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Determination of the Susceptibility of the Rail Running Surface to Cracks

Ireneusz MIKŁASZEWICZ[1], Robert BIŃKOWSKI[2], Jakub MICHALIK[3], Michał SZYMAŃSKI[4]

Summary

The article presents one of the main types of rail defects – cracking – and the factors that influence its size. A new test method was used, involving pressing a 60° cone into a prepared rail section. It was found that the forming surface crushing of the material caused by the load, as well as the driving dynamics of the rolling stock, is the reason for the formation of *head checks* on the rail surface. Additionally, it was observed that the structure of the layer of the rail running surface has a significant impact on the formation of cracks. A method was proposed to determine the susceptibility of the rail running surface to rail defect formation using the W_p coefficient.

Keywords: rail head check, running surface, susceptibility coefficient

1. Introduction

Ensuring the safe operation of trains at increasing speeds necessitates the reconditioning of the track superstructure, including the use of proper quality rails. The existing track superstructure, especially on lines with heavy train traffic, requires the implementation of monitoring, the purpose of which is, among other things, to assess the condition of the rails as one of the most important factors for safe transport [1]. One of the defects in the rail running surface arising during exploitation and affecting the safe running of freight and passenger rolling stock is cracking.

During use, the rail running surface undergoes significant changes, such as deformations and the formation of surface defects. The main defects posing difficulties are all types of edge cracks, i.e. *head checks* (2223) [2] (Figs. 1, 2) and surface cracks, i.e. *squats* (227) [2] (Fig. 3) [3]. There are also other defects such as *shelling* (222) [2], corrugations, burns, transverse and horizontal cracks or excessive wear [4]. These defects contribute to passenger discomfort while simultaneously posing safety risks. Dealing with these defects is very challenging and requires significant financial investment. During operation, the track is subject to constant observation by the track maintenance service, while tests are carried out at the same time to reveal these defects, e.g. ultrasonic testing, reprofiling of the rail surface by grinding or milling, repairs by local hardfacing or replacement of excessively defective rails with new ones. The employed repairs of the rail running surface do not completely eliminate the detected defects. In the case of rail head checks, grinding is effective only in the initial stage, i.e., when the *head checks* [5] are still shallow, up to 0.5 mm deep – this point is extremely difficult to spot, and urgent grinding is necessary. Further operation leads to the development of these cracks and an increase in their depth within the material. After this stage, rail grinding becomes less effective due to the greater depth of the defects.

The cause, which among other things influences the reduced resistance of the rails to cracking, is the decarbonisation of the running surface [6, 7]. The permissible decarbonisation of rails, as specified by the EN 13674-1+A1:2017-07 standard [8], is a maximum of 0.50 mm. This phenomenon occurs in rails regardless of their profile or the grade of steel from which they are made and depends on the rolling process, i.e., the protective atmosphere in the heating furnace

[1] Eng.; Retired employee of the Railway Research Institute; e-mail: irekmik@o2.pl.
[2] M.Sc. Eng.; Railway Research Institute, Materials and Structure Laboratory; e-mail: rbinkowski@ikolej.pl.
[3] Eng.; Railway Research Institute, Materials and Structure Laboratory; e-mail: jmichalik@ikolej.pl.
[3] M.Sc. Eng.; Railway Research Institute, Materials and Structure Laboratory; e-mail: mszymanski@ikolej.pl.

or the heating and soaking time. As decarbonisation changes, so does the material's susceptibility to surface cracking. The chemical composition of the rails and their hardness also have a significant impact on the condition of the running surface and its resistance to the formation of surface defects [9, 10].

Fig. 1. Rail head checks at their initial stage [photo by I. Mikłaszewicz]

Fig. 2. Head checks of varying severity in the immediate vicinity of the welded joint [photo by I. Mikłaszewicz]

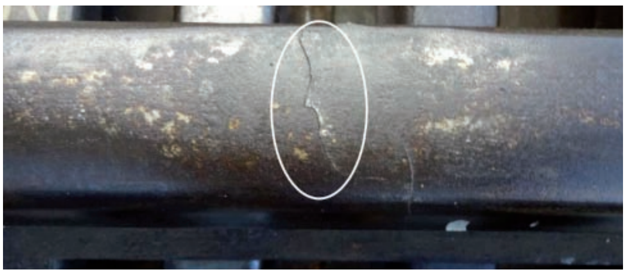

Fig. 3. Rail *squat* defect [photo by I. Mikłaszewicz]

Rails manufactured in accordance with the EN 13674-1+A1:2017-07 standard [8] are delivered to clients. According to the aforementioned standard, the acceptance tests for rails aim to assess the quality of the product, taking into account the requirements for the following parameters: total chemical composition analysis, tensile strength properties, HBW hardness, decarbonisation, sulphur distribution in the rail cross-section, microstructure assessment, rail profile and surface, and internal material cohesion (ultrasonic testing).

2. Material and test methods

In order to determine the W_p coefficient, laboratory tests were undertaken at the Materials & Structure Laboratory of the Railway Research Institute. The material used for the tests were new rails with a 60E1 profile made from R260, R350HT, and R400HT steel grades. The samples were designated as follows: 1 – R260, 2 – R350HT, and 3 – R400HT.

The rail samples were subjected to surface milling to depths of 0.3 mm and 0.5 mm to remove the decarburised surface layer (Fig. 4). The prepared rail surface was then drilled with a core drill of 15 mm diameter to a depth of 8 to 9 mm (Fig. 5). During the sample preparation process, an 8-mm-diameter cylinder was centrally pressed into a cone with a 60-degree opening angle at a force build-up rate of 40 kN/min, recording the indentation force F expressed in kilonewtons and the penetration depth of the cone tip h into the rail material, expressed in millimeters. The test was halted at the moment of material fracture.

Fig. 4. Sections of the three rail grades used in the tests [photo by I. Mikłaszewicz]

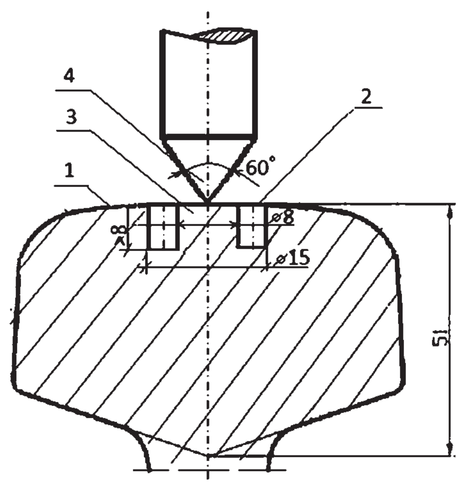

Fig. 5. Diagram of cone indentation into the rail surface: 1) rail, 2) hole drilled using a core drill, 3) rod, 4) cone [photo by I. Mikłaszewicz]

Additionally, a chemical composition analysis was performed, determining the amount of carbon (*C*), manganese (*Mn*), silicon (*Si*), phosphorus (*P*), sulphur (*S*), chromium (*Cr*), nickel (*Ni*), copper (*Cu*), aluminium (*Al*), molybdenum (*Mo*), vanadium (*V*) hydrogen (*H*) and oxygen (*O*), hardness (*HBW* and *HV30*) and strength properties (yield strength $R_{e0.2}$, strength R_m, elongation A_5, and constriction *Z*).

The chemical composition analysis was performed using a Magellan Q8 Bruker spectrometer, while the strength properties were tested on an INOVA FU250 machine, which records force with an accuracy of ±1 N and displacement with an accuracy of ±0.01 mm.

Based on the conducted tests, the susceptibility of the surface layer to cracking was determined using the W_p parameter [kN/mm²]. This parameter was calculated as the ratio of the indentation force *F* to the lateral surface area S_b of the cone pressed into the material.

$$W_p = \frac{F}{S_b}$$

where: *F* – indentation force [kN]; S_b – lateral surface area of the cone [mm²].

After the cone indentation tests, the microstructure of the surface at the beginning, middle, and bottom of the cracked surface layer of the rails made from different steel grades was observed using a Keyence VHX-900F optical microscope.

The analysis of the stresses generated during cone indentation into the rail surface was performed using FEM computer simulation in HyperMesh software, while calculations were performed using the Radioss solver (explicit) The Johnson-Cook elastoplastic model and material failure model for R260 steel were used.

3. Test results

The chemical composition analysis of the tested steel grades used to produce the rails is presented in Table 1, the results for the strength parameters in Table 2, and the hardness in Table 3.

The results for the cracking force *F*, penetration depth *h*, cone area S_b and calculated W_p are shown in Table 4. The graphs (Figs. 6–8) illustrate the relationship between the force *F* and the cone penetration depth *h* for non-milled and milled rails (Figs. 6–8).

Table 1

Elemental content in the tested rails

Sample number / grade	Elemental content [%]											
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo	V	H [ppm]	O [ppm]
1–R260	0.72	1.08	0.31	0.014	0.014	0.076	0.015	0.034	< 0.002	0.005	0.003	≤ 2.5	≤ 20
2-R350HT	0.77	1.10	0.40	0.009	0.009	0.076	0.015	0.013	< 0.002	0.005	0.003		
3–R400HT	0.93	1.23	0.24	0.014	0.012	0.28	0.015	0.011	< 0.002	0.005	0.003		

[Own elaboration].

Table 2

Strength properties of the R260, R350HT and R400HT grade samples

	Sample number					
Parameter	**1.1 – R260**	**1.2 – R260**	**2.1 – R350HT**	**2.2 – R350HT**	**3.1 – R400HT**	**3.2 – R400 HT**
$Re_{0.2}$ [MPa]	427.3 ±14.1	422.3 ±13.9	422.3 ±13.9	–	427.8 ±14.1	417.2 ±13.8
Rm [MPa]	996.7 ±32.9	980.3 ± 32.3	1195.7 ±39.5	1207.7 ±39.6	1389.4 ±45.8	1382.9 ±45.6
A_5 [%]	12.1 ±0.4	12.4 ±0.4	11.8 ±0.4	–	11.8 ±0.4	9.1 ±0.3
Z [%]	20.2 ±0.7	22.0 ±0.7	23.8 ±0.8	–	21.3±0.7	20.4 ±0.7

[Own elaboration].

Table 3

Hardness measurement results for the R260, R350HT and R400HT grade samples

Tested size	Sample number								
	1.1	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**3.1**	**3.2**	**3.3**
HBW	278.7 ±10	286 ±11	285 ±11	295 ±11	353 ±13	349 ±13	401 ±15	398 ±14	396 ±15
HV30	241 ±17	264 ±19	272 ±20	276 ±20	343 ±25	344 ±25	339 ±24	368 ±27	406 ±29

[Own elaboration].

Table 4

Rail surface cracking susceptibility results for the R260, R350HT and R400HT grade samples

Steel grade	Sample no.	Grinding depth [mm]	Surface cracking force [kN]	Insertion depth [mm]	Cone surface [mm^2]	Material cracking susceptibility coefficient W_p [kN/mm^2]	Standard deviation
R260	1.1	0	43.69	5.15	55.63	0.785	0.1404
R260	1.2	0.30	45.84	4.70	46.21	0.992	
R260	1.3	0.50	47.48	4.75	46.92	1.01	
R350HT	2.1	0	54.49	4.72	45.2	1.21	0.6116
R350HT	2.2	0.30	41.53	3.23	24.78	1.67	
R350HT	2.3	0.50	39.75	2.88	17.36	2.29	
R400HT	3.1	0	48.58	4.14	35.87	1.354	0.5513
R400HT	3.2	0.30	45.36	3.08	19.90	2.28	
R400HT	3.3	0.50	49.00	3.58	26.84	1.825	

[Own elaboration].

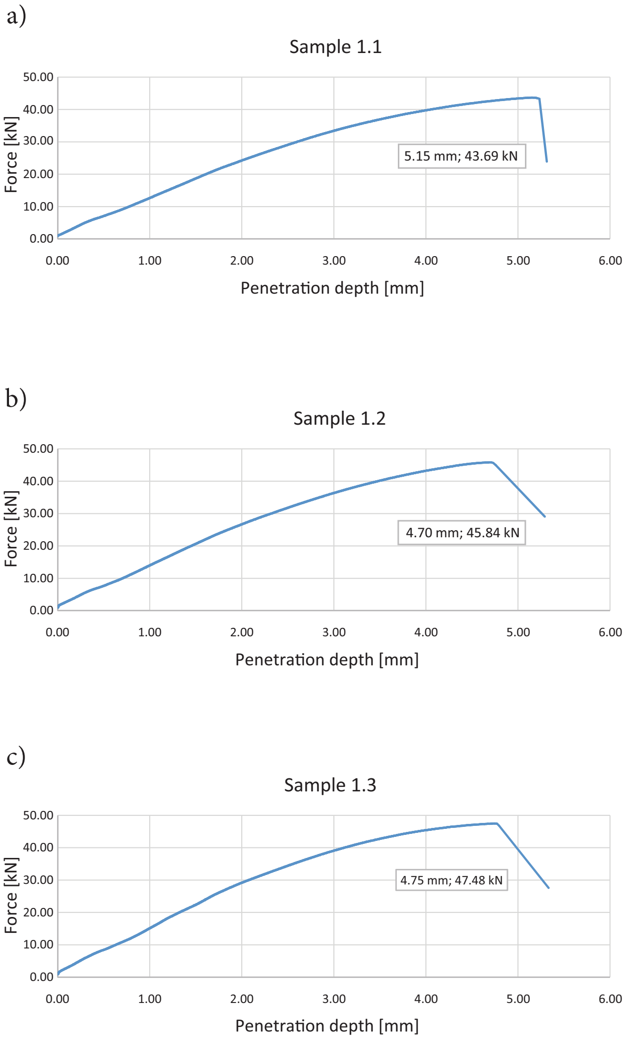

Fig. 6. Relationship between the force and cone indentation depth in R260 rail: a) without milling, b) in a surface milled to a depth of 0.3 mm, c) in a surface milled to a depth of 0.5 mm [prepared by J. Michalik, I. Mikłaszewicz]

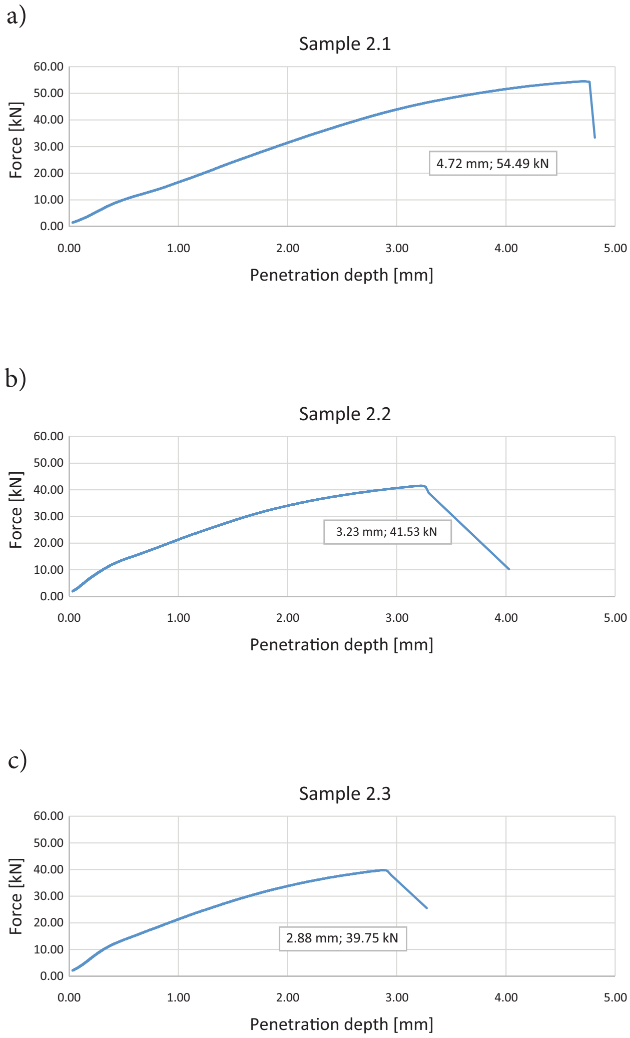

Fig. 7. Relationship between the force and cone indentation depth in R350HT rail: a) without milling, b) in a surface milled to a depth of 0.3 mm, c) in a surface milled to a depth of 0.5 mm [prepared by J. Michalik, I. Mikłaszewicz]

The research results indicate that the susceptibility of the rail running layer to cracking depends on the quality and microstructure of the surface, which in turn is influenced by the final production stage technology, i.e., the final rolling stage, cooling conditions, and rail straightening. The chemical composition of the rail material and the heat treatment of the rail head, particularly in the case of R350HT steel, also have a significant impact on cracking. The results in Table 4 show a pattern where the W_p coefficient rises as rails with greater material strength are used.

Figure 9 shows the microstructure at the beginning, middle, and bottom of the cracked surface layer of R260 rails after cone indentation. A strong crushing of the material is visible near the rail surface, in the middle section, and at the bottom. Meanwhile, Figure 10 shows the structure at the beginning and middle of the surface layer after cone indentation in the R350HT rail.

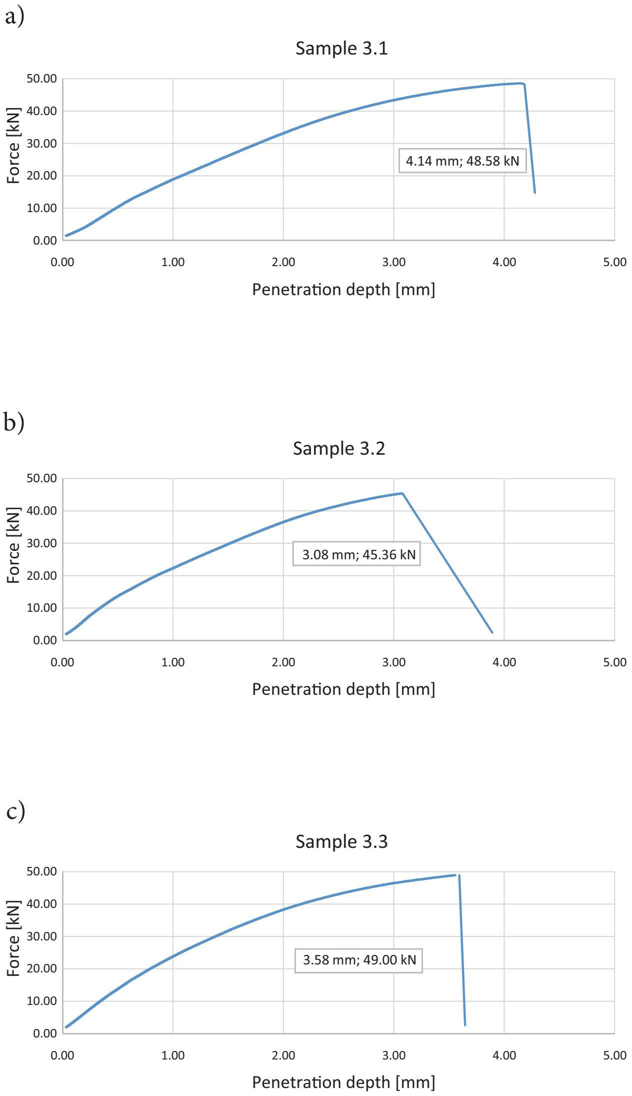

Fig. 8. Relationship between the force and cone indentation depth in R400HT rail: a) without milling, b) in a surface milled to a depth of 0.3 mm, c) in a surface milled to a depth of 0.5 mm
[prepared by J. Michalik, I. Mikłaszewicz]

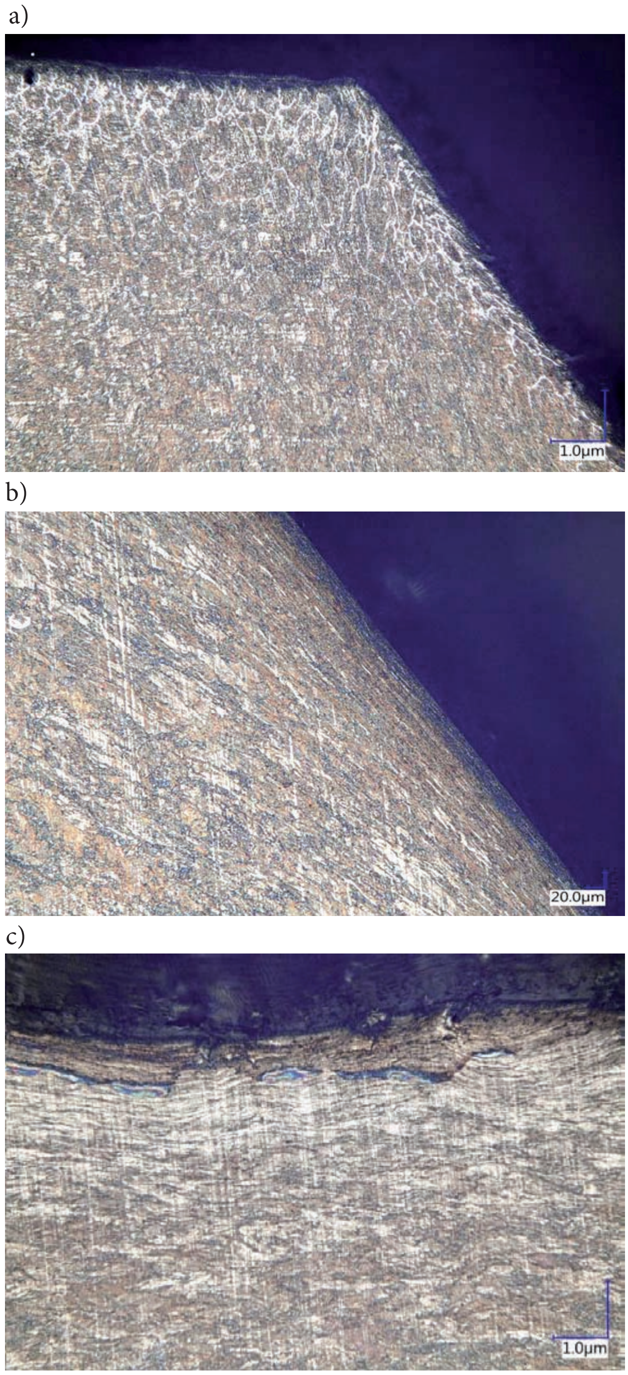

Fig. 9. Cracking of the R260 rail running surface after cone indentation: a) beginning, b) middle, c) bottom near the cone tip
[photo by I. Mikłaszewicz]

a) b)

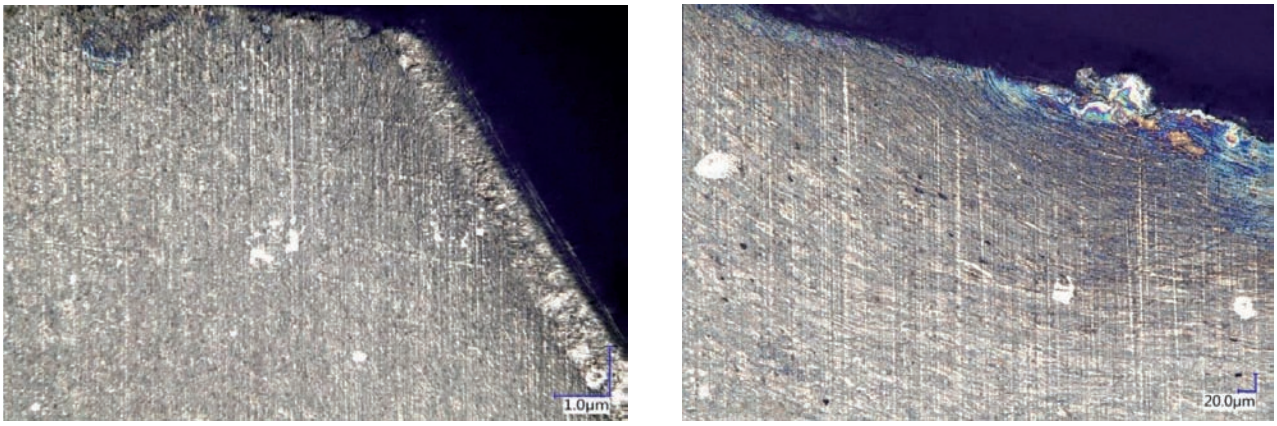

Fig. 10. Cracking of the R350HT rail running surface after testing: a) beginning, b) middle [photo by I. Mikłaszewicz]

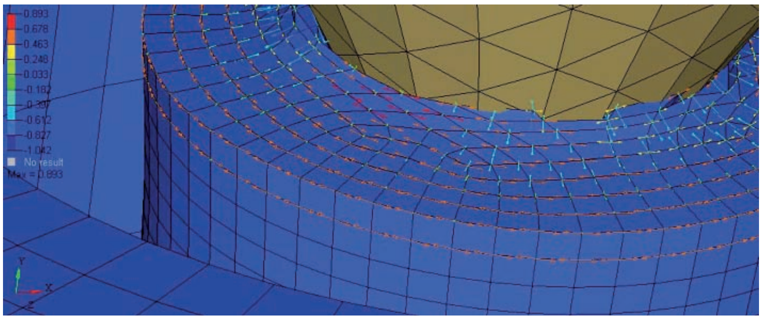

Fig. 11. Principal stresses and their directions in the upper part of the rod just before cracking [prepared by R. Bińkowski]

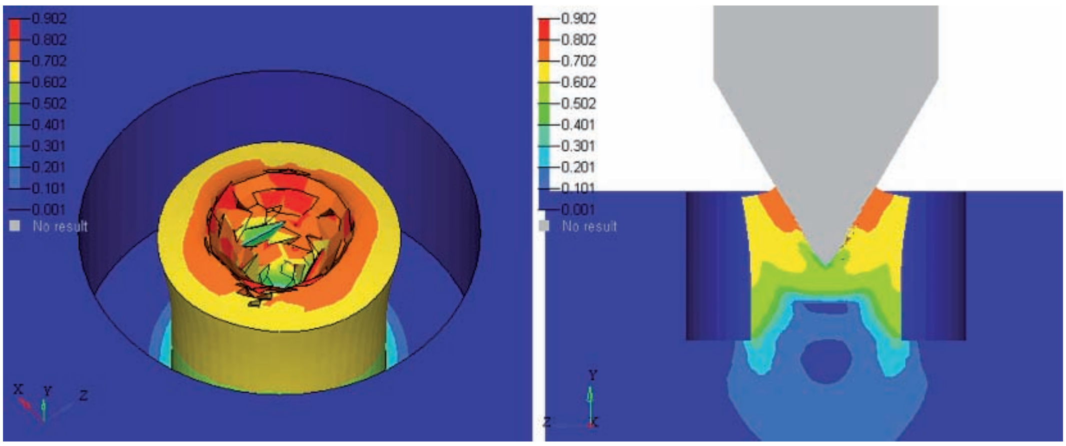

Fig. 12. Reduced von Mises stresses [prepared by R. Bińkowski]

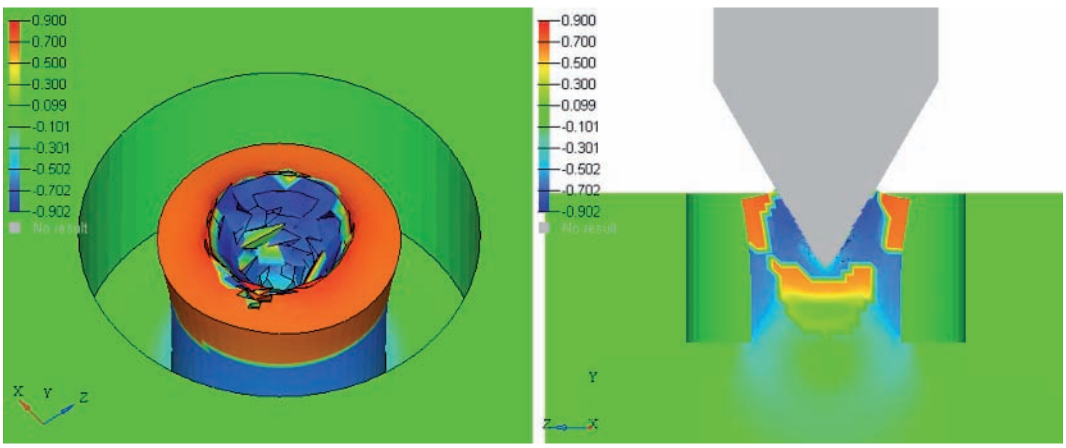

Fig. 13. Reduced von Mises stresses including tension and compression [prepared by R. Bińkowski]

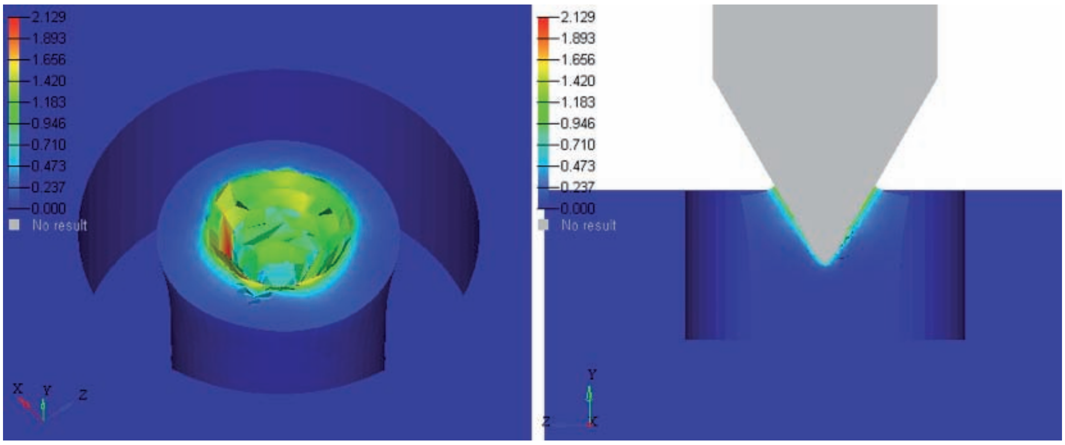

Fig. 14. Result of plastic deformation with the initial material cracking [prepared by R. Bińkowski]

4. Comments and conclusions

The decision to address this topic was based on finding a method to reduce surface cracks in rails of varying severity on the same railway line. During track construction, the installed rails are sourced from several melts of the same steel grade, primarily R260 with a 60E1 profile, so the properties of the tested rail material meet the requirements of the EN 13674-1+A1:2017-07 standard [8].

The mechanism of head checks in rails proceeds as follows: initially, under load from train operation, the rail surface undergoes crushing, which is within the yield strength ($Re_{0.2}$) of the material. During further operation, the material strengthens, and cracks begin to form after the tensile strength (R_m) is exceeded. Therefore, reducing cracks on the rail's running surface would be related to the microstructure state of the rail surface layer and its strength.

The study on the surface layer's susceptibility to cracking using the cone indentation method was based on varying degrees of crushing of the running surface, leading to different degrees of deformation in the rail's surface layer. During cone indentation, the greatest crushing occurs in the surface layer. As the indentation force is applied, the rail surface layer deforms significantly more than the material's interior. Similarly, as described above, when the yield strength $Re_{0.2}$ is exceeded, a process of surface strengthening takes place and once the material's tensile strength R_m is surpassed, cracking occurs from the rail surface into the material.

The chemical composition analysis of R260, R350HT, and R400HT rail samples confirmed the compliance of element content with the requirements of the EN 13674-1+A1:2017-07 standard [8]. The performed tests of strength properties and HBW and HV30 hardness also fall within the requirements of this standard.

Many rail defects arise during railway operation. The small contact fatigue defects that emerge and gradually grow can lead to rail cracking. The proposed method of assessing the running surface's susceptibility to cracking using the W_p coefficient should facilitate the optimal selection of rails that show a delayed onset of rail surface cracks. The W_p coefficient is derived from the relationship between the force applied by a cone with a 60-degree apex angle onto the rail's running surface and the size of the cone's lateral penetration surface. The crushing of the penetrated rail surface due to cone indentation leads to the cracking of the surface layer. The W_p coefficient tests conducted on R260, R350HT, and R400HT rails indicated that the microstructure condition of the running surface significantly influences its resistance to cracking. The resulting perlitic microstructure of the rail running surface layer depends on the cooling rate after hot rolling, as well as the carbon content and the degree of decarbonisation, which is related to the protective atmosphere in the heating furnace used for rolling. The research showed that the W_p coefficient for unmilled surfaces was significantly lower than for milled surfaces in the tested steel grades. The recommended W_p coefficient for R260 steel should be above 0.9, for R350HT it should be above 1.2, and for R400HT above 1.4. The tested R350HT and R400HT rails achieved a progressively higher W_p coefficient depending on the depth of the milled rail running surface layer.

The stresses occurring on the R260 rail running surface during cone indentation, as determined by a finite element analysis (FEA) simulation, reach a level of +900 MPa when calculated as von Mises equivalent stress considering tension (Figs 11–14). When considering both tension and compression, the stresses are also approximately ±900 MPa, which is within the limits required by the EN 13674-1+A1:2017-07 standard for the tensile strength of R260 steel (880 MPa).

Using the W_p coefficient, it is possible to select new rail melts (mainly R260) characterised by a lower susceptibility of the surface layer to cracking due to the high W_p value. Thus, they are suitable for use on lines with higher traffic intensity, leading to a delayed onset of rail surface defects, increased rail longevity, reduced rail replacement frequency, as well as significant financial savings associated with railway line maintenance.

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