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THE INFLUENCE OF CHANGES IN ROLL PASS DESIGN ON THE STATE OF RESIDUAL STRESSES IN RAILWAY RAILS – SUMMARY

The article presents the results of the last stage of work on the impact of changes in the roll pass design on the state of residual stresses in railway rails. The discussed stage includes the summary of industrial experiments of rolling 60E1 rails with a length of 120 meters using a modified pass design of roll grooves. The rolling technology has been deeply modified, ranging from the finishing stand, through the pre-finishing stand, to the semi-finishing stand. The rails in this experiment were cooled using standard cooling technology and then straightened using innovative vertical straightener shaped rollers. Residual stresses were tested using the strain gauge method and the hole-drilling strain gauge method by drilling a hole in the rail axis and at a distance of 14 millimetres from its axis. The resulting tensile stresses in the rail foot were reduced to an average level of less than 43% in relation to the requirements of the EN13674-1 standard.

Keywords: railway rail; residual stresses; pass design of roll grooves; pass design of straightening rollers; strain gauge method

1. Introduction

The role of residual stresses in rails is related to their direct impact on the behaviour of the rail in the track, i.e. the influence on its susceptibility to buckling and the development of contact fatigue defects and even cracks, and thus it affects the safety of transport. This is due to the superimposition of residual stresses on thermal and operational stresses. The parameter that expresses the resistance to fracture of materials is the stress intensity factor, which depends, among others, on the applied stress and the fracture length. Under the influence of tensile stresses, the critical stress intensity factor K_{Ic} is achieved, which is a material feature that determines the fracture toughness and its susceptibility to uncontrolled crack development and, consequently, rail fracture. The total stress in the rail is the sum of residual stress σ_E, thermal stress σ_T ranging from –125 MPa to +125 MPa and stress resulting from operational load σ_v, which reaches the value of even 200 MPa [1]. The relationship between the transferred stress and the crack length with the assumed constant stress intensity factor K_{Ic} equal to 31 MPa·m$^{1/2}$ is shown in Fig. 1. Assuming that the value of thermal stress is equal to 50 MPa and the bending stress of the rail during operation reaches 200 MPa, while the longitudinal tensile stress in the foot of the rail is 250 MPa, according to Fig. 1, a defect with a depth of 1.2 mm will already cause a crack in the rail – case A. If the residual stress in the rail was reduced by half to 125 MPa, the critical crack length would increase to about 2.3 mm – case B. On the other hand, assuming that the operational stress is 100 MPa and the thermal stress is 50 MPa, reducing the residual stresses by half from 250 MPa to 125 MPa will increase the critical fracture length from 2 mm (case C) to 10 mm (case D). Since thermal and operational stresses are not affected in practice, lowering the residual stresses in rails means improving the reliability of rails and increasing the safety of rail transport. The increase in axle loads causes a significant increase in stresses in the rail, while the increase in train speed directly influences the increase in dynamic loads in the rail. Knowing the importance and significance of residual stresses in rails, manufacturers of rails conduct work on reducing them at the production stage, so that the finished product is characterised by the lowest possible level of residual stresses in the rail foot and their favourable distribution along the entire perimeter of the rail. There are many publications available on the theoretical foundations of plastic working and pass design of roll grooves intended for the rolling of railway rails [2-5]. The results of work on the optimisation of straightener rollers' settings, both by means of computer simulations and

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experiments in industrial conditions, are also widely published for example: a model of controlled cooling of rails which takes into account all the key parameters of this process is presented in the paper [6]. In the work [7] it was demonstrated that one of the reasons for the appearance damage and cracks in railway rails accelerating development of typical rail head defects are residual stresses. In turn, in paper [8] adopts explicit dynamics FEM to study on residual stresses where the optimal regulation was obtained, in which the residual stresses are the smallest. The study [9] was also devoted to clarify the residual stress distribution by simulation with a fully three-dimensional model taking into account both the bending and contact process. The work [10] presents the developed model of numerical simulation of the rail stretching process, which enables the study of the basic parameters of the straightener and technology in terms of their influence on the residual stresses. The article [11] is also devoted to the importance of residual stresses and the possibility of their reduction. However, these works did not take into account the possibility of influencing the state of stress by modifying the pass design of roll grooves and straightener rollers. Research on the impact of innovative pass design of both roll grooves and straightening rollers on reducing residual stresses is carried out on a large scale by ArcelorMittal Poland S.A. under the project POIR.01.02.00-00-0167/16 co-financed by the National Centre for Research and Development under the title “Innovative and safe rails with low residual stresses in the foot of the rail”. In the first phase of the study, the works were focused on examining the influence of pass design of vertical and horizontal straightener rollers on the level of residual stress [12-14]. The next stage of the experiments was devoted to determining the possibility of reducing the residual stress by modifying the pass design of roll grooves. Earlier publications in this field presented the results of numerical simulations of the rolling process using the new roll pass design and the results of verification of the theoretical assumptions in industrial experiments on the rolling line of a large rolling mill of ArcelorMittal Poland S.A. [15-16]. This article presents the results of industrial experiments combining both changes in the pass design of roll grooves as well as changes in the pass design of the vertical straightener rollers.

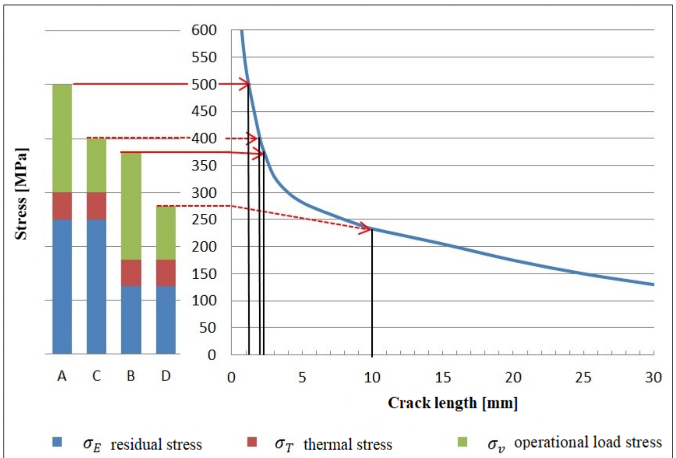

Fig. 1. Dependence of critical crack length on tensile stress [1]

2. The concept and scope of study

Earlier tests designated E and F included examining the influence of changes in pass design of roll grooves of the last two rolling stands, i.e. the finishing and pre-finishing stands, on the shape of the lower surface of the rail foot, which was modified in such way as to reduce the contact pressures of the foot rollers of the vertical straightening machine during the rail strip straightening process [15,16]. Traditional flat foot rollers of a vertical straightener were used in these experiments. This led to the reduction of residual stresses in the rail foot to the average level of 150 MPa against the permissible standard of 250 MPa [17]. The next stage of work, presented in this study, was the application of an even deeper modification of the roll pass design, starting from the finishing stand, through the pre-finishing stand, to the intermediate stand. This test was designated G and was intended to investigate the complementary effect of changes in the pass design of roll grooves on the level of residual stresses in conjunction with the changes in the pas design of vertical straightener rollers. Five 60E1 rails with a length of over 120 metres were rolled as part of this experiment. The first stage of verification of the changes introduced in the rail rolling process was to control the surface of the rail foot on samples taken hot from the rail strip after the last rolling stand. All parameters of the cross-section were also checked for compliance with the tolerance range specified in the standard [17]. Basic parameters of the cross-section, such as: rail height, foot shape and width, rail head width, height of fishplate spaces as well as positive and negative asymmetry, were also registered along the entire length of the rail strip using a TBK laser device. The analysis of geometric features for all the tested parameters confirmed the achievement of the dimensional correctness of the rails in accordance with the developed technology with the achievement of the assumed shape of the bottom surface of the foot, which made it possible to recognise the introduced changes in the pass design of roll grooves as correct. Then the rails were directed to cooling beds, where they were cooled under standard conditions, and after reaching the temperature below 60°C, they were transported to a set of vertical and horizontal straighteners, where they were subjected to straightening. New, innovative vertical straightener rollers were used, while the horizontal straightener was equipped with standard rollers. The straightening experiment is illustrated in Figs 2 and 3. In the discussed rolling and straightening experiment, five rails with a length of 120 meters were used, from which 1 metre sections were then taken to measure residual stresses using the strain gauge method in accordance with the methodology described in Annex C of the EN 13674-1:2011+A1:2017 standard [17]. The test consisted in cutting a 20 mm thick slice of the rail and measuring the released strains, then the residual stresses are calculated from the difference of the set of measurements between the first and second cuts. Strain gauges recording strains were glued in the axis of the rail foot (measuring point F), in the neutral axis on both sides of the rail web (points M1 and M2) and in the axis of symmetry of the rail head (point H). A graphic presentation of the distribution of measurement points is shown in Fig. 4. Trial sections for stress measurement were determined along the rail length in accordance with the methodology adopted so far for all experiments, i.e. 4 metres from the beginning of the rail, in the middle of the rail, and 4 metres from its end. The measured values of the released strains and the calculated values of the longitudinal components of residual stresses for the established measuring points are presented in TABLE 1. The rails used in this experiment were rolled from the R260 steel grade, for which laboratory tests for mechanical properties were performed – TABLE 2, and the chemical composition was checked – the results are given in TABLE 3. The comparison of the level of mechanical properties and chemical composition in the discussed test and previous tests allows to state that the measured values were characterised by slight deviations, and thus the material can be considered homogeneous. The steel structure and sulphur segregation (Baumann method) were also controlled on the samples from the finished rails; the tests confirmed the presence of a fully pearlitic structure required by the standard and the obtaining of positive Baumann models. For selected tests, the residual stresses in the subsurface layer of the rail were also tested by drilling a hole in accordance with the procedure described in the ASTM E837-13a standard [19].

Fig. 2. Vertical straightening machine, *photo. Sylwester Żak*

Fig. 3. Horizontal straightening machine, *photo. Sylwester Żak*

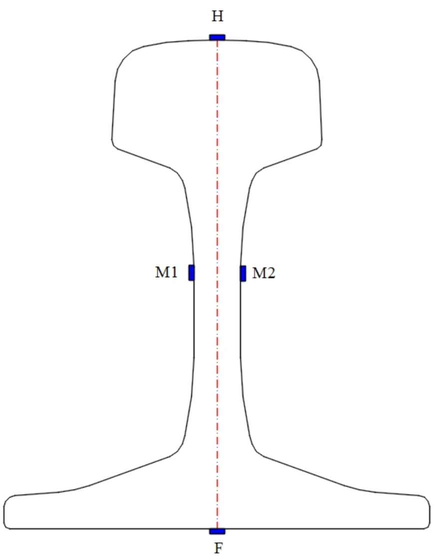

Fig. 4. Location of measurement points

TABLE 1

Average values of released strains and calculated residual stresses for the tested rails

Rail number	**Measurement point**	**Released strains** ε **[µm/m]**	**Residual stresses** σ **[MPa]**	**Standard deviation [MPa]**
Test G Rails 914694 A405, A206, A106, A205, A506	F	–517	107	5.44
	M1	693	–143	5.78
	M2	669	–138	4.53
	H	–1145	237	13.07

TABLE 2

Basic mechanical properties of tested rails

Heat number	**Mechanical properties**				
	Tensile strength R_m **[MPa]**	**Yield strength** R_{p02} **[MPa]**	**Elongation** A_5 **[%]**	**Hardness [HB]**	**Reduction in area** Z **[%]**
914694	977	613	12.9	279	24

TABLE 3

Chemical composition

Heat number	**Element content in weight [%]**					**[ppm]**
	C	**Mn**	**Si**	**P**	**S**	**H**
914694	0.73	1.08	0.32	0.011	0.017	9

3. Results and discussion

In the analysed test, designated *G*, the average level of tensile stresses measured in the axis of symmetry of the rail foot for all performed measurements was 107 MPa with a relatively low value of standard deviation. It is about 43% of the acceptable value set at the level of 250 MPa [17]. The obtained result should be considered as very good and it proves the strong influence of the profiled rollers of the vertical straightener in combination with the changed geometry of the bottom surface of the rail foot on the final result of tensile stresses measured in this area. It should also be emphasised that the recorded relatively low level of tensile stresses in the rail head with an average value of 237 MPa, which is a favourable phenomenon in the operational aspect, at the same time confirms the correct optimisation of the settings of the vertical and horizontal straightener rollers. Compared to the previous tests designated *E* and *F*, where only changes in the pass design of roll grooves were applied, a 30% reduction in the level of residual stresses measured in the rail foot axis was noted [16].

In order to determine the distribution of residual stresses along the entire perimeter of the rail, stress measurements were taken at 16 precisely defined points in accordance with the procedure described in the Technical Conditions of the German Railways DBS 918 254-1 [18] – Fig. 5. The results of these measurements for the selected A206 rail are shown in Fig. 6. A uniform distribution of stresses was observed in relation to the vertical axis of the rail symmetry; some differences in the symmetry of the distribution are visible on the lateral inclinations of the rail head and it is probably related to the used side rail straightening system. Striving for a symmetrical distribution of stresses on the perimeter of the rail is of significant technological importance due to the fact that there is no tendency to bend the rail after the cutting operation.

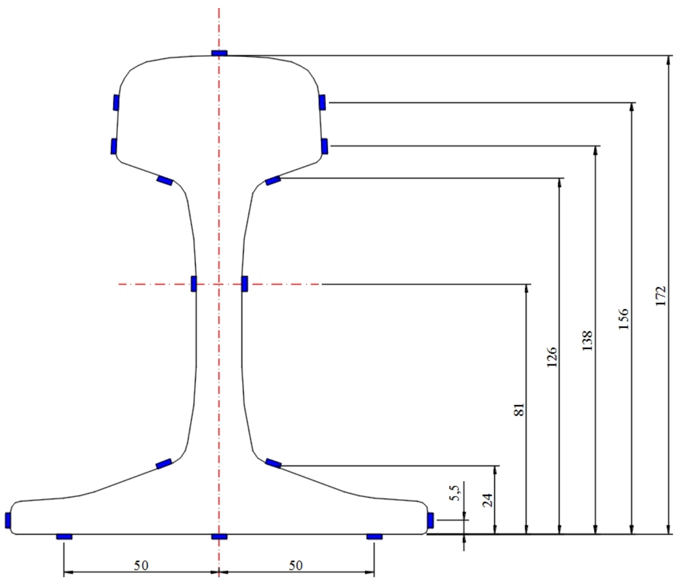

Fig. 5. Identification of strain gauges and location of measurement of released strains according to DBS 918 254-1, all dimensions are given in [mm]

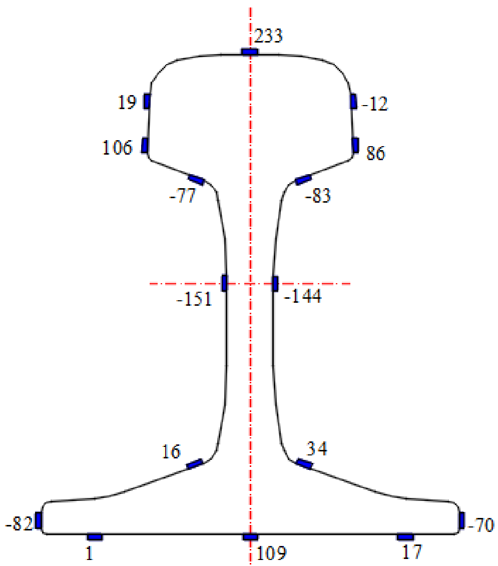

Fig. 6. Distribution of residual stresses on the perimeter of rail A206 – test *G*, all results are given in [MPa]

To explain the mechanism of the influence of the shaped rollers on the reduction of the residual stress level in the rail foot, the method of drilling a hole was used in accordance with the methodology contained in the ASTM E837-13a standard [19]. The measurement was taken from a section of the A206 rail at a distance of 4 metres from its end. The values of the released strains were measured during the drilling of the hole in the axis of the rail foot, i.e. in the area of the greatest modification of the lower surface of the rail foot formed in the rolling process. The results of the recorded strains are given in TABLE 4, while Fig. 7 shows the graphical dependence of the released strains on the hole depth.

TABLE 4

Measured released strains depending on the depth of the hole drilled in the rail foot axis – rail A206

Z [mm]	ε1 [μm/m]	ε2 [μm/m]	ε3 [μm/m]
0	0	0	0
0.1	10	38	37
0.2	10	44	45
0.3	3	49	48
0.4	–7	49	53
0.5	–19	47	56
0.6	–27	43	56
0.7	–31	38	57
0.8	–36	34	60
0.9	–36	33	62
1.0	–35	30	62

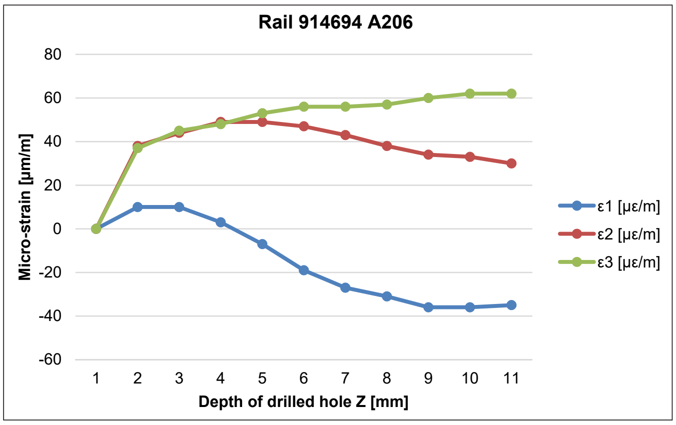

Fig. 7. Dependence of released strains on the depth of the drilled hole – rail A206, measurement in the rail foot axis

TABLE 5 summarises the calculated components of the state of residual stresses of the tested rail required by the standard [19], which marked as follows:

P – uniform isotropic (equally biaxial) stress,

Q – uniform 45° shear stress,

TABLE 5

Residual stress components P, Q, T, normal stresses σ_x, σ_y, uniform shear xy-stress τ_{xy}, principal stresses $\sigma_{\max}$, $\sigma_{\min}$ and clockwise angle β from x-axis to the maximum principal stress direction $\sigma_{\max}$ – rail A206, measurement in the rail foot axis

Rail number	P [MPa]	Q [MPa]	T [MPa]	σ_x [MPa]	σ_y [MPa]	τ_{xy} [MPa]	$\sigma_{\max}$ [MPa]	$\sigma_{\min}$ [MPa]	β [°]
A101	–23	–36	21	13	–59	21	19	–65	–15

T – uniform x-y shear stress,
σ_x, σ_y – uniform normal stress in the direction of x and y,
τ_{xy} – uniform shear stress in the x-y plane,
$\sigma_{\max}$ – maximum (more tensile) principal stress,
$\sigma_{\min}$ – minimum (more compressive) principal stress,
β – clockwise angle from the x-axis to the maximum principal stress $\sigma_{\max}$ direction.

The components of the equivalent uniform principle residual stresses determined in the axis of the rail foot are $\sigma_{\max}$ = 19 MPa and $\sigma_{\min}$ = –65 MPa, and the inclination angle β of the vector $\sigma_{\max}$ is –15°. Small normal stresses σ_x = 13 MPa in the direction parallel to the rail axis of a tensile nature have a sign consistent with the longitudinal residual stresses in the rail foot measured by means of the cutting method. This shows that in the vicinity of the rail axis there are small tensile residual stresses, while much higher longitudinal tensile stresses dominate in a larger area. Normal stresses in the crosswise direction do not exceed the value of σ_y = –59 MPa. For the purposes of comparison, the distribution of residual stresses was investigated in the subsurface layer of the rail foot, but located 14 mm from the foot axis, i.e. in the area where the contact of the rail foot surface and the straightening roller occurs already in the initial stage of straightening and where this contact does not require plastic strain of the foot surface. The recorded strains are listed in TABLE 6, and Fig. 8 shows the distribution of released strains as a function of distance. TABLE 7 presents all components of the stress state required by the standard [19]. The components of the equivalent uniform principle residual stresses determined in the axis of the rail foot at the mentioned distance of 14 mm are $\sigma_{\max}$ = 167 MPa and $\sigma_{\min}$ = –82 MPa, and the inclination angle β of the vector $\sigma_{\max}$ is 0.5°. Normal stresses σ_x = 167 MPa in the direction parallel to the rail axis of a tensile nature have a sign consistent with the longitudinal residual stresses in the rail foot measured by means of the cutting method. This proves the earlier finding that in the vicinity of the rail axis there are small tensile residual stresses, while in a larger area, considerably higher longitudinal tensile stresses prevail. Such a distribution of residual stresses in the foot is also confirmed by the method of cutting the rail by comparing the released strains after the first and second cut. Normal stresses in the crosswise direction do not exceed the value of σ_y = –82 MPa. The largest differences between the study of the stress distribution in the rail foot axis and at a distance of 14 mm from this axis were recorded for uniform normal stresses in the x-axis direction; the difference was 154 MPa. A much smaller deviation of –23 MPa occurred for uniform normal stresses in the y direction. The change in inclination angle β was also noted for principal stresses. The above differences translated into different, in both tests, values of unifirm isotropic stresses, homogeneous tangential stresses at an angle of 45° and uniform x-y tangential stresses. The research carried out by drilling holes will explain the mechanism of the impact of shaped rollers, which, thanks to their innovative design, reduce contact pressures, thus modifying the state of stresses in the surface layer of the rail foot. The change of the contact conditions of the roller surface with the rail material results in a reduction of the total amount of energy introduced as a result of straightening to the entire area of the rail foot, which translates into lower residual stress in this area after the production process.

TABLE 6

Measured released strains depending on the depth of the drilled hole – rail A206, measurement 14 mm from the rail foot axis

Z [mm]	ε1 [µm/m]	ε2 [µm/m]	ε3 [µm/m]
0	0	0	0
0.1	–53	–8	55
0.2	–77	–12	72
0.3	–106	–17	86
0.4	–126	–22	96
0.5	–153	–26	104
0.6	–175	–31	110
0.7	–193	–36	120
0.8	–209	–42	131
0.9	–219	–43	135
1.0	–225	–47	141

All rails submitted to the rolling and straightening experiments were geometrically controlled for compliance with the tolerances of the basic parameters of the cross-section, i.e. rail height, head width, head running surface contour, foot width,

TABLE 7

Residual stress components P, Q, T, normal stresses σ_x, σ_y, uniform shear xy-stress τ_{xy}, principal stresses $\sigma_{\max}$, $\sigma_{\min}$ and clockwise angle β from x-axis to the maximum principal stress direction $\sigma_{\max}$ – rail A206, measurement 14 mm from the rail foot axis

Rail number	P [MPa]	Q [MPa]	T [MPa]	σ_x [MPa]	σ_y [MPa]	τ_{xy} [MPa]	$\sigma_{\max}$ [MPa]	$\sigma_{\min}$ [MPa]	β [°]
A206	43	–125	–2	167	–82	–2	167	–82	0.5

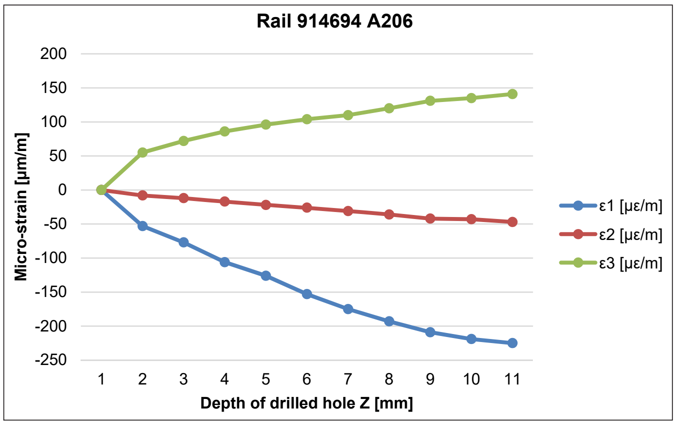

Fig. 8. Dependence of released strains on the depth of the drilled hole – rail A206, measurement 14 mm from the rail foot axis

negative and positive asymmetry and the fishplate space using certified acceptance gauges [17]. Since the geometrical correctness of the product is the primary feature and cannot be deteriorated as a result of the activities aimed at optimising the stress level, the geometry of the rails was also measured with the use of laser measuring devices installed in the production line; the distribution along the entire length of the rail of the amplitude of the vertical and horizontal waviness registered on the rail head was also investigated.

The research on the distribution of residual stresses in the rail foot by drilling openings in the discussed experiment of rolling and straightening of rails confirms the effect of the profiled rollers of the vertical straightener on the reduction of residual stresses in the subsurface layer of the rail foot by changing their size and distribution in the area of contact of the roller with the surface of the rail foot. This was clearly confirmed in a comparative test carried out at a distance of 14 mm from the foot axis, i.e. in the zone of much lower impact of the changed pass design of the shaped rollers. The modified shape of the straightening rollers reduces the value of normal stress σ_x by as much as 154 MPa and changes the angle of the maximum stress vector with respect to the rail axis, thus reducing the magnitude of the residual stresses determined in the strain gauge test from the entire area of the rail foot.

3.1. Calculation of averaged stress

A holistic method of assessing the effectiveness of reducing residual stresses in the rail was proposed by means of averaged stress calculated according to the following formula [20]:

$$\sigma_M = \frac{\int_0^{S_E} |\sigma_L| \cdot dS}{\int_0^{S_E} dS} \text{ [MPa]} \qquad (1)$$

where:

σ_M – averaged stress,
σ_L – longitudinal stress,
S_E – orthogonal surface.

The presented formula is a proposal of a parametric expression the complex stress state in the entire area of the rail with one mean stress value. For the calculations, the theoretical cross-sectional area of the 60E1 rail nominal was assumed to be 76.70 cm^2, then the rail surface was divided into 16 measurement fields corresponding to the places where residual stresses were measured on the rail circumference specified in the standard [18]. The assumed division of measurement fields on the rail cross-section along with their dimensions is shown in Fig. 9, and the calculated area of a given field corresponding to a specific residual stress measurement point is given in TABLE 8. For rail A206 from the analysed test *G*, the averaged stress determined according to the above methodology was 78 MPa and was the lowest of all tests using the modified pass design of roll grooves (TABLE 9). The calculated value of averaged stress for a randomly selected rail produced in the technology used so far was also given for comparison. Over 20% reduction of the averaged stress in the *G* test in relation to the reference measurement was observed. The presented method of calculating the averaged stress is of practical importance, as it can serve as an indicator of the effectiveness of reducing residual stresses in the rail. It includes the evaluation of stresses not only by measuring at one point, as indicated in the standard [17], but significantly increases the number of these points to 16, which also correspond to small areas on the rail cross-section. It thus reflects a more complete picture of the stresses on the perimeter of the rail, taking into account the occurrence of both tensile and compressive stresses. It can be assumed that rails with a lower

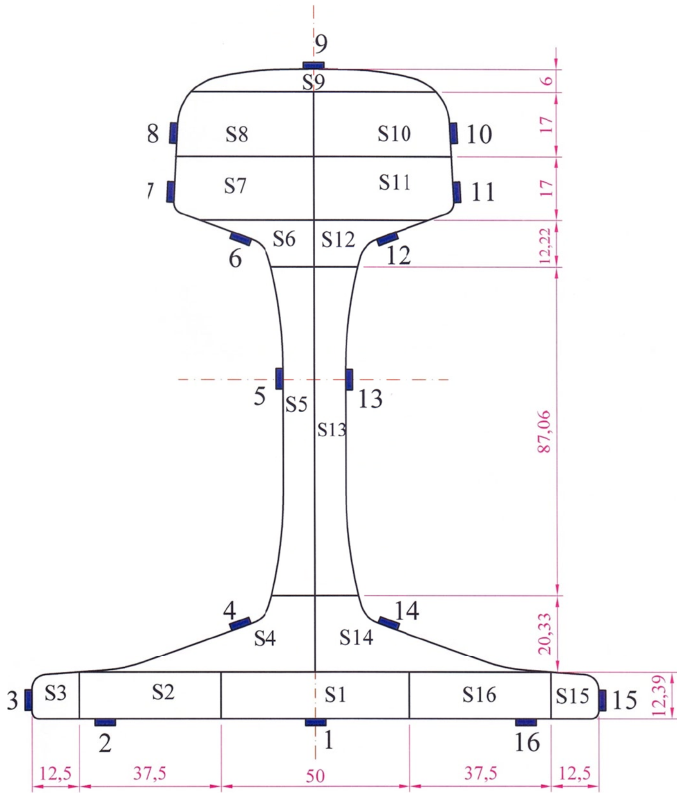

Fig. 9. Division of measurement areas in rail 60E1 for 16 measuring points for residual stresses on the rail perimeter, all dimensions are given in [mm] – source [20]

level of averaged stress will show a lower tendency to permanent strain and loss of coherence. Thus, it will have a direct impact on their behaviour on the track and, consequently, on the safety of railway traffic.

TABLE 8

Surface areas for measurement areas from Fig. 9, source [20]

Area	Surface area [mm^2]
S1	619.64
S2	464.71
S3	145.56
S4	551.97
S5	776.62
S6	210.7
S7	616.85
S8	604.04
S9	309.45
S10	604.04
S11	616.85
S12	210.71
S13	776.62
S14	551.97
S15	145.56
S16	464.71

TABLE 9

Calculated values of averaged stresses of rails in individual tests

Reference measurement [MPa]	Test D variant 1 [MPa]	Test D variant 2 [MPa]	Test E [MPa]	Test F [MPa]	Test G [MPa]
99	79	83	89	84	78

The evaluation of the effects of each rolling and straightening experiment should include the analysis of the values of the introduced stresses after straightening, their distribution on the rail cross-section, averaged stress and parameters of the cross-sectional tolerance and straightness with regard to the requirements of the standard as superior values. An important aspect is the control of the amount of tensile stress in the rail head. The process of optimising the distribution of residual stresses must not lead to their simple shifting from one area of the rail to another, e.g. from the foot to the head. Correctly performed stress reduction should result in a reduction of their size in the most critical part of the rail, which is the foot, without causing them to increase in other places around the perimeter of the rail, especially in the head.

4. Conclusions

The conducted experiments in industrial conditions in the rolling unit and in the straightening unit as well as laboratory tests have contributed to the extension of knowledge in the field of the influence of the shape of tools, such as rolls and straightening rollers, on the state of residual stress in the rails. In the discussed test, both the modification of the pass design of roll grooves and the modification of the pass design of vertical straightener rollers were applied. This made it possible to achieve a significant reduction of residual stresses in the rail foot to an average level of 107 MPa in relation to the requirements of EN13874-1, which specifies the allowable stress value at the level of 250 MPa. The obtained results also constitute a significant reduction of their size in relation to the values obtained during the production of rails with the use of standard rolling and straightening technology.

Obtaining such a low level of residual stresses and their favourable distribution on the cross-section expressed as averaged stress in the rail will have a direct impact on the operational properties of the rails in the track by increasing the critical depth of cracks starting from the foot, and thus will increase safety in rail traffic. Lower residual stress in the rail lowers the average level of operational stresses, which slows down the crack development.

Acknowledgements

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