confirms the need to use the developed new and repair track profiles for grinding in order to avoid the cost of repairing wheel pair defects.

Results of the conducted research confirmed the effectivity of the developed method in creation of repair profiles for rail head grinding and the developed asymmetric rail profiles. Their usage will reduce the side wear of the rail, as well as the number of wheel repair turning in "Latvijas dzelzceļš" network.

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