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The Reliability and Durability of Welded Joints in Steel Rails: a Methodology for Process Control at Modern Rail Welding Facilities

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Abstract. The objective of this study is to develop a methodology for controlling the technological process of rail joint welding at rail welding facilities, ensuring the reliability of welded joints. Based on the data obtained from rail welding enterprises, an improved methodology was developed for assessing the stability of the technological process used in the production of welded rail joints, as well as the overall quality level of welding operations at rail welding facilities (RWFs). It has been established that the continuous increase in train weight and speed imposes strict requirements on the quality of rails in operation. The developed methodology makes it possible to identify a key cause of premature rail failure - manufacturing defects, particularly welding defects arising during the production of long welded rails, as well as during the repair and welding of used rails.

Keywords: railway rails, welded rails, continuously welded rails, rail welding facilities, train traffic safety.

Introduction

The introduction of long freight trains with increased axle loads has significantly heightened the demand for smooth and stable rail track geometry. A key requirement for meeting this demand is maintaining the proper condition of rail ends and extending the length of continuously welded rail (CWR) tracks.

During railway operation, defects and damage inevitably develop in rails due to the influence of rolling stock, environmental conditions, and other factors - posing varying degrees of risk to train traffic safety. Common issues include increased head wear and bending deformations. The service life of new rail ends may range from several months to several years, depending on traffic intensity, axle loads, and the quality of routine track maintenance.

Rails represent the most critical and expensive component of the railway superstructure. Consequently, when surface defects occur, the restoration of rail ends using welding (build-up welding) is widely employed. The restoration of rail ends and CWR sections via build-up welding, followed by hardening, has become a standard and widely applied method to extend the service life of rails and other metallic track elements.

However, build-up welding is not always an economically effective solution. The deposited metal layer may delaminate from the base metal even before the end of its service life, especially on track sections with deteriorated sleepers or fastening assemblies, or where rail joints have excessive gaps.

Currently, in JSC "NC "Kazakhstan Temir Zholy" (KTZ), the monitoring and inspection of restored rail ends and CWRs is carried out by the "Track Diagnostics Center," a subsidiary of KTZ. The center utilizes non-destructive testing methods, primarily ultrasonic testing (UT), to detect internal rail flaws. Portable inspection equipment includes flaw detection trolleys such as the "KSPRUT," "Avikon-31," and "RDM-22" models. Mobile inspection systems include a flaw detection railcar and a mobile diagnostic complex equipped with track geometry, ultrasonic, and video inspection technologies integrated into a single railcar unit.

However, in areas where welding procedures were not properly followed, ultrasonic testing becomes less effective. Signal attenuation occurs in the build-up welded zone due to differences in grain structure between the deposited and base metals. This can hinder the timely detection of critical defects in rails that pose serious risks to train operations [1].

Strict adherence to the rail welding process is essential, and all restoration work must be performed by certified specialists who have undergone specialized training. Furthermore, welding repairs are only permitted when ambient temperatures are above +5 °C and in the absence of adverse weather conditions (rain, snow, fog, etc.). If blind gaps are present in rail joints, welding work is prohibited.

It is important to note that only rails of types R75, R65, and R50, categories T1, T2, and N, manufactured in accordance with GOST R 51685-2000 or corresponding technical specifications, and installed in either jointed or continuously welded tracks, may be repaired using build-up welding. These rails must have operational damage such as head deformation, delamination, plastic flow, or vertical wear as classified under surface defect criteria located in the rail head near joints.

Welding of rails of category B (highest quality category), as defined by GOST R 51685-2000, is strictly prohibited. Thus, the ability to detect critically defective rails in welded sections is primarily determined by the degree to which restoration work has complied with approved technological procedures - followed only secondarily by the qualifications of the specialist performing the monitoring.

Rails must meet the following requirements: they must be sufficiently strong, durable, and reliable in operation - that is, wear-resistant, hard, and at the same time adequately tough (non-brittle), as they are subject to impact-dynamic loads.

The main type of rail currently used in track infrastructure is the R65 rail and other rails with similar characteristics, with a mass of no less than 60 kg per linear meter. Also in use are R75, R50, R43, and lighter rails. In this study, R65 and similar rails, including R75, will be referred to as “rails with a mass of not less than 60 kg/m,” while R50 and similar types will be referred to as “rails with a mass of not less than 50 kg/m.”

Standard rail lengths are 25 and 12.5 meters; shortened rails may measure 24.92; 24.84; 12.46; 12.42; or 12.38 meters. The length of continuously welded rail strings is determined by project specifications based on local conditions.

Rails are installed with a standard inward cant of 1:20 (i.e., inclined toward the center of the track relative to the sleeper surface) both on straight and curved sections. For wooden sleepers, this inclination is achieved using steel baseplates; for reinforced concrete sleepers, the inclination is built into the rail seat design.

During comprehensive rail replacement projects on major railway lines, depending on traffic loads, two types of new rails are primarily laid: R75 and R65, both conforming to ST RK GOST R 51685-2005 (Table 1). On the tracks of industrial facilities, rails of types R50 (ST RK GOST R 51685-2005) and R43 (GOST 7173-54) are used. Railway infrastructure also contains rails of the same types but installed in earlier years (see Table 2). Rails that are reused after prior service are referred to as used rails (or second-use rails).

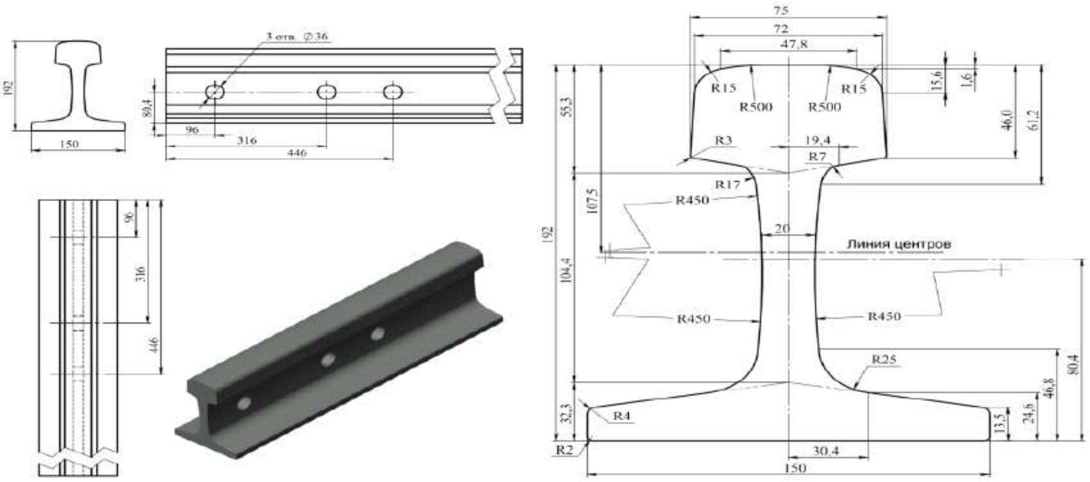


Fig. 1. - Rail type R75 according to ST RK GOST R 51685-2005

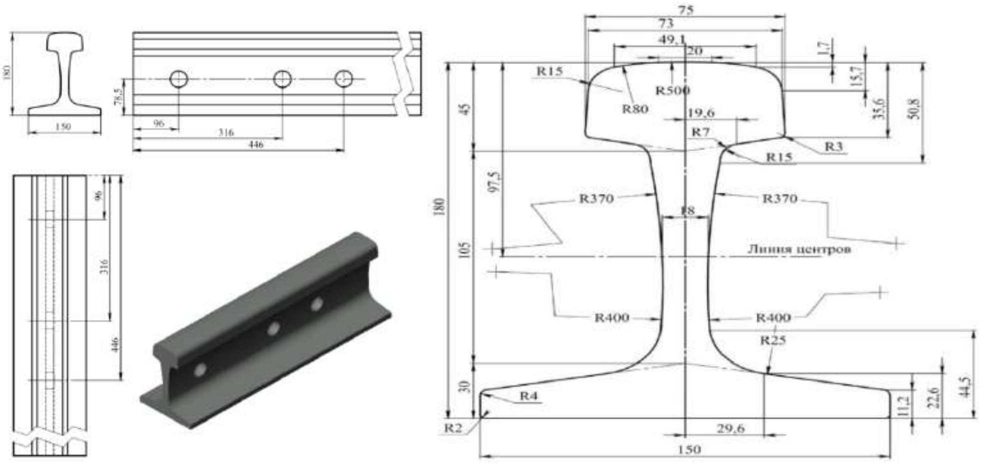


Fig. 2. - Rail type R65 according to ST RK GOST R 51685-2005

Table 1. Key Performance Characteristics of Rails

Parameter Name	Parameter Value for Rail Type				
	R43	R50	R65	R65K	R75
Figure Number in the Document	5	4	3	2	1
Cross-sectional Area of the Rail, cm^2	57,0	65,99	82,65	82,38	95,037
Distance from the Center of Gravity, mm					
to the bottom of the foot	68,5	70,50	81,30	80,60	88,20
to the top of the head	71,5	81,50	98,70	100,40	103,8
Distance from the Center of Twist, mm					
to the bottom of the foot	-	40,10	39,40	38,20	45,80
to the top of the head	-	111,90	140,60	141,80	146,20
Moment of Inertia of the Rail About the Vertical Axis, cm^4					
of the entire rail	-	375	564	557	665
head	-	91	106	103	143
foot		278	445	439	508
Moment of Inertia of the Rail About the Horizontal Axis, cm^4					
of the entire rail	1489	2011	3540	3495	4491
head	-	986	1728	1698	2198
foot	-	915	1539	1532	2005
Moment of resistance (section modulus), cm^3					
along the bottom of the flange или at the bottom of the flange	217	285	435	434	509
along the top of the head или at the top of the head	208	245	358	348	432
along the side face of the flange	45	55	75	73	89
Torsional moment of inertia of the rail, cm^4	-	201	288	285	401
Warping moment of inertia, cm^6	-	1,0 x 10^4	1,9 x 10^4	1,84 x 10^4	2,6 x 10^4
Flexural rigidity of the rail cross-section, kN/cm^2					
under pure torsion	-	163,2 x 10^6	233,5 x 10^6	229,4 x 10^6	325,0 x 10^6
under constrained torsion	-	144,0 x 10^6	180,0 x 10^6	177,0 x 10^6	234,0 x 10^6
Theoretical linear mass per meter of the rail (at a steel density of 7850 kg/m^3), kg	44,65	51,80	64,88	64,67	74,60
Area of the rail cross-section elements, % of the total area					
Head	42,8	38,12	34,11	33,52	37,42
Web	21,3	24,46	28,52	28,78	26,54
Base	35,9	37,42	37,37	37,70	36,04
Coefficient of linear thermal expansion of steel, $\alpha \cdot 10^{-6}$ °C^{-1}			11,8		

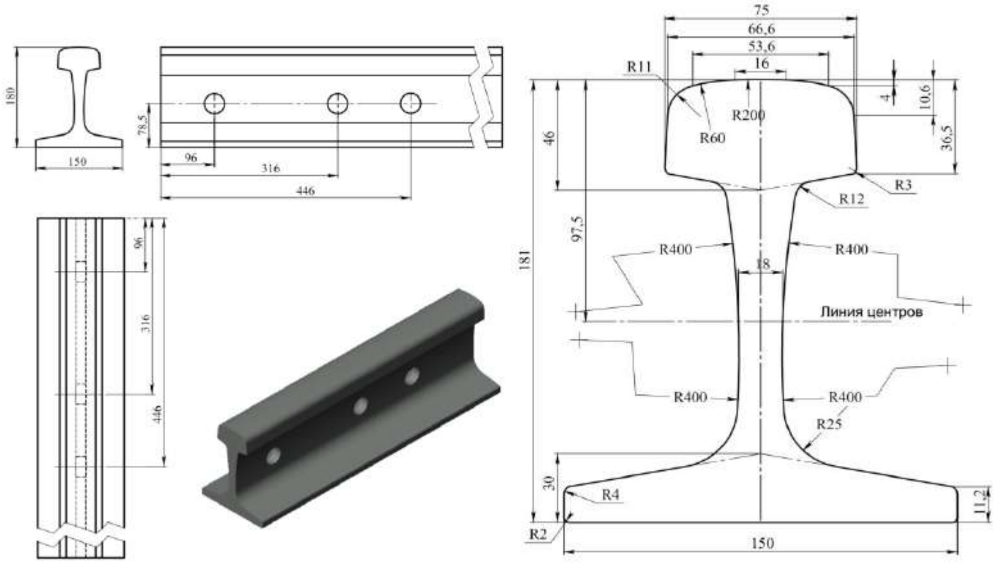


Fig. 3. - Rail type R65K according to ST RK GOST R 51685-2005

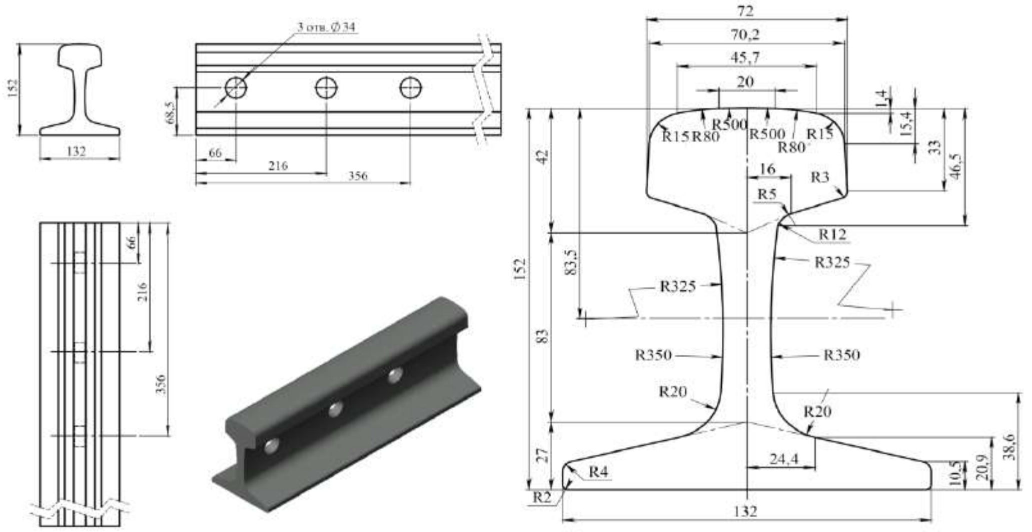


Fig. 4. - Rail type R50 according to ST RK GOST R 51685-2005

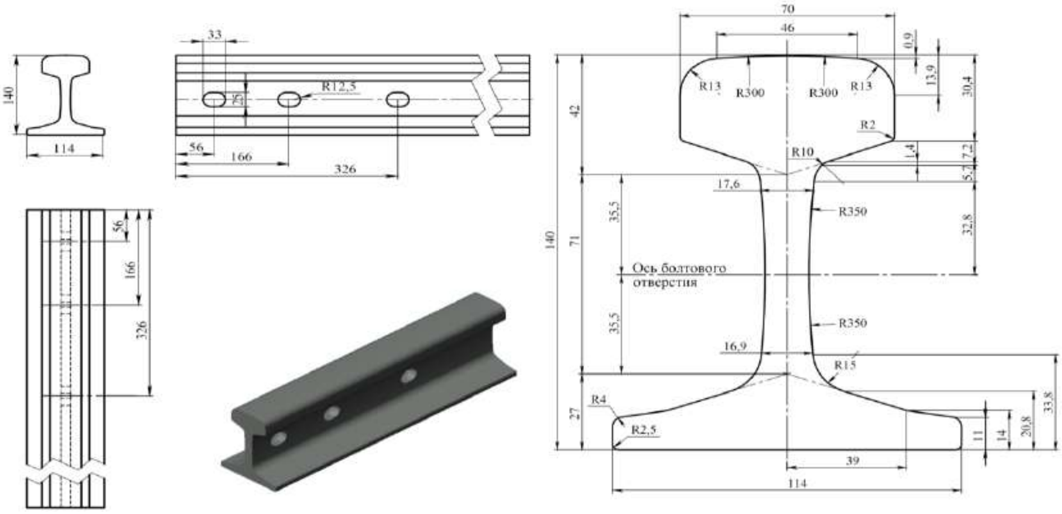


Fig. 5. - Rail type R43 according to GOST 7173-54

Table 2. Some characteristics of rails that are no longer produced but still used in track

Parameter	R75	R65		R50		R43
	GOST 16210-77	GOST 8161-63	GOST 8161-75	GOST 7174-65	GOST 7174-75	GOST 7173-54
Figure number in the document	6	7	8	9	10	11
Mass of 1 meter of rail, kg	74,4	64,64	64,72	51,63	51,8	43,61
Rail height, mm, including:	192	180	180	152	152	140
Head height	55,3	45	45	42	42	42
Web height	104,4	105	105	83	83	71
Base height	32,3	30	30	27	27	27
Rail head width, mm						
at the top	72	72,8	73	70	70	70
at the bottom	75,0	75,0	75,0	71,9	72	70
Rail base width, mm	150	150	150	132	132	114
Rail web thickness at midsection, mm	20	18	18	16	15,5	13,5
Cross-sectional area, cm²	95,04	82,6	82,9	65,9	65,8	55,7
Metal distribution over the profile, %						
Head	37,42	34,2	34,11	38,2	38,12	42,83
Web	26,54	28,4	28,52	24,4	24,46	21,31
Base	36,04	37,4	37,37	37,4	37,42	36,86
Moment of inertia about the axes, cm⁴:						
about the horizontal axis	4491	3548	3540	2018	2037	1472
about the vertical axis	665	569	564	375	377	257
Section modulus, cm³:						
at the bottom of the base	509	436	435	286	287	214
at the top of the head	432	359	358	248	251	206

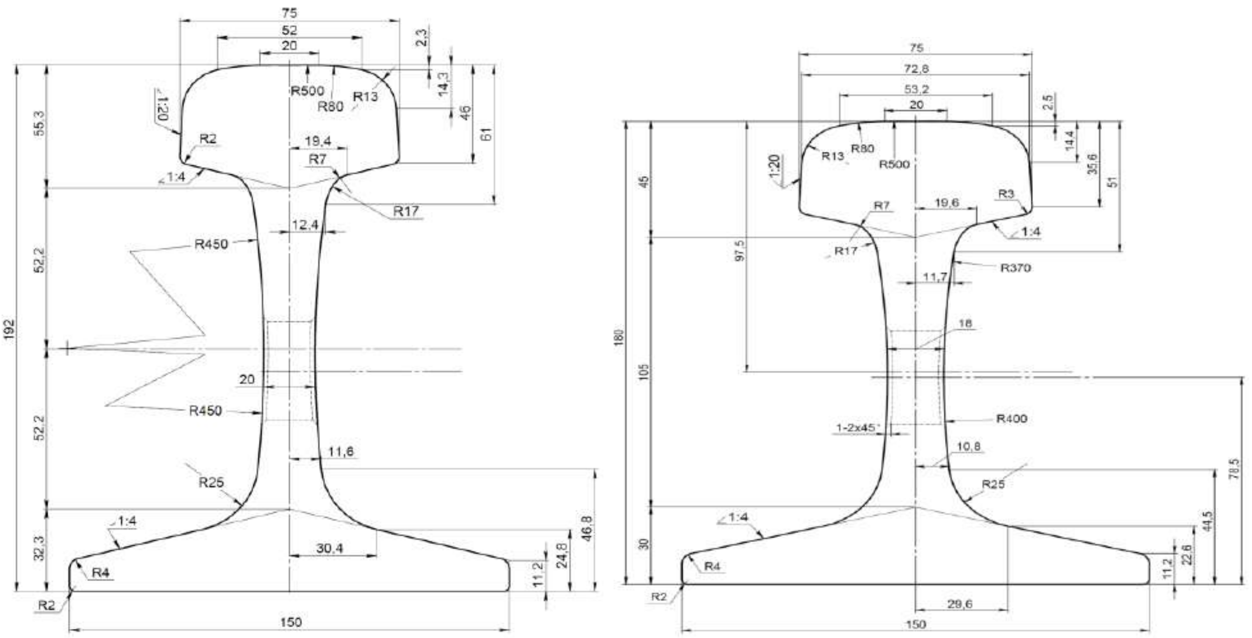


Fig. 6. - Rail type R75 according to GOST 16210-77. Figure 7. Rail type R65 according to GOST 8161-63

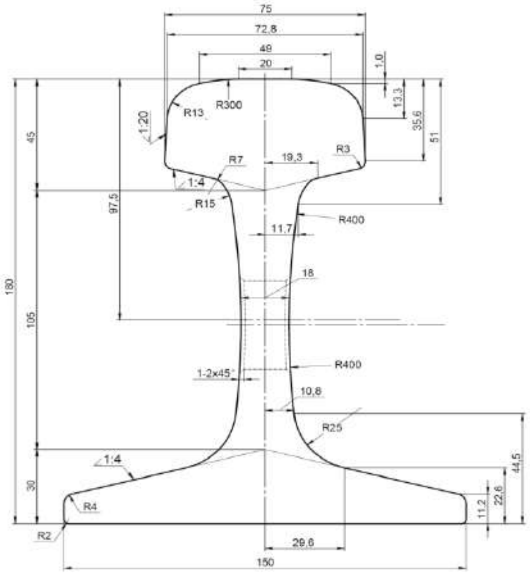


Fig. 7. - Rail type R65 according to GOST 8161-75.

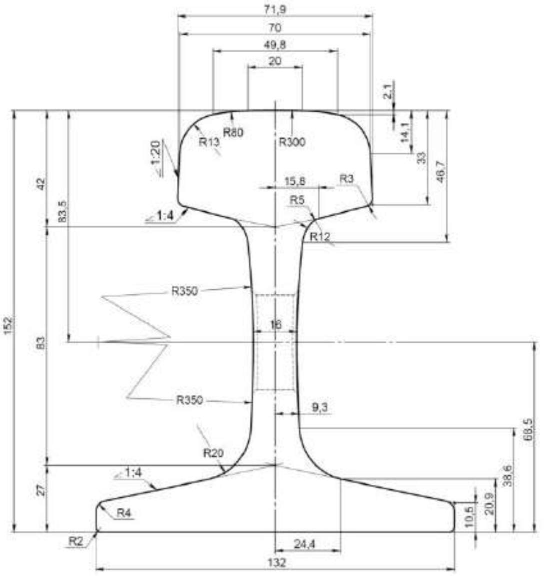


Fig. 8. - Rail type R50 according to GOST 7174-65.

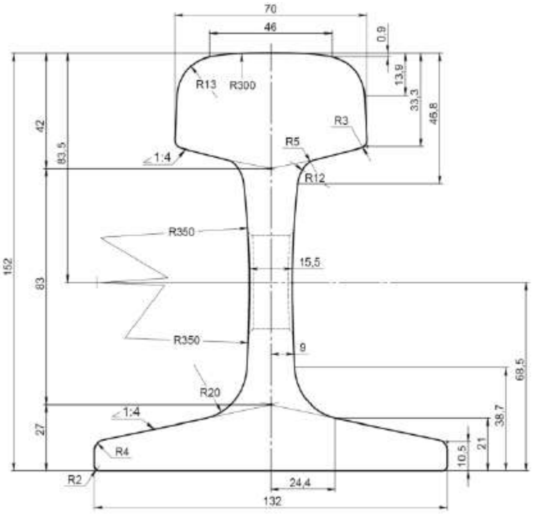


Fig. 9. - Rail type R50 according to GOST 7174-75.

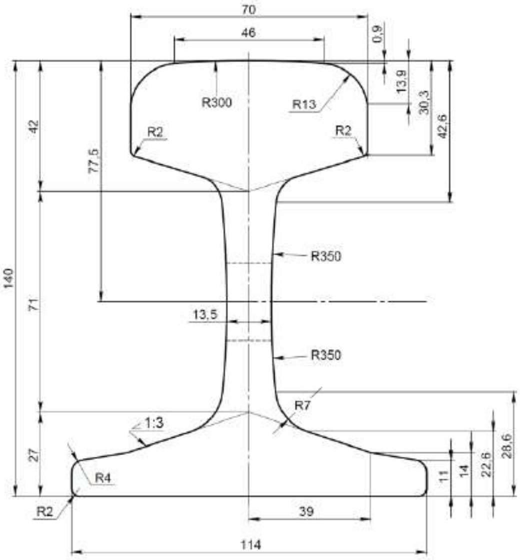


Fig. 10. - Rail type R43 according to GOST 7173-54.

Predominantly, interdendritic chemical inhomogeneity develops in weld seams. Zonal segregation is significantly less pronounced and manifests as slight enrichment in sulfur and certain other elements at the weld surface - under a wide penetration profile - and along the weld axis - under a narrow penetration profile. The degree of interdendritic inhomogeneity and zonal segregation largely depends on the cooling (solidification) conditions of the weld metal and its chemical composition.

Diffusion processes occurring in the fusion zone have a considerable influence on the quality of the welded joint. Due to the different solubilities of chemical elements in the liquid and solid phases, the chemical compositions of the boundary region of the base metal and the adjacent region of the weld metal differ substantially.

In some cases, a significant variation in chemical composition is observed along the weld length and at specific sections, i.e., macroscopic inhomogeneity of the weld. This variation is usually caused by fluctuations in the welding regime, changes in the composition of welding materials, and other technological factors.

The physical inhomogeneity observed in the weld metal is associated with the formation of so-called secondary boundaries, which occur in regions where imperfections in the metal's crystal lattice are concentrated. Physical inhomogeneity noticeably affects the weld's resistance to brittle transition, intergranular corrosion, and other mechanical and chemical properties.

1. Analysis of Statistical Data on Welded Rail Joints Quality

In accordance with the guidelines provided in the technical materials "Classification of Rail Defects CP-NTD/45-03", "Catalogue of Rail Defects CP-NTD/46-03", and "Indicators of Defective and Critically Defective Rails CP-NTD/47-03" [1,2], rails in which at least one defect is detected in a welded joint are classified as critically defective and are subject to immediate replacement.

To identify welding defects, all welded joints at rail welding enterprises (RWE) are subjected to visual inspection and ultrasonic testing in accordance with ST AO 39745182-044-2010 and ST AO 39745182-045-2010, following the Ultrasonic Testing Instruction for Welded Rail Joints at RWEs [4].

According to inspection data, each welded joint is evaluated using a qualitative (binary) criterion: acceptable or defective. The primary causes of defects in welded rail joints are generally attributed to malfunctions of the rail welding machines and inadequate preparation of the rail ends to be welded.

Welded joints in which defects are detected during inspection at the rail welding enterprise undergo repair; therefore, they are considered as in-plant rejects rather than finished product defects. The rail welding technological process includes: preparation of rail ends for welding, the welding itself performed according to the appropriate operational mode of a rail welding machine, and non-destructive testing of the welded joints, all carried out according to unified methodological guidelines [3].

Changes in the technological process are the prevailing factors in the formation of welding defects, as well as in the overlooking of such defects during inspection [4]. In this regard, it was necessary to improve the methodology for monitoring the rail joint welding process at JSC "NC "KTZh" RK, ensuring the reliability and durability of welded joints [5].

Since the introduction of ultrasonic testing at rail welding enterprises, the accumulation and consolidation of welded joint inspection data have been carried out. Analysis of these data has shown that, thanks to the automated welding process, the average percentage of in-plant rejects at various RWEs of JSC "NC "KTZh" over any given period is insignificant. However, it was found that in-plant rejects due to random deviations in the technological process do occur.

To promptly eliminate deviations in the technological process that lead to welding defects, it was advisable to improve the methodology for monitoring the rail joint welding process at JSC "NC "KTZh" RK, ensuring the reliability and durability of welded joints.

For this purpose, it was necessary to improve the monitoring of this process at rail welding enterprises, based on the statistical analysis of visual inspection and ultrasonic testing data. The control procedure involves calculating the average value of in-plant rejects $R_{к}$ over a specified preceding period for each k-th RWE, for example, over a year, and comparing this value with the average value of in-plant rejects ρ_i or the current period (month), as shown in Table 3.

For ease of comparison, rail welding control charts at RWEs are used (Figure 11), which indicate the average value over the preceding period and the control limits - upper $K_{в}$ and lower $K_{н}$, - within which changes in the current in-plant reject value are not considered indicative of deviations in the technological process. If in any month (for example, July) the in-plant reject value R_i exceeds the upper control limit $K_{в}$, this indicates that deviations have occurred in the technological process, leading to an increase in the number of defective joints.

Table 3. Average in-plant rejects over a year

Parameters	Month											
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Number of inspected joints ni	1900	2060	2210	2050	2060	1912	1500	1900	1620	1900	2030	2020
Number of rejected joints mi	9	1	2	1	4	1	10	5	3	2	3	4
Reject rate $pi = mi / ni$, %	0,05	0,10	0,05	0,20	0,20	0,05	0,55	0,20	0,15	0,10	0,15	0,20

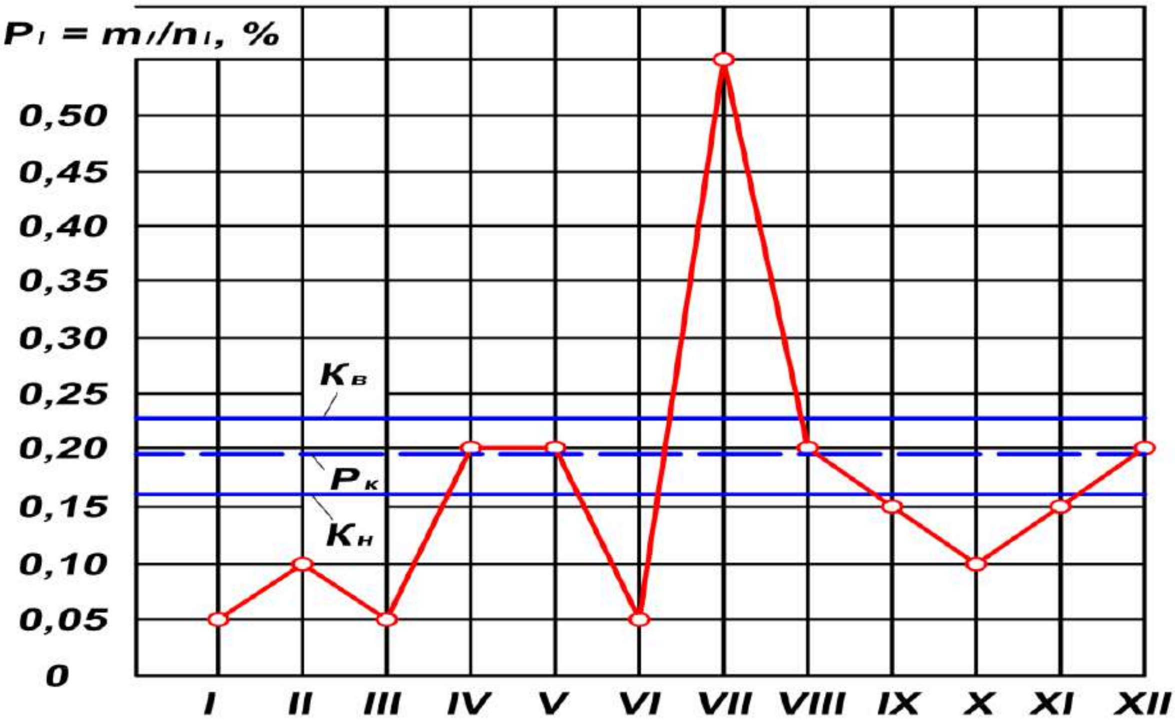


Fig. 11. – Rail Welding Control Chart at RWEs

Thus, exceeding the upper control limit indicates a deviation in the stability of the technological process and serves as a signal for intervention in the rail welding process, while falling below the lower control limit may indicate either an increase in the stability of the technological process or a possible oversight of defects, serving as a signal for an inspection of the non-destructive testing of welded joints.

If control charts allow the assessment of the stability of the rail welding process within each RWE, then comparing the average in-plant reject values for a given RWE $\overline{P}_{\kappa}$ with those of the other RWEs enables the evaluation of the technological level of the welding process at RWE κ Considering that practically identical rail welding machines, ultrasonic testing devices, and welding and inspection technologies are used across all RWEs, it is necessary, for the purpose of assessing the technological level of the welding process, to use charts similar to the aforementioned control charts, which should display:

- average in-plant reject values for all k-th RWEs, where $\overline{P}_{\kappa}$ κ-x where $\kappa = 1 \div \kappa_0$ over the preceding period, e.g., 12 months;
- $\overline{P}_{\Sigma}$ Average in-plant reject value across all RWEs over the preceding 12 months:

$$\overline{P}_{\Sigma} = \frac{\sum_{1}^{\kappa_0} \overline{P}_{\kappa}}{\kappa_0} \tag{1}$$

Upper $K_в$ and lower $K_н$ control limits, the exceeding of which indicates possible deviations in the welding technology or in the non-destructive testing process at the given RWE.

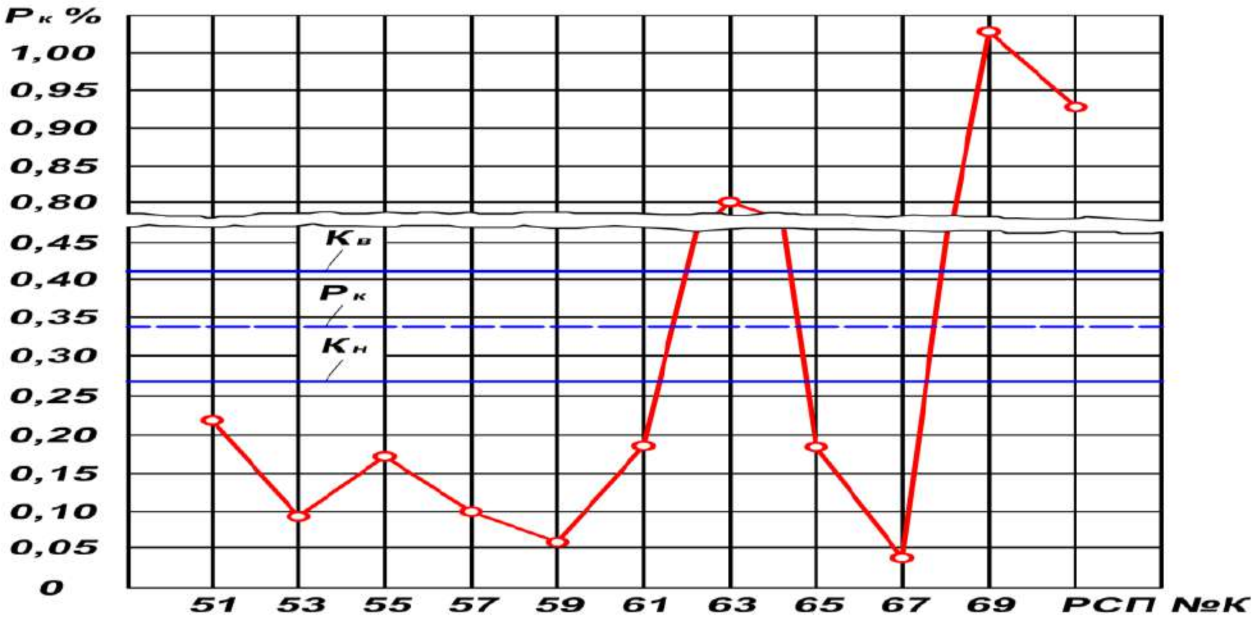


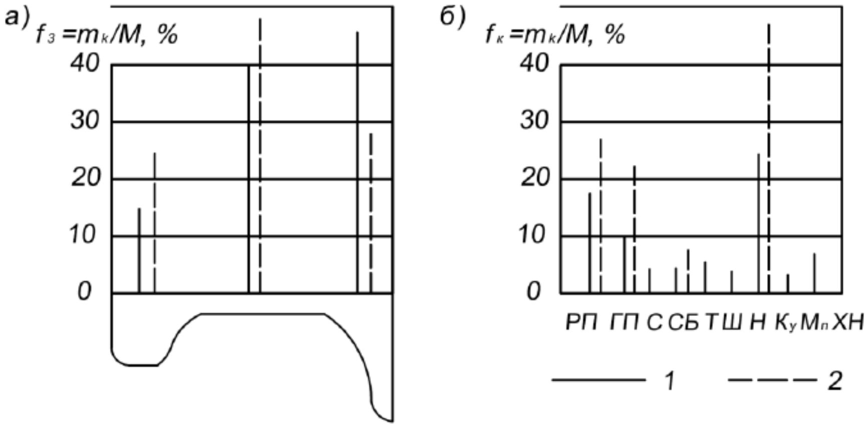
Fig. 12. – Example of a chart of average in-plant rejects for 2020 by RWEs

In addition to the annual average reject charts for all RWEs, information on the distribution of defects along the rail cross-section and by defect type over a sufficiently long period, e.g., one year, is highly useful for assessing the level of the technological process, both for individual RWEs and collectively for all RWEs, as shown in Figure 12.

The assessment of the stability of rail welding technological processes should be conducted independently at each RWE, whereas the evaluation of the technological process level should be centralized. Data collection for assessing the level of rail welding processes is carried out through Defective Joint Reports and Cards, which must be submitted quarterly to the designated data processing center.

Data accumulation and processing are performed using computers according to a specialized software program. To prevent disclosure of average in-plant reject values by RWE, each RWE is assigned a new index during data processing.

The implementation of this methodology for assessing the stability and level of the welded joint manufacturing process will contribute to improving the quality of rail welds, thereby reducing repair costs for rejected joints and minimizing the likelihood of installing welded rails with defective joints in the track.



1 – for all rail welding enterprises (RWEs); 2 – for a single RWE; r_n – porosity, overburn; g_n – gas bubble s – silicate inclusion; sb – gray silicate inclusion; t – crack; sh – slag; – lack of fusion K_u – crater shrinkage; M_p – matte spot; XN – defect type not specified

Fig. 13. – Example of defect distribution for a total of M = 1000 units, detected at RWEs, by rail cross-section zones (a) and by defect types (b). Note – Each RWE is assigned a numerical code as an index

To determine weldability, methods simulating the welding process are used. For example, base metal plates are subjected to heat treatment that reproduces the changes the metal undergoes during welding.

The quality of welding is greatly influenced by the quality of welding materials. The primary type of welding materials used in assembly are electrodes for manual welding. Electrodes are delivered to construction and assembly sites by their manufacturers. Each batch of electrodes must have a certificate indicating the manufacturer, date of production, batch number and mass, standard, diameter, type and grade of electrodes, mechanical properties of the deposited metal, allowable sulfur and phosphorus content, recommended welding parameters, and drying conditions. In addition, each pack of electrodes has a label, which depending on the packaging method is either attached outside or inserted inside. The label specifies the intended use of the electrodes, their diameter, grade and type, recommended welding and drying parameters, manufacturer, production date, and batch number.

The quality of welding is also significantly influenced by the wire used in mechanized welding and as filler in gas welding. Wire is supplied in coils, equipped with metal tags indicating the standard designation, melt number, and manufacturer. The manufacturer and its quality control department also stamp the tag. Each batch of wire must be accompanied by a certificate specifying its grade and diameter, chemical composition, melt number, standard, batch mass, and the manufacturer's name.

If the strength of the welded joint is lower than that of the base metal, it is permissible to use flat and round specimens with identical cross-sections for testing. The length of the gripping part of such specimens may be chosen according to the design of the testing machine, while any changes to other dimensions are not allowed.

For testing welded joint sections, round specimens with a working part diameter of 3–10 mm are used. These specimens are cut along the weld axis in the corresponding zone of the joint for multilayer welding.

2. Improved Methodology for Assessing the Stability of the Rail Welded Joint Manufacturing Process

The assessment of the stability of the technological process is carried out at RWEs using control charts, which are prepared annually in the format shown in Figure 13(a). Based on the calculation data, the control chart displays lines corresponding to the average in-plant reject rate (in percent) and the control limits K_v and $K_н$.

To calculate the average reject rate R(%), it is necessary to count the number of inspected joints N and the number of rejected joints M for the preceding year, and then compute their ratio.

$$\overline{P} = \frac{M}{N}100 \tag{2}$$

Control limits:

$$K_в = \overline{P} + 3\sqrt{\frac{\overline{P}(1-p)}{N/12}} \tag{3}$$

$$K_н = \overline{P} - 3\sqrt{\frac{\overline{P}(1-\overline{P})}{N/12}} \tag{4}$$

To assess the level of the rail welding technological process for the current month, the in-plant reject rate p_i for this month is calculated and compared with the average in-plant reject rate.

The in-plant reject rate p_i(%) for the current i-th month is calculated as the ratio of the number of rejected joints m_i during the given month to the number of inspected joints n_i for that month:

$$p_i = \frac{m_i}{n_i}100 \tag{5}$$

It is recommended that control data and in-plant reject rates for each month be recorded in the table presented above (Table 3):

1. The calculated value of p_i is marked on the control chart with a point. If the plotted point falls outside the upper control limit K_v, this indicates that deviations may have occurred in the technological process, causing an increase in the number of defective joints;
2. The broken line obtained by connecting the plotted points on the chart illustrates the pattern of changes in the rail welded joint manufacturing process at the RWE;
3. Filling in the table and the control chart can be performed by defect inspectors based on the data from the inspection log.

3. **Dynamic testing**

Dynamic tests include impact bending and fatigue (endurance) tests.

Impact bending tests involve determining the impact toughness of the welded joint at normal, reduced, and elevated temperatures corresponding to service conditions. The tests are conducted on specially prepared specimens with a notch, which may be located along the weld axis, the fusion line, or in the heat-affected zone on the side of the weld opening. The location of the notch depends on the purpose of the test. When testing weld metal or base metal, the notch can be made on either side of the specimen.

Tests are performed using pendulum impact testers with different maximum energy capacities. For use in laboratories of construction and assembly organizations, the MK-30A pendulum tester is recommended, which has 15 energy reserve steps and a total technical service life of 17,500 hours. After testing a welded joint, the fracture structure is examined to identify defects. Impact toughness is determined as the ratio of the work expended to fracture the specimen to the cross-sectional area at the notch prior to testing.

Fatigue (endurance) tests determine the metal's resistance to cyclic loads under bending, tension, and torsion. Variable loads are applied using symmetric, asymmetric, and pulsating loading cycles.

Axially loaded tests are conducted on cylindrical or flat specimens of special shape and specified dimensions, cut transverse to the welded joint. These tests determine the endurance limit of the specimen. A quantitative measure of fatigue strength is the number of cycles the welded specimen withstands before failure.

4. **Hardness measurement**

To evaluate changes in the weld metal and heat-affected zone, as well as to assess the degree of hardening in the welded joint zones and heterogeneity of mechanical properties, the hardness of welded joints is measured. Typically, hardness is determined on metallographic sections using three methods:

1. Indentation with a hardened steel ball of 1.568 mm diameter or a diamond cone with a 120° apex angle (Rockwell method);
2. Indentation with a square-based diamond pyramid with an angle of 136° between opposite faces (Vickers method);.
3. Indentation with a standard hardened steel ball of specified diameter (Brinell method).

Hardness measurements across the cross-section of a butt weld are carried out in two directions: along the longitudinal axis of the weld and from the center toward the base metal. Specimens are prepared to include all zones of the welded joint: base metal, weld metal, and heat-affected zones, with hardness measured in each of these three regions.

4. Improved Methodology for Assessing the Level of the Rail Welding Technological Process at RWEs

The improved assessment of the level of the rail welding technological process at RWEs is carried out centrally at the Central Track Laboratory using technological process level charts (hereinafter referred to as level charts).

Level charts are prepared twice a year, covering the preceding 12 months, in the format shown in Figure 13(b).

Based on the calculation data, lines corresponding to the average in-plant reject rate across all RWEs and the control limits $K_v$and $K_n$are plotted on the level chart.

The average in-plant reject rate is determined using formula (6).

$$\overline{P}_{\Sigma} = \frac{\sum_{\kappa=1}^{\kappa_0} \overline{P}_{\kappa}}{\kappa_0} \tag{6}$$

where $\bar{R}_k$is the average in-plant reject rate at the k-th RWE for the studied period (12 months);

k – the RWE number;

k_0 – the total number of RWEs under investigation.

Note: The values are determined based on data received from RWEs.

The control limits are determined using the following formulas:

$$K_{\text{в}} = \overline{P}_{\Sigma} + 3\sqrt{\overline{P}_{\Sigma}(1-\overline{P}_{\Sigma})/12}; \tag{7}$$

$$K_{\text{н}} = \overline{P}_{\Sigma} - 3\sqrt{\overline{P}_{\Sigma}(1-\overline{P}_{\Sigma})/12}. \tag{8}$$

To assess the level of the rail welding technological process at a given k-th RWE for the studied period, the value for this RWE is compared with the value for all RWEs.

If the value exceeds K_v, this indicates that the RWE has potential for improving the level of the rail welding technological process.

If the value falls below K_n, this indicates that the RWE has achieved a high level of welding quality or that there may be deviations in the non-destructive testing procedures of welded rail joints at the RWE.

The improvement of the rail welded joint technology involves analyzing the condition of welded rail joints installed in the track during the studied period, which are subjected to two-stage ultrasonic testing by distance inspectors.

Additional information on the level of the rail welding technological process is presented in the form of defect distributions in the welded joints. These distributions are calculated and plotted based on the inspection data of welded joints produced during the period for which the level charts were prepared.

Macrostructural analysis is used as a preliminary method to assess the quality of welded joints obtained by different welding methods. The macrostructure of welded joints is examined either with the naked eye or at 30× magnification on the surfaces of macrosections cut from these joints. Macrostructure can also be studied on fracture surfaces of welded specimens after mechanical testing.

Macrostructural investigation allows determination of the weld shape and size, its internal structure, and the presence of various defects in the weld metal and base metal, such as lack of fusion, cracks, slag inclusions, pores, and others.

When examining the macrostructure of welded joints, templates are cut from the inspected joint in the plane of the weld cross-section to prepare sections. Sometimes, to determine the weld crystallization pattern in the welding bath, a section is prepared from a template cut along the longitudinal axis of the weld.

The section surface must include the full cross-section of the weld. To eliminate areas corresponding to unstable welding conditions, samples for sections are cut 20–30 mm away from the start or end of the weld.

For etching in microstructural studies of aluminum alloy welds, a 0.5% aqueous solution of hydrofluoric acid is used as a reagent.

For preparation of microsections of corrosion-resistant steels, electrolytic etching is used, which provides a significantly more uniform microstructure reveal than conventional etching. Electrolytic etching is also suitable for low- and medium-alloy steels. It is especially effective when high-quality surface preparation is required (for electron microscopy studies) and when work-hardening effects in the surface layer need to be removed.

The study of a microsection typically proceeds as follows. After polishing (before etching), the section is examined under a microscope at 100–500× magnification to detect pores, oxide films, and microcracks in the weld. Non-metallic inclusions appear as dark spots against the bright background of the microsection. Microcracks appear as thin, black, wavy lines. After etching, the microsection is examined under a microscope to determine the weld structure across the entire cross-section, including the types and proportions of structural components and the presence and distribution of carbides, nitrides, sulfide, and oxide inclusions.

When the study is not performed immediately after microsection preparation or is conducted multiple times with intervals, proper storage of the sections is necessary. Since the surface must be protected from oxidation during storage, a passivating solution is applied during polishing and rinsing, followed by careful washing with alcohol and drying.

Conclusion

1. To ensure the timely elimination of deviations in the technological process that lead to defects in welded rail joints, it is advisable to implement process control at rail welding enterprises based on statistical analysis of visual inspection and ultrasonic testing data.
2. Based on the obtained data, an improved methodology has been developed at rail welding enterprises for assessing the stability and level of the rail welded joint manufacturing process at RWEs. The application of this improved methodology will contribute to enhancing the quality of rail welds, thereby reducing repair costs for rejected joints and minimizing the likelihood of laying welded rails with defective joints in the track.
3. The statistical analysis of visual inspection and ultrasonic testing data involves monitoring and calculating the average in-plant reject rate for a specified preceding period for each RWE, for example, one year, and comparing this value with the average in-plant reject rate for the current period (month). It has been established that the main causes of defects in welded rail joints are malfunctions of rail welding machines and poor preparation of the rail ends to be welded.
4. To calculate the potential for improving the level of the rail welding technological process, the formulas for determining the average reject rate $R(\%)$ should be applied. This requires counting the number of inspected joints $N$and the number of rejected joints $M$for the preceding year and then computing their ratio.

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