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INFLUENCE OF VERTICAL STRAIGHTENER ROLLER SHAPE ON RESIDUAL STRESS LEVEL IN RAILWAY RAILS

The required rail straightness is achieved by straightening with roller straighteners. The consequence of the straightening operation is the introduction of residual stresses to the straightened rail. An excessive level of residual stresses accumulated in the rail during use in the track may lead to its damage or fracture.

ArcelorMittal Poland S.A., in cooperation with Łukasiewicz Research Network – Institute for Ferrous Metallurgy, carried out a research project (POIR.01.02.00-00-0167/16) the aim of which was to reduce residual stresses in railway rails by changing the technological parameters of the straightening process. The results of the presented study relate to rails 60E1 and 60E2. The study includes the measurement, testing, calculations and analyses of the obtained results. The conducted research indicates the possibility of obtaining a low level of residual stress in the rails for a system consisting of a 7-roller vertical straightener and a 9-roller horizontal straightener by changing the roller settings, the shape of the rollers, the shape of the rail foot and its curvature.

Keywords: Stress; methodology; straightening; roll; rail

1. Introduction

Modern rail transport with high train speeds requires high-quality tracks. The required rail straightness is achieved by straightening with roller straighteners. The consequence of the straightening operation is introducing internal residual stresses to the straightened rail. The level of residual stresses measured in the rail foot axis, defined by the European Standard, should not exceed 250 MPa for rails of all steel grades. An excessive level of residual stresses accumulated in the rail during use in the track may lead to its damage or fracture. Therefore the level of residual stresses in the rail significantly affects the safety of railway transport. The demand for minimising residual stresses by rail users is due to the fact that the existing residual stresses, quasi-static thermal stresses and dynamic stresses arising during track operation overlap with the existing residual stresses.

ArcelorMittal Poland S.A., in cooperation with Łukasiewicz Research Network – Institute for Ferrous Metallurgy, carried out a research project (POIR.01.02.00-00-0167/16) the aim of which was to reduce residual stresses in railway rails by changing the technological parameters of the straightening process. The results of the presented study relate to rails 60E1 and 60E2. The 60E1 type rails are currently the basic rails used on standard-gauge railway lines in Poland, and the 60E2 type rails in Germany. The study includes the measurement, testing, calculations and analyses of the obtained results.

2. Effect of residual stresses on rail cracking

A high level of residual stresses decreases rails' resistance to cracking. It is assumed that due to the use of the rail in the track, the maximum tensile stress when bending is 100 MPa. Thermal stresses in summer are compressive at the level of 100 MPa, and in winter, tensile stresses are also at the level of 100 MPa [1]. As a result of the superimposition of operational and thermal stresses on the residual stresses, cracks and fractures of the rail may occur, starting from single surface or subsurface cracks originating from the rail foot or the rail head.

In the foot of the rail, the level of internal stresses remains unchanged throughout the life of the rail in the track. Critical depths of cracks starting from the rail foot can be significantly increased (even several times) by lowering residual stress.

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Moreover, at lower residual stresses, the average operating stress level is lower, which slows down crack development.

In addition to the above-mentioned cracks, the rail head may have defects starting from shelling, head checking or squatting. To counteract these fatigue defects at the interface between rails and wheels, it is desirable to obtain low internal tensile stresses also in the rail head. Vertical tensile stresses in the web are associated with high longitudinal tensile stresses in the rail head and foot. In the case of high-strength rails, they can lead to a slow growth of horizontal longitudinal cracks in the web without external influences. The introduction of service loads, in this case, may lead to a rapid development of the crack, which may branch and eventually lead to a breakage of the rail head and even the entire section.

The rail, after cooling and before straightening, has low residual stresses varying along its height in the range from about –50 MPa (web centre) to about +100 MPa (head and foot). As a result of plastic deformation of the rail during the straightening process, stresses overlapping with the residual stresses after cooling are introduced into the rail. After straightening, high internal tensile stresses appear in the rail head and foot, which decrease towards the rail centre and transform into compressive stresses in the web. The internal tensile stresses in the rail foot may locally exceed even 300 MPa. The value allowed by the European standard is a maximum of 250 MPa in the centre of the bottom surface of the rail foot. Rail manufacturers using appropriate straightening technologies are able to keep residual stress in the rail foot well below 223 MPa [3-5].

3. Distribution of residual stress in the rail and the possibility of their reduction

The level and distribution of the values of residual stresses in the rail cross-section results from the straightening operation in the vertical and horizontal plane. During the operation of the rail in the track, residual stresses are superimposed by the stresses resulting from working loads (static and dynamic). In order to illustrate the dependence of residual stress distributions and stresses from working loads, the course of permissible stress changes in the vertical plane of the profile is shown in Fig. 1.

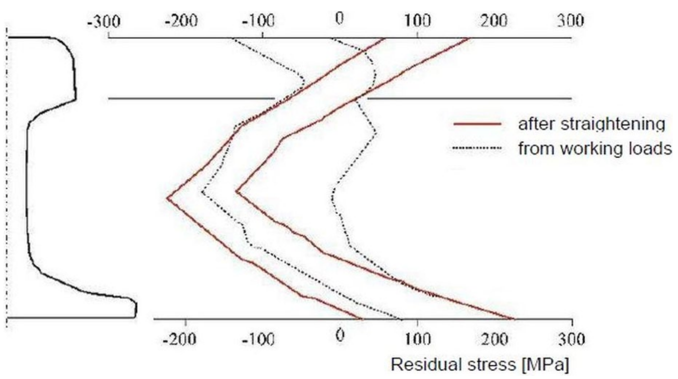

Fig. 1. Stress distribution from working loads and residual stresses after straightening [2]

4. Methodology

4.1. Cutting method

In accordance with the requirements of the PN-EN 13674-1 standard, residual stresses in the rails must be measured using the cutting method in the axis of the bottom surface of the foot. The cutting method relies on the releasing of residual stresses by dividing the tested component into small parts and measuring the deformations that are then released. Residual stresses in the foot, head and web were determined for the tested 60E1 rails after cooling and straightening using the cutting method. The course of deformation release and typical places of deformation measurement are shown in Figs. 2 and 3. For rails after straightening, the measurement of stresses in the foot axis complies with the requirements of the PN EN13674-1 rail standard [6].

For selected tests of rails after straightening using the cutting method, the residual stresses were also determined in other places of the head, web and foot. The measurement of the deformations in the longitudinal direction was taken in the foot in the roller impression zone in accordance with the requirements of PN EN 13674-1, outside the imprint zone on the bottom and top surface of the foot, in the head on the running and side surfaces, on both sides of the web (in the neutral axis) and in the web-foot and web-head transition. The measurement of the

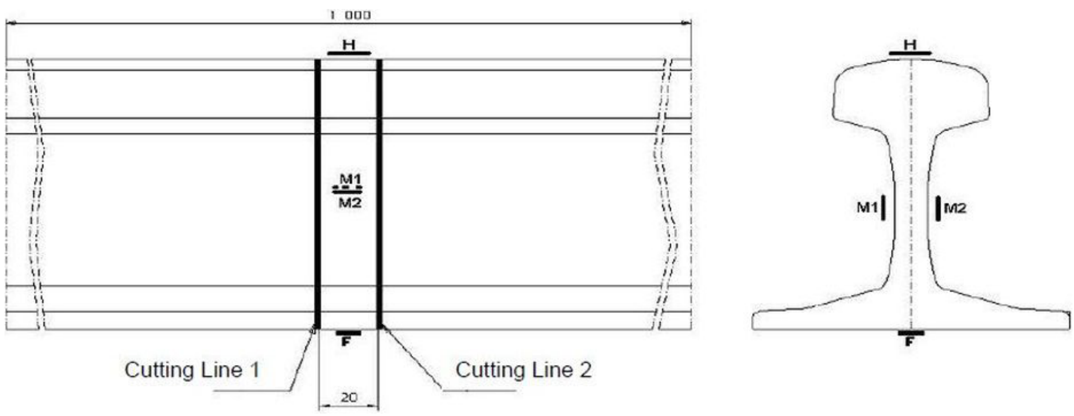

Fig. 2. Course of release and measurement locations for deformations in 60E1 rail tests

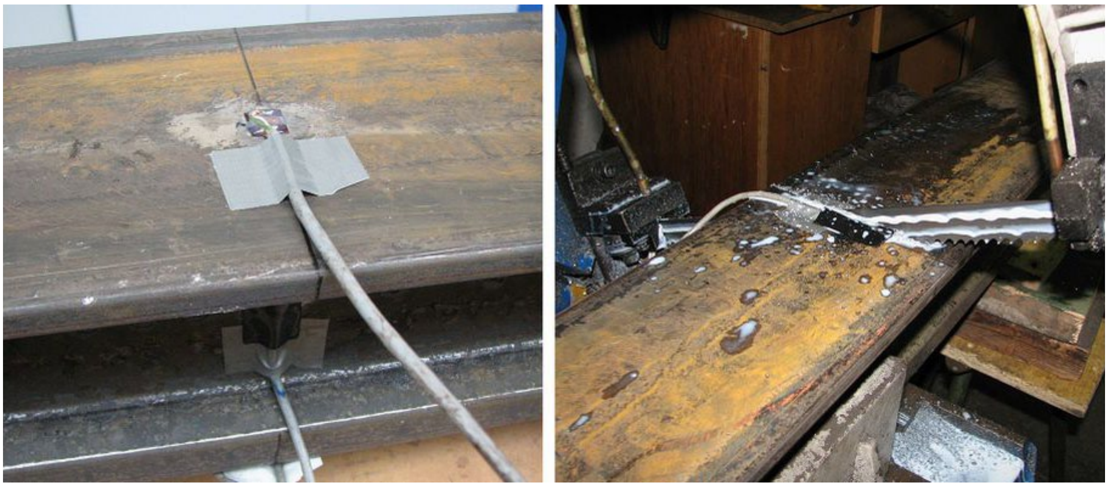

Fig. 3. Cutting method for tests on rail 60E1

released deformations was performed using Hottinger Baldwin Messtechnik strain gauges (from Germany) with a 3 mm base and fixed strain gauges k = (1.97; 1.98; 2.00; 2.04) ±1% of the 3/120 LY11 type glued on the rails. The released deformations were measured with a resolution of 1 μm/m with a digital Vishay Measurements Group VMG P3 deformation meter (from USA) with an inaccuracy of ±0.1%. The values of residual stresses were determined using Young's modulus $E = 2.07 \cdot 10^{11}$ Pa [7-9].

4.2. Drilling method

The measurement of residual stresses using the hole drilling method (Mathar's method) consists in a strain gauge measurement of the released deformations around the hole drilled in the material and the calculation of the amount of stresses on the basis of deformation changes (Fig. 4a). This method enables the determination of the equivalent homogeneous main stresses and their inclination angles in relation to the strain gauge axis, as well as the distribution of these stresses up to half the depth of the drilled hole.

Residual stresses were determined using the Vishay Measurements Group VMG (USA) RS 200 system (Fig. 4b). The measurement of the released deformations at the measurement points was taken with the use of VMG CAE-06-UL062-120 strain gauge rosettes with a resolution of 1 μm/m with the use of a P3 strain gauge. The measurement procedure is covered by ASTM Standard E837-9 [10], and detailed requirements are included in the Measurements Group Tech Note TN-503-4 guidelines.

5. Investigation of the effect of roller shape on the level of residual stresses

After rolling and cooling, the rails are straightened in a set of vertical and horizontal straighteners at a temperature not higher than 50°C. A schematic illustration of the rail straightening process is shown in Fig. 5a. The position of the rail in the straightening rollers of the vertical straightener is shown in Fig. 5b, and in the rollers of the horizontal straightener in Fig. 5c.

a)

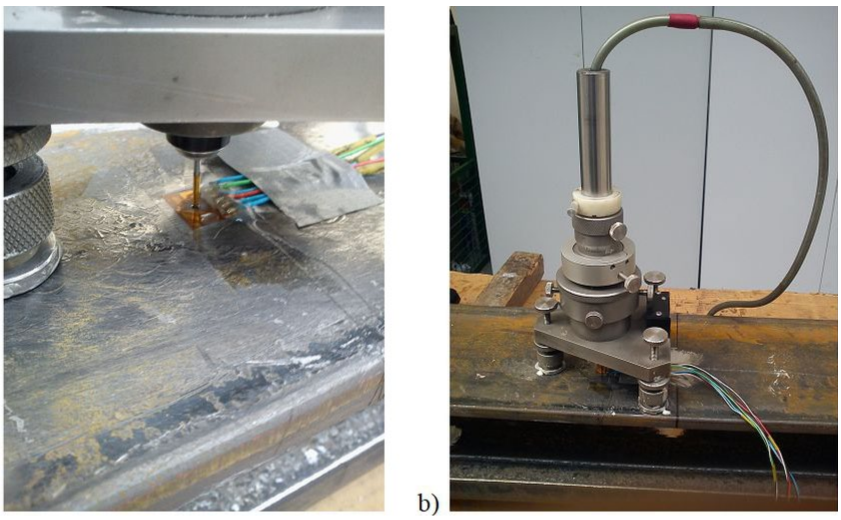

Fig. 4. Drilling method for tests on rail 60E1: a) release of deformations by drilling, b) RS 200 system

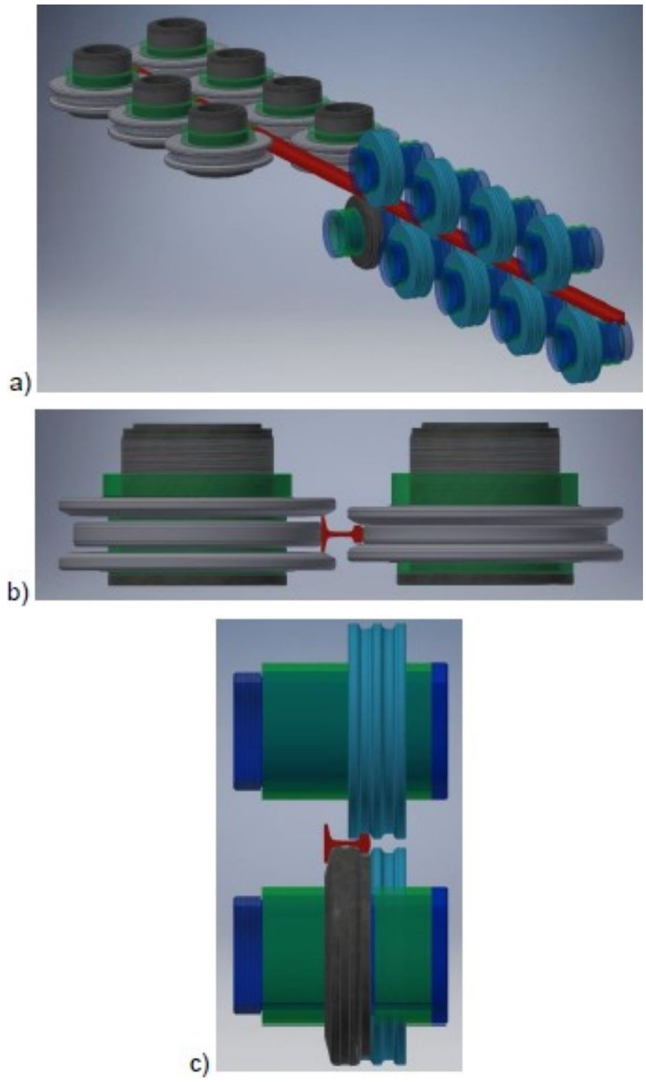

Fig. 5. Scheme of straightening railway rails a) set of straighteners: the first vertical (7 rollers), the second horizontal (9 rollers) b) rail in the vertical straightener c) rail in the horizontal straightener

Reducing the final level of residual stress in the rail foot after straightening in vertical and horizontal straighteners requires:

– reducing the current level of residual stress in the foot after straightening with a vertical straightener by changing the settings, changing the contact stresses of the roller and the strip, and the distribution of these stresses,
– reducing the increase of residual stress during straightening with a horizontal straightener, and their allowable increase should not exceed 40÷50 MPa.

Taking into account the specificity of straightening in roller straighteners for a strip with variable curvature along its length, one should aim to obtain:

– the smallest possible deformation necessary to obtain a straight strip after straightening,
– significant plastic deformations changing in alternating bends of successive straightening stages, ensuring obtaining a straight strip,
– a change in the size of the surface of contact of the roller with the straightened strip.

Higher settings mean greater roller pressure forces and larger impressions, especially on the rail foot; lower settings mean enlarged plastically deformed areas. As shown by the results of the residual stress test, the web of the rail undergoes elastic deformation, and small areas of the foot and the head are plastically deformed. The previously forced state of residual stresses (NW) in successive bends affects their final distribution, either causing an earlier plastic deformation in the section under consideration or preventing such deformations from occurring when the sign of residual stresses and the sign of the applied stresses are opposite. Considering the complex shape of the rail, the limitations related to the test method as a function of many variables of the phenomenon of contact of the roller with the strip and the heterogeneous spatial state of residual stresses in successive passes in the straightener rollers, the prediction of the final distribution and the level of residual stresses is subject to great uncertainty.

Looking for a method to reduce the residual stress in the foot axis, straightening tests were carried out by changing the following process parameters:

– reducing the contact pressure of the R3 and R5 rollers by increasing the flat active surface of the rollers,
– changes in the distribution of contact forces by the use of shaping rollers,
– changes in the distribution of contact pressures by a different combination of the construction of the shaping rollers on the R3 and R5 shafts and the use of different settings.

The adopted changes are conditioned by the slight possibility of changing the shape of R2, R4, R6 head rollers adjusted to the rail head profile and having a slight impact on the residual stress of the profile of the other foot rollers – R1 and R7.

The changed roller shape for which the tests were performed was as follows:

- flat roller with an active width of 80 mm,
- roller with a 30 × 0.5 mm cutting in the middle,
- flat concave roller with a width of 80 mm,
- flat concave roller with a width of 60 mm,
- flat convex roller with a width of 60 mm.

5.1. R3 roller with cutting 30 × 0.5 mm – test RP

The test was carried out by replacing a typical R3 roller of a vertical straightener with a width of the flat contact surface equal to 50 mm with a roller with a cut of 30 × 0.5 mm and a width of 80 mm. For vertical and horizontal straighteners, the settings used in the current straightening technology were applied. However, straightening with a roller with cutting creates a stripe with a width of the cutting and a height of about 0.29 mm. The test allowed to experimentally determine how the distribution of the foot's residual stresses affects the transfer of the contact stresses of the foot roller beyond the vertical axis of the rail. The residual stress testing was carried out for samples taken after the following rollers: R2 – test RP2, R3 – test RP3, after R7 – test RP7 and after straightening using a vertical and horizontal straightener – test 916Y101. The distribution of residual stresses in the foot of the rail after straightening with the R3 and R7 roller is shown in Fig. 6.

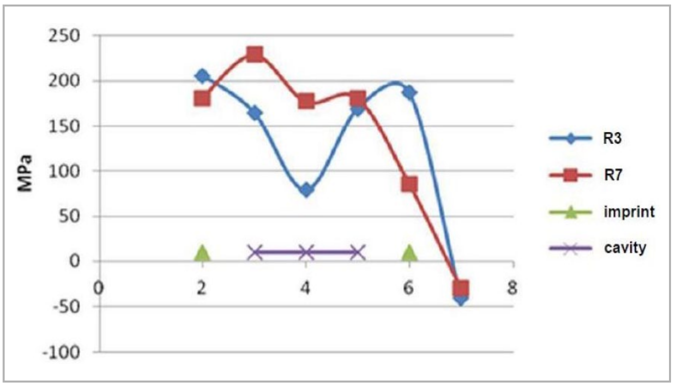

Fig. 6. NW distribution in the rail foot after straightening with R3 and R7 of a vertical straightener with the R3 roller with 30 × 0.5 mm cutting

The obtained foot residual stress distribution after straightening with the R3 roller with cutting differs from the residual stress distribution after straightening with the 50 mm wide R3 flat roller. After straightening with an R3 flat roller (sample taken after the R3 roller), a uniform distribution of residual stresses of approx. 250 MPa is obtained in the area of the impression, and small compressive stresses are obtained outside the zone. After straightening with the R3 roller with cutting in the space between the imprints at the edge, residual stresses were obtained at the level of approx. 165 MPa, and in the middle – approx. 80 MPa. In the area of roller impressions, residual stresses reach the values of approx. 210 MPa and 190 MPa, respectively, and outside the area of impressions, compressive residual stresses are approx. –40 MPa. Despite the observed asymmetry in the position of the roller in relation to the rail axis, similar values of residual stresses are found at the level of approx. –215 MPa on both sides of the web, which means that bending in the transverse direction does not change them in the longitudinal axis of the rail. The residual stress level in the rail axis generated by the roller is lower in the foot (250 MPa → 80 MPa) and higher in the head (30 MPa → 170 MPa) in relation to the R3 flat roller despite the exact same level of residual stress in the foot and head after R2 in both cases.

After straightening with successive rollers and after R7, in the cutting zone of the R3 roller and the R5 and R7 roller impressions, the residual stress increases to approx. 230 MPa (from 165 MPa) in the proximal part of the rail, increases significantly from 80 to 180 MPa in the middle of the impression and does not change at the part farthest from the rail axis. In the R3 area of the imprint, on the one hand, residual stresses practically do not change, and on the side more distant from the rail axis, they decrease from 190 to 90 MPa. Hence, the R5 and R7 rollers generate higher residual stresses in sections with greater stiffness and in places where higher contact stresses occur. However, the nature of residual stress distribution in R3 is retained.

The residual stress of the rail straightened using a vertical straightener with the R3 roller, selected after straightening using a vertical and horizontal straighteners, is approx. 270 MPa in the rail foot axis and approx. 220 MPa in the head axis. There is a significant dispersion of residual stresses on both sides of the web –110 MPa and –230 MPa after straightening using a horizontal straightener, despite their equal values in the web of the rail after R7.

5.2. Flat R3 and R5 rollers with a width of 80 mm – PR test

The test was carried out by introducing, instead of the currently used rollers R3 and R5 of a vertical straightener with a contact surface width of 50 mm, rollers with a width of 80 mm and keeping the currently used settings of the vertical (R2 = 20.8 mm; R4 = 14.0 mm; R6 = 3.5 mm) and horizontal straightener. The residual stress test was carried out for tests taken after R3 – test PR3, after R5 – test PR5, after R7 – test PR7 and after straightening using a vertical and horizontal straightener – test PR9.

5.3. Concave R3 roller, flat R5 roller with a width of 80 mm – WR test

The test was carried out using, instead of the currently used R3 and R5 rollers, a vertical straightener with a width of a flat contact surface equal to 50 mm, a concave R3 roller with a width of 80 mm, and a flat R5 with a width of 80 mm. The currently used vertical and horizontal straightener settings were maintained. The residual stress test was carried out for tests taken after R3 – test WR3, after R5 – test WR5, after R7 – test WR7 and after straightening using a vertical and horizontal straightener – test WR9.

5.4. Comparison of NW distributions of rails straightened with a set of R3/R5 rollers with a width of 50 mm, 80 mm and 80 mm concave/flat – tests NR, PR, WR

TABLES 1÷4 show the values of residual stresses after R3, R5 and R7 and their increments after R3, R4, R5 and R6 on the cross-section of rails straightened with the same settings of the NR, PR and WR rollers.

The distribution of residual stresses after R3, R5 and R7 and their increments after R3, R4, R5 and R6 on the cross-section of rails straightened with the same settings of the NR, PR and WR rollers are shown in Figs. 7-12.

The comparison of the obtained residual stress distributions shows that the use of both the widened and the concave R3 roller lowers the level of residual stresses caused by this roller, compared to a typical 50 mm wide flat roller. A greater reduction of residual stress by about 50 MPa on both the foot and the head sides is obtained when using a concave roller. The use of a flat, widened R5 introduces much higher residual stresses on

TABLE 1

Residual stresses and their increments on the rail cross-section after R3 of rails straightened with a set of NR, PR and WR rollers with a width of 50 and 80 mm

Rail cross-section (figure in Table 8.1)	NW, MPa	NW, MPa			NW increment, MPa		
	NR2	NR3	PR3	WR3	NR3	PR3	WR3
1	–6	249	224	187	255	230	193
2	134	–91	–75	–45	–225	–209	–179
3	76	–59	–7	–6	–135	–83	–82
4	–141	–174	–171	–183	–35	–36	–48
5	–185	–35	–79	–67	150	106	118
6	–59	10	10	–5	69	69	54
7	225	31	120	121	–194	–105	–104

TABLE 2

Increment of residual stresses on the rail cross-section in R4 → R5 of rails straightened with a set of NR, PR and WR rollers with a width of 50 and 80 mm

Rail cross-section (figure in Table 8.1)	NW, MPa		
	NR	PR	WR
1	108	116	184
2	–51	–22	–68
3	–88	–88	–83
4	28	11	31
5	33	64	36
6	56	9	–14
7	–10	–54	–74

TABLE 3

Residual stresses on the rail cross-section after R5 and R7 of rails straightened with a set of NR, PR and WR rollers with a width of 50 and 80 mm

Rail cross-section (figure in Table 8.1)	NW, MPa		NW, MPa		NW, MPa	
	NR5	NR7	PR5	PR7	WR5	WR7
1	357	207	360	241	371	225
2	–142	–24	–97	–39	–113	–37
3	–147	–29	–95	–52	–89	–67
4	–146	–158	–160	–160	–152	–170
5	–2	–94	–15	–49	–31	–56
6	66	–59	1	–37	–19	–40
7	21	276	66	209	47	55

TABLE 4

Increment of residual stresses on the rail cross-section in R6 of rails straightened with a set of NR, PR and WR rollers with a width of 50 and 80 mm

Rail cross-section (figure in Table 8.1)	NW, MPa		
	NR	PR	WR
1	–150	–119	–146
2	118	58	76
3	118	43	22
4	–12	0	–18
5	–92	–14	–25
6	–125	–38	–21
7	255	143	8

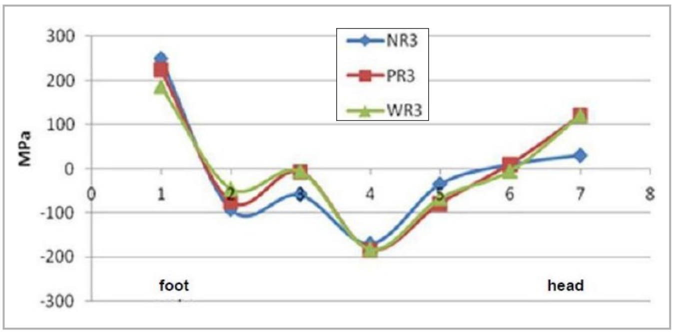

Fig. 7. Residual stresses on the rail cross-section after R3 straightened with 80 mm wide rollers (PR3, WR3) and 50 mm wide rollers (NR3)

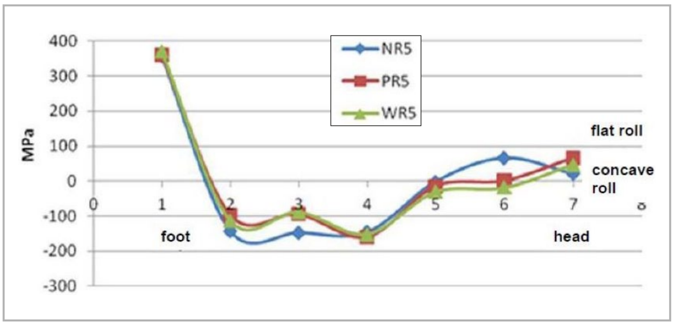

Fig. 8. Residual stresses on the rail cross-section after R5 straightened with 80 mm wide rollers (PR5, WR5) and 50 mm wide rollers (NR5)

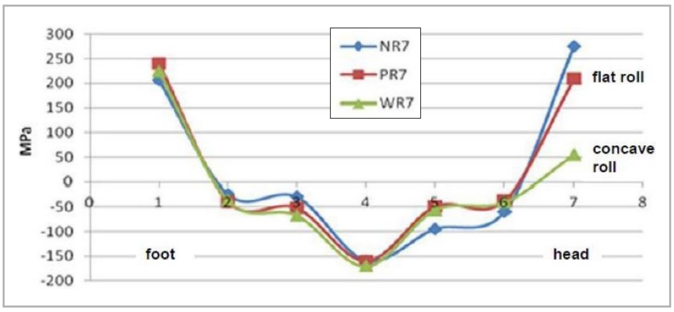

Fig. 9. Residual stresses on the rail cross-section after R7 straightened with 80 mm wide rollers (PR7, WR7) and 50 mm wide rollers (NR7)

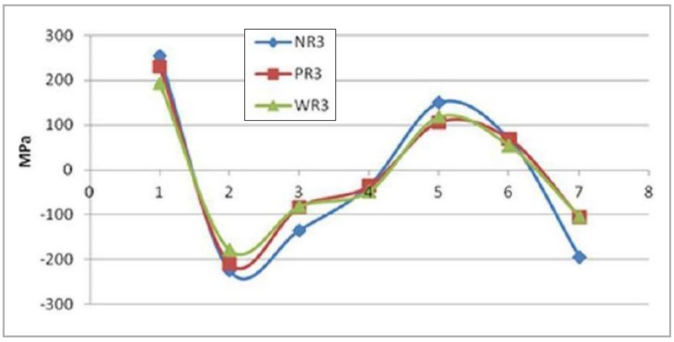

Fig. 10. Increments of residual stresses of rails after R3 straightened with 80 mm wide rollers (PR3, WR3) and 50 mm wide rollers (NR3)

the foot side than in the head, resulting in a similar level (approx. 350 MPa) after R5 than a typical 50 mm roller, and in the centre of the foot after R7 – 207 MPa (NR), 225 MPa (WR)

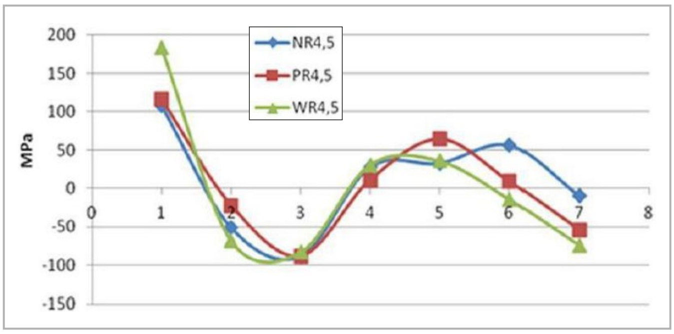

Fig. 11. Increments of residual stresses of rails R4 and R5 straightened with 80 mm wide rollers (PR5, WR5) and 50 mm wide rollers (NR5)

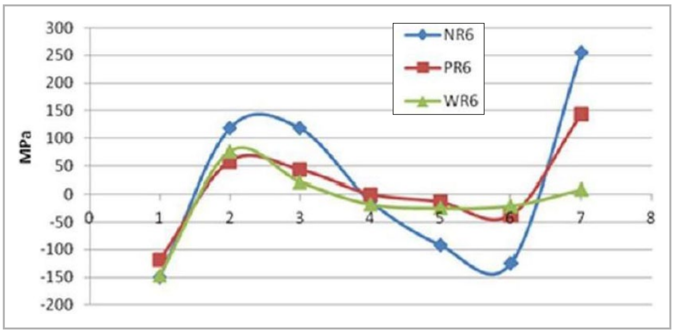

Fig. 12. Increments of residual stresses of rails after R6 straightened with 80 mm wide rollers (PR7, WR7) and 50 mm wide rollers (NR7)

and 241 MPa (PR). The tested R3/R5 combination introduces significant changes in the level of residual stresses revealed by the average values on the rail cross-section after R7, the values of which are as follows:

PR 83 MPa,
WR 65 MPa,
NR 94 MPa.

Also, the level and distribution of residual stresses, especially in the foot after R7, has an impact on the change of residual stress in the foot and head axis during straightening the rail with a horizontal straightener. TABLE 5 summarises the residual stresses in the foot and head axis after R7 of the vertical straightener, after HR9 of the horizontal straightener and their increments in the rail foot and head during straightening in a horizontal straightener, for the tests carried out.

The obtained data show that the highest increase of residual stresses in the foot axis during straightening with a horizontal

TABLE 5

Changes in residual stresses of the foot and head during straightening with a horizontal straightener of rails straightened according to MR ÷ RP with a vertical straightener

Test identification		NW_{R7}, MPa	NW_{HR9}, MPa	ΔNW, MPa
MR	F	237	300	63
	H	237	248	11
NR	F	209	289	80
	H	326	269	–57
DR	F	191	252	61
	H	329	315	–14
PR	F	241	313	72
	H	209	200	–9
WR	F	225	332	107
	H	55	168	113
RP (cutting)	F	229	270	51
	H	238	218	–20

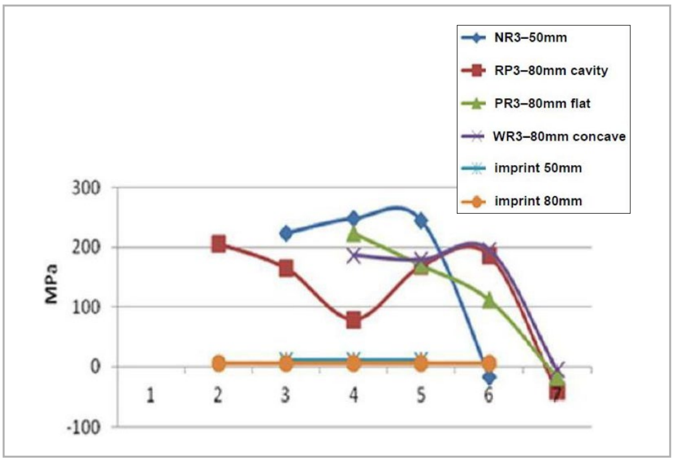

Fig. 13. Distribution of residual stresses of rail feet after R3 straightened with 80 mm wide rollers (RP3, PR3, WR3) and 50 mm wide rollers (NR3)

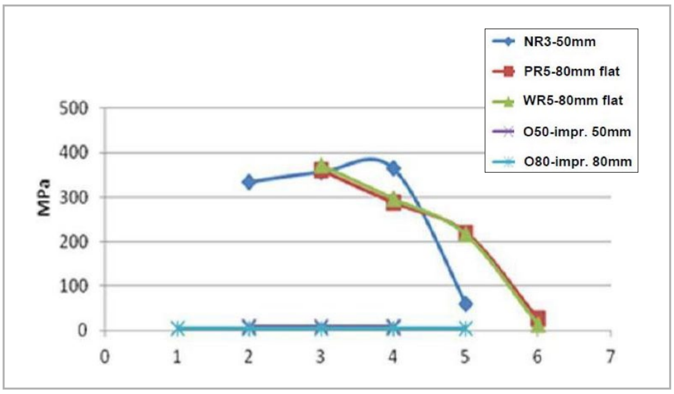

Fig. 14. Distribution of residual stresses of rail feet after R5 straightened with 80 mm wide rollers (PR5, WR5) and 50 mm wide rollers (NR5)

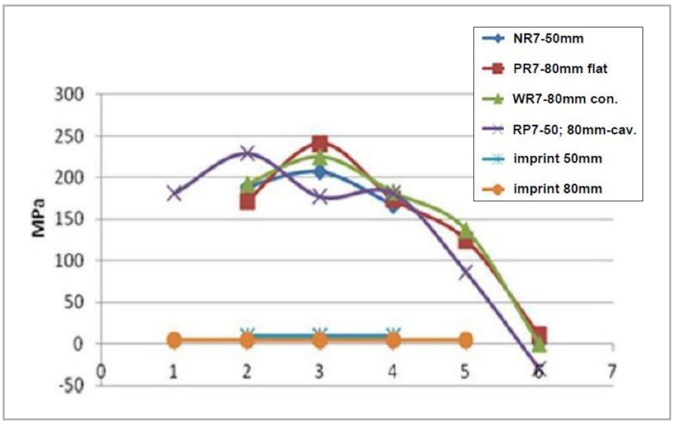

Fig. 15. Distribution of residual stresses of rail feet after R7 straightened with 80 mm wide rollers (RP7, PR7, WR7) and 50 mm wide rollers (NR7)

straightener occurs for the WR test with a concave roller R3 with a width of 80 mm. The distributions of residual stresses in the rail feet obtained for the same settings after R3, R5 and R7 with sets of rollers of the vertical straightener NR, RP, PR and WR are shown in Figs. 13-15.

The obtained residual stress distributions of the foot of rails straightened with a set of R3/R5 rollers with a width of 80 and 50 mm, despite the same settings, generate different values at the same points on the width of the foot. R3 rollers with a width of 80 mm, with cutting and concavity, generate lower residual stress in the foot axis than in the contact zone, while flat rollers, both 80 and 50 mm wide, cause the highest residual stresses in the foot axis. The wider R5 roller (80 mm) generates similar residual stress distributions in the foot surface layers, regardless of their distributions in the previous rolls (R1÷R4), while significant changes in residual stress distributions are observed in the foot area on the rail cross-section, as well as after the last roller R7 and the same R6 setting. The distributions of residual stresses in the foot, and especially the level of residual stress in the places corresponding to the contact zone of the rollers during straightening, influence their increase in the foot and head axis during straightening with a horizontal straightener (TABLE 5).

5.5. Series of tests with rollers R3 and R5 with an active width of 50, 60 and 64 mm and different settings

In order to check the possibility of reducing residual stress in the foot of the rails straightened using a vertical and horizontal straightener, a series of straightening tests were performed according to the diagram presented in TABLE 6. The settings of the vertical straightener rollers were calculated for the conducted experiments and are different from the technological settings used in the large rolling mill.

TABLE 6

Schematic overview of the rollers' installation, vertical straightener settings and identification of tests

Test	Roller R3	Roller R5	Setting N	Setting D	Identification of sampled rails
1N 2D	WY64 WY64	W60 W60	X	X	1HR9, 1R7, 1R3, 1R5 2HR9, 2R7, 2R3, 2R5
3N 4D	W60 W60	W60 W60	X	X	3HR9, 3R7, 3R3, 3R5 —
5D 6N	N50 N50	W60 W60	X	X	5HR9, 5R7, 5R5 6HR9, 6R7, 6R5

The TABLE 6 includes:

- N – setting – R2 = 20.0 mm; R4 = 14.0 mm; R6 = 3.5 mm,
- D – setting – R2 = 22.8 mm; R4 = 16.9 mm; R6 = 2.0 mm,
- WY64 – convex roller with a width of 64 mm,
- W60 – concave roller with a width of 60 mm,
- N50 – flat roller with a width of 50 mm,
- HR9 – test after horizontal straightener; R7, R5, R3 – rail tests after R7, R5, R3.

The tests were carried out for the same horizontal straightener roller settings: HR1 = 0 mm; HR3 = 16.0 mm; HR5 = 8.0 mm; HR7 = 4.0 mm; HR9 = 1.0 mm.

The distributions of residual stresses on the rail cross-sections are shown in Fig. 16, and in the foot axis and 57 mm from the foot edge – in Fig. 17. TABLE 7 shows residual stresses after strengthening using HR9 of a horizontal straightener.

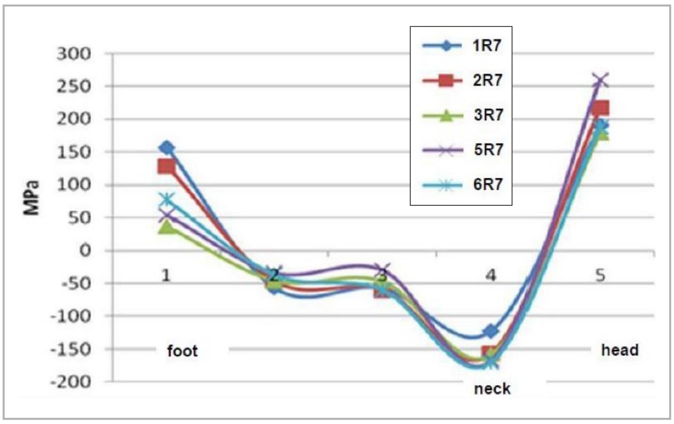

Fig. 16. Distribution of residual stresses after R7 on the rail's cross-section – tests 1÷6

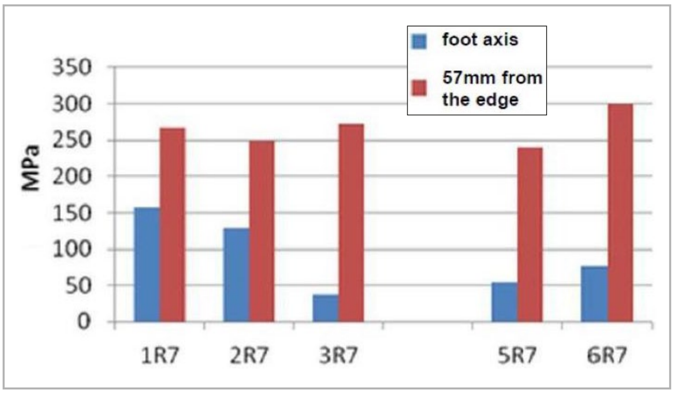

Fig. 17. Residual stresses in the foot axis and 57 mm from the foot edge after R7 – tests 1÷6

TABLE 7

Released deformations and residual stresses of the rail foot, web and head after straightening using a vertical and horizontal straightener (HR9) for tests 1÷6

Test	Identification	Released deformations ε, μm/m F	M1	H	Residual stresses σ, MPa F	M1	H
1N	1HR9	–1186	637	–786	246	–132	163
2D	2HR9	–1362	403	–381	282	–83	79
3N	3HR9	–908	577	–473	188	–119	98
5D	5HR9	–967	409	–813	200	–85	168
6N	6HR9	–1087	555	–912	225	–115	189

The straightening tests carried out with a set of R3/R5 rollers with an active width of 50, 60, 64 mm, different profile and the settings currently used N and enlarged D indicate the possibility of controlling the residual stress level in the foot axis after R7 of the vertical straightener as well as the final residual stresses after HR9 of the horizontal straightener.

After R7, for the currently used settings N, the set of rollers R3 convex – R5 concave (tests 1, 2) generates higher residual stresses (157 MPa) in the foot axis than the increased setting D. Then, for the N setting, the increase in the foot's residual stresses during straightening with a horizontal straightener reaches lower values, and the final values after HR9 do not exceed the allowable values.

For the currently used N settings, the set of rollers R3 concave – R5 concave (test 3) generates the lowest residual stresses in the rail axis obtained in this series of tests after R7 (37 MPa) and the lowest after HR9 (188 MPa). However, after straightening, concave rollers R3/R5 leave an undeformed zone around the rail axis and an incorrect profile for the present rail foot profile after rolling.

Set of rollers R3 flat 50 mm – R5 concave (test 5, 6), both for the N and D roller settings, generates small residual stresses in the foot axis after R7: 77 MPa and 54 MPa and respectively after HR9: 225 MPa and 200 MPa.

TABLE 8 summarises the foot, web and head residual stresses after R7 and HR9 and their changes during straightening with a horizontal straightener of rails straightened in tests 1÷6.

TABLE 8

Changes in residual stresses of the foot, web and head during straightening with a horizontal straightener of rails straightened in tests 1÷6

Test identification		NW_{R7}, MPa	NW_{HR9}, MPa	ΔNW, MPa
1N	F	157	246	89
	M	–122	–132	–10
	H	190	163	–27
2D	F	129	282	153
	M	–157	–83	74
	H	217	79	–138
3N	F	37	188	151
	M	–158	–119	39
	H	179	98	–81
5D	F	54	200	146
	M	–167	–85	82
	H	259	168	–91
6N	F	77	225	148
	M	–170	–115	55
	H	188	189	1

Increase of residual stress in the foot axis during straightening using a horizontal straightener is approx. 150 MPa (except for test 1), while for the head and web, the greatest increase occurred for tests with settings D. Such a high increase of residual stresses in the foot axis during straightening in the horizontal straightener, much higher than that obtained during the NR, PR and WR tests, is caused by the forced distribution of residual stresses in the rail foot after R7 of the vertical straightener, which is indicated by the obtained results (Figs. 16 and 17).

5.6. Examination of a batch of rails straightened with a concave roller R5 with an active width of 60 mm and different settings

The reduction of the residual stress level in the rail foot axis during tests 5D and 6N for flat rolls R1, R3, R7 with an active width of 50 mm and an R5 concave roller with an active width of 60 mm of the vertical straightener was confirmed by straightening a larger part of the rails (approx. 40 pcs) by measuring residual stresses after straightening in the vertical and horizontal straightener. The straightening was carried out using the following sets of setting values of the vertical straightener, calculated with the help of a developed program:

- setting N: R2 = 21.0 mm; R4 = 14.0 mm; R6 = 3.0 mm
- setting D0 R2 = 23.0 mm; R4 = 17.0 mm; R6 = 6.0 mm
- setting D R2 = 23.0 mm; R4 = 15.0 mm; R6 = 4.0 mm

and horizontal straightener roller settings: HR1 = 0 mm; HR3 = 16.0 mm; HR5 = 8.0 mm; HR7 = 4.0 mm; HR9 = 1.0 mm.

Measurements of the profile and waviness of all straightened rails were made, and samples were taken from the selected rails (every 5th straightened rail) for testing residual stresses after a geometry test. The results of the residual stress measurements in foot axis F and F1 (57 mm from the foot edge), in the centre of the web M, and in the head axis H are presented in TABLE 9.

TABLE 9

Released deformations and residual stresses of the rail foot, web and head after straightening using a vertical straightener with concave roller R5 and horizontal straightener of rails straightened with settings N, D0 and D

Test Rail No.	Identification	Released deformations ε, μm/m	Residual stresses σ_R, MPa
1.1N P357A406	F	–1006	208
	M	438	–91
	H	–450	93
1.2N P357Y506	F	–1000	207
	F1	–381	79
	M	435	–90
	H	–422	87
1.3N P357A408	F	–1046	217
	M	452	–94
	H	–450	93
1.4N P357Y109	F	–944	195
	M	434	–90
	H	–537	111
2.0D0 P357Y110	F	–637	132
	F1	–583	121
	M	576	–119
	H	–1368	283
2.1D P357A111	F	–946	196
	F1	–465	96
	M	477	–99
	H	–1024	212
2.2D P357Y412	F	–856	177
	F1	–405	84
	M	404	–84
	H	–1044	216

The mean values and standard deviations NW in the axis of the foot, web and head, determined for the tested set of rollers and N settings are as follows:

foot (207 ± 8) MPa
web (–91 ± 2) MPa
head (96 ± 9) MPa

The increased settings of the vertical straightener rollers (D0 and D) reduce the value of residual stresses in the foot axis to approx. 140 MPa for the D0 settings and approx. 180 to 200 MPa for the D settings, however, the residual stresses in the rail head increase compared to those obtained for settings N. The NW distribution in the imprint zone on the foot is characterized by maximum stresses of 180 to 220 MPa in the foot axis and approx. 80 to 100 MPa 57 mm from the foot edge (F1) for settings N and D and 130 and 120 MPa for the D0 setting, respectively. The study of the equivalent homogeneous main residual stresses at a distance of 57 mm of the foot edge (as in F1) shows that $\sigma_{\min} = 19$ MPa $\sigma_{\max} = 113$ MPa, vector inclination angle $\sigma_{\max}\,\beta = -22°$, and the determined longitudinal and transverse components of the residual stresses, including the point for the 2.1 mm layer are $\sigma_L = 102$ MPa, $\sigma_T = 30$ MPa. Distribution $s_{\max}$ at the depth of the drilled hole is characterised by stresses of approx. 85 MPa in the 0.2 to 1.1 mm layer and stresses of approx. 105 MPa in the 1.1 to 2.1 mm layer. TABLE 10 summarises the mean values and standard deviations of maximum vertical straightness V of horizontal H of the rails of the proper groups of rails straightened with settings of N, D0 and D of the vertical straightener.

TABLE 10

List of mean values and standard deviations of straightness V and straightness H of straightened rails with settings N, D0 and D

Setting	Straightness V		Straightness H	
	$\bar{E}_V$, mm	S_v, mm	$\bar{E}_H$, mm	S_h, mm
N	0.19	0.04	0.24	0.03
D0	0.21	0.07	0.24	0.03
D	0.19	0.04	0.20	0.04

The obtained results, except for $\bar{E}_V$ for D0, are within the uncertainty range 2σ, which means that more than 95% of the straightened rails will not exceed the correct vertical straightness V and horizontal straightness H required by the PN EN 13674-1 standard for a class A rail, respectively ≤0.3 mm/3m for V and ≤0.45 mm/1.5m for H. The increased expected value $\bar{E}_V$ and the standard deviation for the D0 setting, although it provides more than 68% of the results that meet the requirements, indicates a greater residual stress imbalance between the foot and the head and the sensitivity of the process to any random instabilities.

6. Summary

In order to obtain the desired changes in the residual stress distributions on the rail cross-section after straightening in the vertical straightener and the final residual stresses on the vertical and horizontal straighteners, the following modifications were proposed on the basis of the results of the study:

– change in the settings of vertical straightening rollers in relation to the settings currently used for the use of foot rollers with normal and enlarged active width,
– simultaneous change of the shape of the R3 and R5 foot rollers, or only one of them, and the change of the settings of the vertical straightener.

The study of residual stresses in straightened rails according to the proposed changes show that the impact on the level of residual stresses after the use of a vertical straightener and on the final level after the use of a horizontal straightener depends to a lesser extent on the settings and to a greater extent on the shape of the rollers. The performed straightening tests and tests on residual stresses in the rails showed that:

– increasing the active width of the R3 and R5 rollers (lowering the contact stresses) results in an increase in residual stress in the rail foot after the vertical straightener to 240 MPa and the final stress after the horizontal straightener to 310 MPa,
– the use of concave wide roller R3 and flat wide roller R5 causes a significant reduction in the average residual stresses on the cross-section, their slight increase to about 230 MPa in the foot axis after the use of a vertical straightener and a significant increase to about 330 MPa in the final residual stresses along the horizontal straightener axis,
– the use of an R3 convex roller and an R5 concave roller reduces the residual stress in the rail foot axis after R7 to approx. 160 MPa in the case of normal settings and to approx. 130 MPa in the case of increased settings, but only in the first case the obtained level of residual stresses in the rail foot axis after straightening with a horizontal straightener is lower than permitted by the standard,
– the use of a flat R3 roller and a concave R5 roller results in a significant reduction of the residual stresses in the foot axis after R7 to approx. 80 MPa in the case of normal settings and to approx. 50 MPa in the case of increased settings, and after straightening with a horizontal straightener, the residual stresses in the foot do not exceed 230 MPa and 200 MPa, respectively, which is lower than the permissible values,
– the lowest level of residual stresses in the foot axis of approx. 40 MPa after R7 and 190 MPa after straightening in a horizontal straightener was obtained for rails straightened with concave R3 and R5 rollers with normal settings, but the stripe in the foot axis for the current shape of the rail foot obtained after rolling prevents the use of such a set of rollers.

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