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# Head Checks and the Useful Life of Rails

# Zoltán Major<sup>a,\*</sup>, Róbert Horváth<sup>b</sup>, Ferenc Horvát<sup>a</sup>

<sup>a</sup>Széchenyi István Egyetem, 9026. Győr, Egyetem tér 1, Hungary
<sup>b</sup>H - Planer Mérnökiroda Kft., 7140. Bátaszék, Perczel utca 75., Hungary majorz@sze.hu

Transport systems, including railways, are an important part of everyday life in modern societies. Whether it is passenger or freight transport, railways are an environmentally friendly solution with their robust throughput capacity and modern electrified lines. The significant changes in transport needs over the last fifty years have partly modified its role, increasing both track speed and axle load. Head Checks (HC) appeared on the MÁV (Hungarian Railway Corporation) network in the early 2010s. This phenomenon had been an unknown problem in Hungary before. Several cases abroad (e.g., a train derailment at Hatfield station in 2000 with four fatalities) have highlighted the extreme danger of this phenomenon. Materials and railway track experts at Széchenyi University have been working on the subject of HC defects in rail heads for several years. The results of research work carried out for MÁV Zrt. form the base of this article. The novelty of this article is the complexity consideration. Not only the structural changes of the rail material were investigated, but also the time/traffic load-dependent crack evolution was mathematically described. Based on the strategy outlined in the report of the research work, MÁV has taken up the fight against HC cracks, which were initially proliferating. The modern laboratory test in this article is based on the tests of Csizmazia and Horvát (2014). The stresses causing damage were investigated previously by Horváth and Major (2023). The economic analysis is based on Róbert Horváth's own calculation results.

## 1. Introduction

In all modes of transport, the most important requirement is traffic safety, which has particular importance in rail traffic because of the high speed and the huge weight of trains. Anomalies in the rail-wheel contact can be a direct source of danger, so their early detection and effective management are essential. Detection of rolling contact fatigue defects (Head Checks, squats, Belgrospis) is not difficult on the basis of the defect signs on the rail head, but assessing their depth extent and dangerousness in terms of rail breakage is a more difficult task, requiring considerable instrumentation and expertise. The speed restrictions that have to be applied because of defects increase the travel time, and trains' braking and acceleration cause significant additional traction energy consumption. The procedures to reduce/eliminate the defect (rail grinding, rail milling, rail replacement) impose a significant financial burden on the operator. A thorough understanding of this phenomenon is therefore important for both safety and economic reasons. It is also a major issue from a sustainability point of view. Detecting and repairing defects in time can ensure a longer service life. Longer lifetimes can lead to significant material and energy savings, which can have environmental benefits, for example, in terms of life-cycle-related carbon emissions (Csutora and Harangozo, 2017), especially through the use of renewable energy (Hamburger and Harangozo, 2018). However, these initiatives aiming for decarbonization (Győri et al., 2021) require new business models and innovative solutions as well (Dobos and Csiszárik-Kocsir, 2023), for all areas of life and all types of businesses (Csiszárik-Kocsir and Varga, 2023).

## 2. Examination methods of the problem

In the Laboratory investigation chapter, we present the results of a laboratory study (Csizmazia and Horvát, 2014). Then, we present a theoretical description of the evolution of the stresses that cause material structure distortion in the rail head, which was published in more detail in 2023 (Horváth and Major, 2023). After that we

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discuss the importance of field measurements. In the relevant points of the Methodology section, we also reflect on the available international results.

#### 2.1 Laboratory investigation

By far, the most common among the rolling contact fatigue failures are HC defects, which usually occur in the outer rail of curves with high superelevation (m > 100 mm) and in turnouts without rail inclination. HC failures can also occur in isolation but are more typically found on longer lengths of track, such as full curves lying in superelevation. The cracks are typically very close together (1-3 mm) and run nearly parallel (see Figure 1). The danger of this phenomenon lies in the fact that repeated traffic impacts can cause cracks to penetrate deep into the rail cross-section and lead to sudden rail head breakout or full cross-section rail fracture.



Figure 1: "S" shaped HC cracks and gauge corner spalling (Csizmazia and Horvát, 2014)

When a vehicle is travelling in a curve, the wheel-rail contact point on the outer (superelevated) rail is displaced towards the rail's gauge corner (and on the wheel towards the flange root), creating high contact stress. In the same way, in turnouts, the wheel-rail contact surface is pushed towards the gauge corner. The high contact stresses and small slips of the wheel on the rail head contribute to rolling contact fatigue. This explains why cracking is frequent in superelevated curves and turnouts without superelevation.

Depending on the class of the rail steel, a layer with about 0.4 - 1.0 mm thickness develops, cold-formed by the vehicle wheels, in which the hardness of the rail material increases very significantly, up to one and a half times the hardness of the original texture (see Figure 2). In the hardned crust, the strain capacity of the material is exhausted, leading to the appearance of cracks. After crack initiation, the presence of fluids (precipitation water, swaying engine oils) will cause cracks to grow during trains' passes due to high contact and sliding stresses. This is due to the confined fluid, which is not compressible, and in a closed crack under wheel load, very high local pressures will develop, exceeding the normal compressive stress of the rail material. The crack penetrating through the hardened crust will follow the direction of elongation of the longitudinally elongated contexture particles deeper and deeper into the rail head.

The propagation of cracks in the rail head is shown in Figure 3, and the theoretical stages of crack growth are shown in Figure 4.



Figure 2: Results of microhardness measurements (Csizmazia and Horvát, 2014)

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Figure 3: Crack surfaces (Csizmazia and Horvát, 2014)



Figure 4: Crack growth phases

The success of increasing the useful life of a rail depends on its ability to withstand wear and rolling contact fatigue. This is a problem for all classes of rail quality. Rail manufacturers are trying to solve this by increasing the hardness of the rail material. Higher hardness increases wear resistance but, in addition, delays the removal of the fatigue or near-fatigue layer by vehicle wheels. So, it reduces the ability of the rail to wear to a profile that better matches the passing wheel profiles. Thus, RCF cracks may develop sooner in the case of harder grades of steel if the wheel and rail profiles are such that high contact stresses can occur. Therefore, an appropriate prevention and profile grinding regime (forced wear and contact stress treatment) should be implemented to take full advantage of the higher RCF resistance, thus increasing the useful life of the rail. The presented research (Csizmazia and Horvát, 2014) is based on one of the most comprehensive series of tests carried out in Hungary, in the course of which some new methods were applied that are not used in everyday practice, such as the CT scan.

#### 2.2 Theoretical background

According to the Hertzian formula commonly used in railway construction, the value of the contact stress depends only on the wheel load and the radius of the wheel tread, which is a strong approximation the real stress distribution. The maximum value of the shear stress in the rail head can be calculated from the average value, taking into account the Poisson's ratio of the rail material. The contact stress formulae used in railway construction are a repeated simplification of the original simplified Hertz formula. If we ask why new failure phenomena have developed compared to the previous ones, we can justifiably think of increased loads, but this would be too simple an answer since the railways have taken preventive measures, increased the cross-section, tensile strength and hardness of the rails, and designed new rail and wheel profiles. However, if we look at the theory used in the calculations, the error of the approximation becomes apparent since while real values were used for the material properties, a highly hypothetical approximation was used for the half-width of the contact ellipse. Forgetting the fact of the approximation, the profession has only noted and applied the simplifying relation, which gives sufficiently reassuring results. However, life has not proved this to be reassuring, as a large part of the rail network is subject to rolling contact defects. In order to determine the results obtained by the original Hertzian calculation and to apply them in practice, it is advisable to refer to Ponomarev's book (Hungarian edition: 1965), which allows the real problem to be fully examined. Based on the book, we discussed in detail in a technical bulletin, which was published at the time of writing this article, the method of calculating the contact and shear stresses within the rail head. The calculations carried out have shown that the values of the stresses generated can be up to 2-3 times higher than those calculated from the approximate relationship and that, depending on the location of the contact point, the value of the stresses generated can exceed the limit value for each rail material. This unfavourable contact location is precisely the curvature of the rail heads at the gauge corner, which is also the location of the HC defects. The results, determined according to an approximate and an exact calculation method, are summarised in Table 1 for a wheel load of 60 kN, together with some contact geometries encountered in practice.

Case	Wheel	Curvature	Curvature	Shear stress in	Shear stress	Ratio [-]
	tread	radius of the	radius of	the rail head	in the rail	
	radius	wheel tread	the rail head	[N/mm <sup>2</sup> ]	head [N/mm <sup>2</sup> ]	
	[mm]	[mm]	[mm]	exact	approximate	
1.	460	~	300	339	149	2,27
2.	460	-330	300	167	149	1,12
3.	460	-330	80	506	149	3,39

Table 1: Value of shear stresses inside the rail head

The values in Table 1 illustrate the pseudo-safety assumed using the approximate method. If we want not only to verify the reliability of the method but also to evaluate the results obtained, we need to have threshold values. We have derived them for frequent rail qualities according to Esveld (2001) and summarised them in Table 2.

Table 2:	Threshold	values f	for shear	stresses	occurrina	inside	the ra	il head
			0. 00	0	0000000000000000			

Material	Shear stress limit in	Material	Shear stress limit in
	the rail head		the rail head
	[N/mm <sup>2</sup> ]		[N/mm <sup>2</sup> ]
R200	196	R320 Cr	312
R220	222	R350 HT	339
R260	254	R350 LHT	339
R260 Mn	254	R370 CrHT and R400 HT	369

Note:

• R: rail steel,

• number: Brinell hardness of the rail steel,

• Cr/Mn: chrome/manganese alloying materials,

• HT: heat treatment of the rail section.

A comparison of the results summarised in Table 1 and the limits summarised in Table 2 leads to a surprising result. It appears that in the case of the conical design corresponding to the primal railway wheel (case 1) the Hertz stress value requires a sufficiently high-quality rail steel compared to the design corresponding to the wear profile (case 2). When the contact of the wear profile is applied to the gauge corner (case 3), it becomes apparent that damage is certain to occur. When investigating more complex problems, finite element modelling offers opportunities for engineers (Zhang et al., 2023).

Given the above, it is not surprising that railway companies are working on different strategies to tackle the problem. One of these efforts is to increase the tensile strength of rail steel. However, this results in a more rigid rail steel, as the elongation at break of such steels is reduced. Another important endeavour is to ensure an adequate level of maintenance. It is an important task for railway infrastructure operators to maintain the original shape of the rail profile and to deal with HC defects. The theoretical background of the calculations was presented in detail by Horváth and Major (2023). The novelty of the method presented in the article is that it overcomes the limitations of the application of approximate formulas and provides an accurate value of the magnitude of the contact stresses and the shear stresses occurring in the rail head.

#### 2.3 Field tests

The rail is the most expensive part of the railway track. Its manufacture and installation is a major logistical challenge, requiring considerable technical expertise, as it involves moving and installing 120-metre-long rails in one piece. The maintenance of sections affected by HC defects requires a method that is capable of removing the damaged parts to just the necessary extent. The basis of any modern maintenance strategy is a high-level measuring technique in order to detect defect locations and defect depths as accurately as possible (Mićić et al., 2023). According to the Hungarian annual measurement programs, depending on their traffic load, each railway line is subjected to one or two ultrasound, rail profile, equivalent conicity and eddy current measurements done by a track survey train. The combination of the different techniques is necessary because only by using them simultaneously can a proper picture of the depth of the defects be obtained. Once the measurement results have been processed, the rail machining plan for the next semester or year is determined. On high-traffic tracks, rail failure caused by HC defects is inevitable without regular rail maintenance (rail grinding or rail milling). Since beyond a certain failure depth (3-5 mm), the progression of HC defects penetrates steeply into the rail head (see Figure 4), only a defect removal procedure or rail replacement can repair the damaged rail when this value

is reached. If the depth of the defects is not allowed to exceed a critical point, the service life of the rails can be increased by repeated minor interventions.

#### 3. Results

As the actual costs of rail maintenance and replacement are considered company secrets almost anywhere in the world, this article uses "units" to compare various intervention methods based on their respective costs. This approach makes possible the comparison of the relative costs of intervention methods irrespective of country and currency. These units have been derived from Róbert Horváth's professional experience as technical director of a company in the field of railway construction and maintenance.



Figure 5: Results of eddy current measurements

A good example is the railway line Budapest – Hegyeshalom border, section between 235+35 – 252+08 hectometer section number. The outer rail of the curved right track was replaced in 2011. Figure 5 shows the eddy current measurement in April 2016, with HC defects of critical depth in the sections marked in red. In this case, a small correction is no longer sufficient, and the consequence of not having done the maintenance may be a very costly rail replacement. Taking the curve shown as an example, we examined the useful life of the rails and the resulting maintenance costs for two possible strategies. In the case elaborated, we considered the annual average wear rate characteristic to this track section to be 0.4 mm and the previously measured progression rate of HC defects to be 0.7 mm/y. According to Hungarian standards, after being subjected to a certain amount of wear and gross tons of traffic load, the rail can be moved to a lower-class railway line, where it can remain on the track for several years, which is called second lay. The rail is also the most "expensive" component in terms of its ecological footprint, i.e., the most polluting component in terms of its production, transport, and installation, so bearing in mind the life cycle emissions, it is important to prolong its life cycle as much as possible.

If the operator follows a strategy of no maintenance, he will have to spend 100 units every four years to install new rails. Another strategy that the operator can choose is regular maintenance, whereby the depth of HC defects in the rail head is measured annually and never allowed to reach a critical crack depth.

As described before, rail grinding is effective if the amount of material removed is always just the necessary amount, and in terms of frequency, it is essential to always maintain the rail profile. Preventive grinding, carried out annually, ensures that both of these requirements are met. The growth rate of HC defects in the example curve is 0.7 mm/year. Preventive grinding removes approximately 0.4 mm of material at a cost of 2.25 units. Preventive grinding alone can only adequately compensate for the rate of defect development for two years. A major correction is required every 3 y when 1.1 mm of material is removed at a cost of 16.67 units.

Figure 6 shows the variations in annual maintenance (grinding) and rail replacement costs. In the case where the operator carries out the grinding works according to a good strategy, the total cost in the fourth year is 23.4 units. In contrast to replacing the rails at a cost of 100 units, this is much less expensive while keeping the original rails in service. By the eighth year, the total cost is still only 46.81 units compared to 200 units for rail replacement. It is evident that timely maintenance has a significantly more favourable impact on life-cycle costs. Over 10 y, the total life-cycle costs are 70 % lower, and over 20 y they are 60 % lower. In terms of ecological footprint, it is obvious without any serious calculations that regularly maintained rails are significantly more beneficial than replacing them. If diagnostic and repair technologies are properly applied in the development of maintenance strategies for transport infrastructure, a significantly more sustainable operation of the infrastructure can be achieved. By extending the useful life of individual infrastructure elements, in this case, the rails, as much as possible, the life cycle costs can be minimised, and the environmental impact can also be significantly reduced.





#### 4. Conclusions

In this article, we briefly described the very dangerous HC defects occurring in the rails of modern railway tracks, which require special maintenance work. We presented the characteristics of the contact stress that causes the defect and the diagnostic measurement methods that can be used to detect the phenomenon. Using the known properties of a real track section, we compared two operator strategies and showed that the aspects of sustainability and cost-effective operation can be applied effectively simultaneously. As our analysis illustrates, good practice can lead to significant cost savings and a significant reduction in the amount of rail material used. Over a 20-year analysis cycle, the use of grinding can save up to two rail replacements and 3 rail replacements in terms of material installed. Since our research is based on a limited amount of analysed data, the conclusions that can be drawn cannot be considered complete, nor are the results of similar analyses available from our previous work, and therefore we cannot make comparisons with them. As a planned continuation of our research, we aim to obtain additional data and to complement our analysis with ecological footprint research, thus broadening the methodology of the engineering analysis. Our objective in the future is to explore the stress state in the rail head even more precisely in order to model the crack propagation more accurately.

#### References

- Csiszárik-Kocsir Á., Varga J., 2023, Innovation and factors leading to innovative behaviour according to Hungarian businesses, In: Szakál, A. (ed.) IEEE 17th International Symposium on Applied Computational Intelligence and Informatics SACI 2023 : Proceedings, IEEE Hungary Section, 291-297, DOI: 10.1109/SACI58269.2023.10158548.
- Csizmazia F., Horvát F., 2014, Management of rail head damage defects, development of their maintenance technology, Determination of technical requirements taking economic aspects into account. K+F report, 2013-2014. (in Hungarian), <<a href="https://www.mavcsoport.hu/sites/default/files/hazai\_kutatasi\_jelentesek">https://www.mavcsoport.hu/sites/default/files/hazai\_kutatasi\_jelentesek</a> \_gyujtemenye.xlsx>, accessed 21.11.2023.
- Csutora M., Harangozo G., 2017, Twenty years of carbon accounting and auditing A review and outlook. Society and Economy, 39, 459–480.
- Dobos O., Csiszárik-Kocsir Á., 2023, Individual-level perception of research, development and innovation in the life of Hungarian enterprises, In: Szakál, A. (ed.) IEEE 17th International Symposium on Applied Computational Intelligence and Informatics SACI 2023: Proceedings, IEEE Hungary Section, 343-348, DOI: 10.1109/SACI58269.2023.10158662.

Esveld C., 2001, Modern Railway Track, MRT-Productions, Zaltbommel, Netherlands.

- Győri Zs., Kahn Y., Szegedi K., 2021, Business Model and Principles of a Values-Based Bank Case Study of MagNet Hungarian Community Bank. Sustainability, 13, 9239.
- Hamburger Á., Harangozó G., 2018, Factors affecting the evolution of renewable electricity generating capacities: A panel data analysis of European countries. International Journal of Energy Economics and Policy, 8, 161–172.
- Horváth R., Major Z., 2023, Examination of rail stresses arising in the railway rail-wheel connection. Sínek Világa, 4, 2-9 (in Hungarian).
- Mićić M., Brajović L., Lazarević L., Popović Z., 2023, Inspection of RCF rail defects Review of NDT methods. Mechanical Systems and Signal Processing, 182, 109568.
- Zhang S.Y., Liu Q.Y., Ding H.H., Spiryagin M., Wu Q., Guo L.C., Wang W.J., 2023, Predicting crack initiation for rolling contact on rail having a surface indentation. Wear, 530-531, 205041.

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