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# DEVELOPMENT OF INDUCTORS FOR BULK AND SURFACE HEAT TREATMENT OF WELDED BUTT JOINTS OF RAILWAY RAILS

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The paper presents the concept of bulk and surface heat treatment of the welded butt joint of a railway rail by two or more inductors with the purpose of achieving favourable phase transformations of metal and normalizing its structure in the weld zone. Performed computations and experiments resulted in development of split inductors without magnetic circuits, which allow performance of bulk and surface induction heat treatment. Conducted experiments on heating a welded butt joint of a rail by the developed split inductors without the magnet cores demonstrated heating uniformity characteristics acceptable for bulk heat treatment of rails, limit temperatures and rates of heating of the main rail working areas both on the surface and in-depth of a narrow heating zone. 19 Ref. 2 Tables, 8 Figures.

*Keywords: inductor, induction heating, bulk heat treatment, surface heat treatment, welded butt joint of railway rails, normalizing of weld zone metal*

In connection with development of high-speed railway transportation in Ukraine, the task of producing high-quality continuous welded rails of greater length and increased strength from hypereutectoid steels remains urgent. In Ukraine and in a number of countries in the world, rails are joined by flash-butt welding, both in the stationary rail-welding enterprises, and under the road conditions, by the technology and with application of equipment developed by PWI. Weld heat treatment is more and more often used in the world practice, in order to improve the metal structure in the weld and near-weld zone, and increase the reliability of the welds [1].

In metallurgical enterprises the rails are heat treated during manufacture. Engineering solutions for performance of induction heat treatment (HT) of the entire rail surface [2], or its head surface [2, 3] are known. Some inductor designs allow performance of HT in keeping with the technical requirements, which were in force during their development, but need upgrading now, in connection with the change of the composition of rail steel, which is close to alloyed steels, their manufacturing method, and change of the cross-section geometry towards the reinforcement. For these purposes, PWI developed an inductor design, which ensures more effective heating of the rail head surface [4].

At the same time, requirements to the rail welded butt joint become higher. Welded butt joints of rails of R65 type from low-alloyed steel (Cr–Si–V) of K76F grade, manufactured in Ukraine, at increase of the train speed and of the load in the wheel-rail system also require HT [3], in order to avoid formation of unfavourable structures and produce normalized structure of the metal, with the structure becoming closer to the base metal both by its kind and mechanical values, as well as reduction of unfavourable residual stresses.

HT performance is also due to the need to correct the technological inheritance of the quality values (properties) of the metal in the weld zone, which starts from metallurgical processing and runs through the entire process of rail manufacture. The technological inheritance of metal quality includes fluctuations of the distribution of chemical elements, mechanical values and local stress-strain state, which are of a random nature and have an essential impact on the structure life cycle [5], if they occur in the weld zone.

In order to conduct HT of welded butt joints of the railway rails, the most effective is application of induction heating [1], performance of which is regulated by technical normative guidelines [6] and use of equipment, with which it is performed. The working tools of the induction units are inductors, which can be with and without magnetic circuits.

The work on development of the technology of performance of induction HT of the welded butt joints of railway rails and designing the respective equipment, is performed by many countries of the world [1]. In RF SPC «Magnit M» Ltd. developed complexes for

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HT of rails [7, 8], which include multiturn inductors without magnet cores. Such complexes operate under the shop and track conditions with working current frequency of 6.0–8.0 and 2.4–8.0 kHz. For construction of the railways, split single-turn high-frequency inductors with parallel conductors without magnetic circuits were developed in PRC [9, 10].

PWI performed work on development of the technology and portable equipment to ensure uniform heating of the rail weld with reduced heating zone [11, 12] for 2.4 kHz working frequency of current. The equipment is designed for correspondence of normative requirements [6] to the European standard EN 14587-21–2005. Used as a work tool, is a split inductor with magnetic flux concentrators in the form of magnetic circuits [13, 14], which ensures in a sufficiently short time (180 s) the required bulk uniform heating to the specified temperature of all the rail areas.

The objective of the work is description of development at PWI of a test sample of a complex-shaped split inductor without magnetic circuits with a narrow zone of bulk heating of the welded butt joint of R65 rail, at 2.4 kHz working frequency of current.

The base of development of a test sample of complex-shaped split inductor without magnetic circuits, was the concept of performance of bulk and surface HT of the butt welded joint of a railway rail by two or more inductors.

The development was mainly focused on performance of bulk HT of a welded butt joint as the main operation.

The test sample of a complex-shaped split inductor without magnetic circuits and its main characteristics and geometrical parameters were determined by preliminary calculations of a model of an induction system of «inductor–workpiece», taking into account the above requirements to HT of welded butt joints. Preliminary results on development of inductors for HT of both the welded butt joint of the rails and of the rails proper were also taken into account.

Because of the complex cross-sectional shape of railway rails, different volume of the metal in its elements, namely its head, web and foot, and well as the difference in the geometry of different types of rails, it is rather difficult to perform uniform induction bulk heating of the main working elements of the rail. And it is exactly fulfillment of this condition which ensures high-quality HT of the welded butt joint. However, even in this case, short zones of lower hardness form on both sides from the inductor edges along the rail longitudinal axis. This is due to the steel exposure to the impact of the temperature field in the region of 700–350 °C, for sufficiently long time for formation of incomplete recrystallization zone. At rail operation, surface deformations can develop in these areas from rolling wheels.

In order to avoid this phenomenon, the concept was proposed of performance of bulk and surface HT of the welded butt joint of the railway rail by two and more inductors, in order to obtain favourable phase transformations of metal and normalizing its structure in the weld zone. For this purpose, it is proposed to perform in incomplete recrystallization zones additional surface HT by a pair of inductors for producing surface hardening of the metal in these zones. Surface HT can be performed simultaneously with bulk HT, or after performance of bulk HT by the main inductor. The electric and geometrical parameters of the additional pair of inductors and thermal heating cycle can differ from the parameters and cycle of the main inductor.

It is desirable to perform surface HT at higher frequency of current (more than 2.4 KHz), in order to reduce penetration of induced currents and thermal flows in-depth of the rail metal. Here, the metal is not exposed to intensive thermal impact inside the rail. The thermal fields which propagate from an additional pair of inductors over the rail surface promote refinement of the metal grains, producing uniform structures in the specified rail areas of a lower hardness, and also promote increase of its hardness and shortening of the extent of the above-mentioned zones of metal softening on the rail surface. Surface HT can be performed around the entire perimeter of the rail cross-section or over the head surface.

As the volume of the metal of welded butt joint of the rail, subjected to surface HT, is smaller than the volume of metal, subjected to bulk HT, smaller power is required for its performance, and even smaller — at surface HT of just the rail head, respectively.

In development and manufacturing of the structure of a split inductor without magnetic circuits for bulk HT of welded butt joints of railway rails, the following factors should be taken into account:

- possibility to perform HT under stationary conditions in rail-welding enterprises, on the track, in particular, in a confined space and on the already assembled railway track at its repair;
- complexity of inductor design, which is due to bringing together — bringing apart its branches relative to the rail;
- possible presence of electric contact at closing of the inductor branches with provision of its reliable connection and unhindered passage of high-frequency current through it, particularly, at long-term use, that determines reliable operation of the entire split inductor.

When developing the designs of split inductors without magnetic circuits to perform bulk HT of weld-

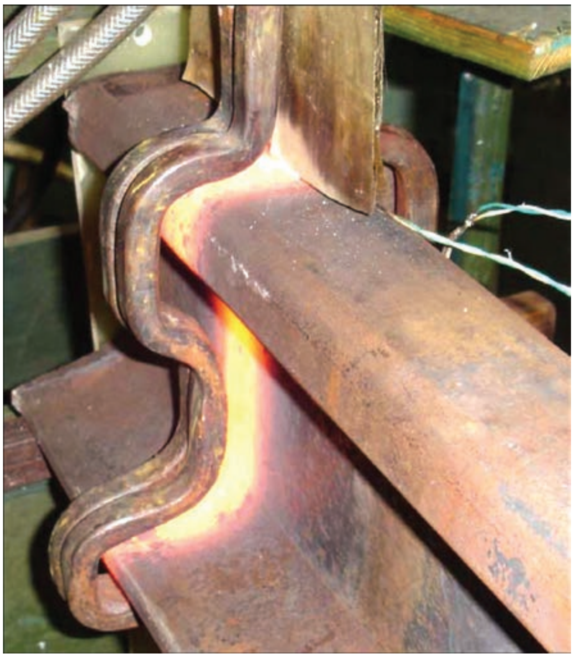

**Figure 1.** Performance of bulk HT of the welded butt joint of a railway rail of R65 type by split inductor without magnetic circuits

ed butt joints of railway rails, the test sample of one-piece inductor without magnetic circuits (Figure 1) for rail-welding enterprises and materials of works [2, 15–17] were taken as the base.

The design of a split inductor without magnetic circuits with electric contact for joining the two inductor branches (Figure 2) was developed, in which, compared to the inductor in Figure 1, the distances between the rail side surfaces and the inductor were reduced and equalized. Such an inductor is designed to perform surface HT of rails, as it can quickly and uniformly heat a narrow zone around the entire perimeter of the rail to uniform small depth by higher frequency currents (more than 6 kHz). The inductor is designed to perform HT in rail-welding enterprises and on the track.

A design of a split inductor without magnetic circuits or electric contact between the two parts of the inductor (Figure 3) was developed, in which, compared to the inductor in Figure 2, the distances between the side surfaces of the rail and the inductor were corrected, in order to ensure uniform bulk heating of all the rail parts. The inductor is designed to perform bulk HT in rail-welding enterprises and on the track.

This inductor design greatly simplifies its manufacture and use and improves the reliability of its operation, as the electric contact between its branches is absent. However, due to large distances between the rail side surfaces and the inductor and greater length of induction wires, the inductance and resistance of the inductor increase, leading to greater electric losses and the need to increase the capacitance, that compensates the system inductance, and this leads to its higher price during production and operation.

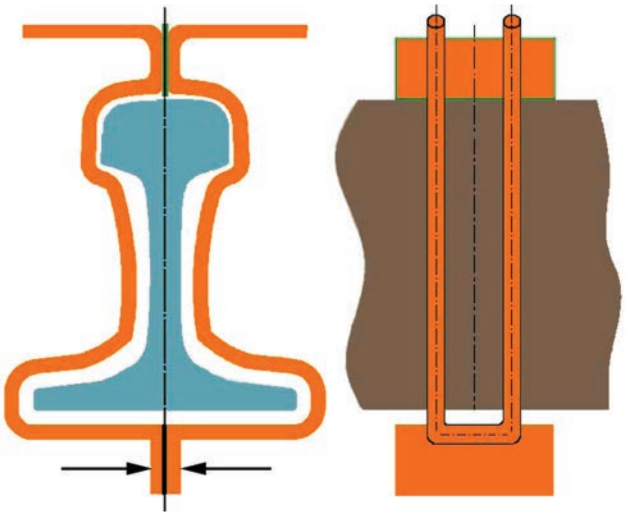

**Figure 2.** Design of a split inductor without magnetic circuits with electric contact for closing inductor branches, designed for conducting surface HT of narrow surfaces of rails

A design of the split inductor without magnetic circuits was proposed, in which the task of uniform bulk heating of all the main parts of the rail is solved comprehensively. The design has different distances between the side surfaces of the rail and the inductor, but much smaller than in the design in Figure 3. Unlike the previously considered designs, this inductor has different configuration in the longitudinal direction of the rail (Figure 4). The design contains higher reliability electric contact with greater area of the surfaces being joined, which are removed beyond the inductor working zone. The inductor is designed to perform bulk HT in the rail-welding enterprises and on the track. This inductor design for uniform bulk

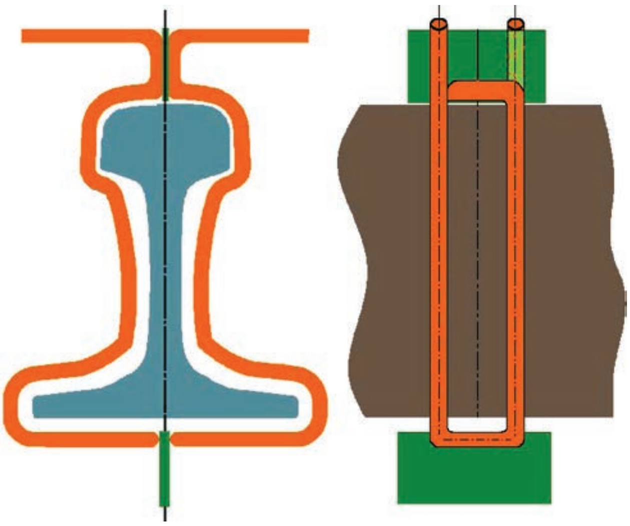

**Figure 3.** Design of a split inductor without magnetic circuits or electric contact between the inductor halves, designed for bulk HT of railway rails

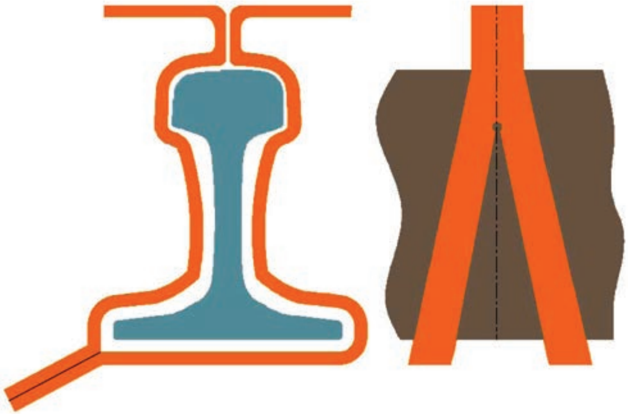

**Figure 4.** Design of a split inductor without magnetic circuits with higher-reliability electric contact taken out of the working zone, for closing the inductor branches, which is designed to conduct bulk HT of railway rails

heating of rail parts was defined as the priority one for implementation.

The procedure of work [18] and the data of earlier conducted experiments on performance of bulk HT by the inductor in Figure 1, which was also designed by this procedure, were used for estimated calculation of the parameters of split inductor without magnetic circuits (Figure 4).

The following parameters were taken as the base ones: $f$ is the induction current frequency; $S$ is the the cross-sectional area of the rail elements and their percentage value $S_{\%}$ of the total cross-sectional area; $l$ is the length of the rail areas around the perimeter.

Based on the dependencies between the electromagnetic characteristics [18] and geometrical parameters of railway rail of R65 type, which is to be heat-treated, calculation of the electromagnetic and geometrical parameters of «inductor-rail» system was performed, using the dependence of specific surface power $p$ on magnetic field strength $H$ at frequency $f = 2.5$ kHz [18], which is close to that of the available power source TPChT-160/2.4 and similarity of distribution of the strength of the magnetic field [19], which forms at distance δ between the surface of the object being heated and the inducing conductor.

The main parameters of the system have been determined and calculated: $S_s$, $M$ are the surface area of the rail elements which are heated, and their weight; $H$, $p$ are the magnetic field strengths and specific powers on the heating surfaces of rail elements; Δ is the depth of magnetic flux penetration into the rail elements; δ is the distance (nonmagnetic gap) between the heated surfaces of the rail elements and the inductor; $P$ are the powers applied to the rail elements at heating.

The listed parameters at the start of heating, when the rail metal has magnetic properties, are shown in Table 1.

Proceeding from the rail configuration, the highest magnetic field strength should be created in the most massive area of the surface — the rail head. On smaller bodies and thinner areas, the magnetic field strength should be lowered.

A test laboratory sample of this inductor (Figure 5) from sheet copper with reinforcement by water-cooled tubes was manufactured, which allows conducting bulk HT of the welded butt joint of the rails.

The inductor ensures a more concentrated distribution of the magnetic field in the rail head, due to a continuous conductor over its surface and small clearance (gap) between the conductor and the rail. Above the rail web and foot the inductor conductors are made in the form of two parallel branches, the area of which becomes smaller towards the foot, thus reducing the heated area under them. In the foot area, the conductors are also removed from each other that enables heating to be performed in the area of the thinnest end portions of the foot — the base points. In terms of

**Table 1.** Parameters of the induction system at heating of R65 rail

| Parameters | Head | Web | Foot | Rail |
|---|---|---|---|---|
| Cross-sectional area $S$, cm$^2$ | 28.19 | 23.57 | 30.89 | 82.65 [6] |
| Cross-sectional area $S_{\%}$, % | 34.1 | 28.5 | 37.4 | 100.0 |
| Heating area under the inductor, $S_a$, cm$^2$ | 79.1 | 124.7 | 129.0 | 332.8 |
| Length around the perimeter $l$, cm | 18.5 | 29.0 | 30.0 | 77.5 |
| Rail element mass $M$, kg | 8.375 | 5.940 | 8.066 | 22.381 |
| Distance between the inductor and surface δ, cm | 0.8–1.0 | 2.4–2.8 | 2.6–3.2 | – |
| Magnetic field strength $H$, A/cm | 1200.0 | 765.5 | 740.0 | – |
| Specific surface power $p$, W/cm$^2$ | 290 | 145 | 130 | – |
| Penetration depth Δ, cm | 0.120 | 0.095 | 0.090 | – |
| Applied power $P$, kW | 22.944 | 18.081 | 16.770 | 57.775 |

**Figure 5.** Laboratory test sample of a split inductor without magnetic circuits

design, the gap between the inductor conductors and the rail is made with its increase from the head to the web and foot. Such an inductor design allowed uniform heating to be performed.

Conducting experiments on performance of induction bulk HT of the welded butt joint of the railway rail demonstrated achieving almost simultaneous and uniform heating of parts of different weight and area, namely the head and foot and quite close to them heating of the web center, without its overheating. It should be noted that the temperature at the ends of the rail base points after passing the phase transformation point $A_{c3}$ (Curie point) stabilized, and practically did not rise further on, because of complete disappearance of the metal magnetic properties, which is associated with the magnetic field penetration into the zone of the volume of base point ends, that lead to reduction of the density of eddy currents, which heat the metal of base point ends, that is not critical as the base point ends are no the most loaded elements of the rail.

It is experimentally confirmed that the power applied during performance of induction bulk HT to each part of the rail, is close to the power determined by calculations.

Bulk HT of the welded butt joint of the rails by a split inductor without magnetic circuits was performed in a narrow zone (40 mm) on both sides from the transverse weld. Rail heating was conducted in the laboratory equipment, which included: power source — thyristor frequency of 160 kW power and 2.4 kHz current frequency (TPChT-160/2.4) converter: matching single-phase high-frequency transformer TZ-800 (hardening transformer), battery of cosine capacitors for compensation of the reactive power; and test inductor.

Monitoring of electric parameters of the unit was performed as follows: digital multimeters UNI-T

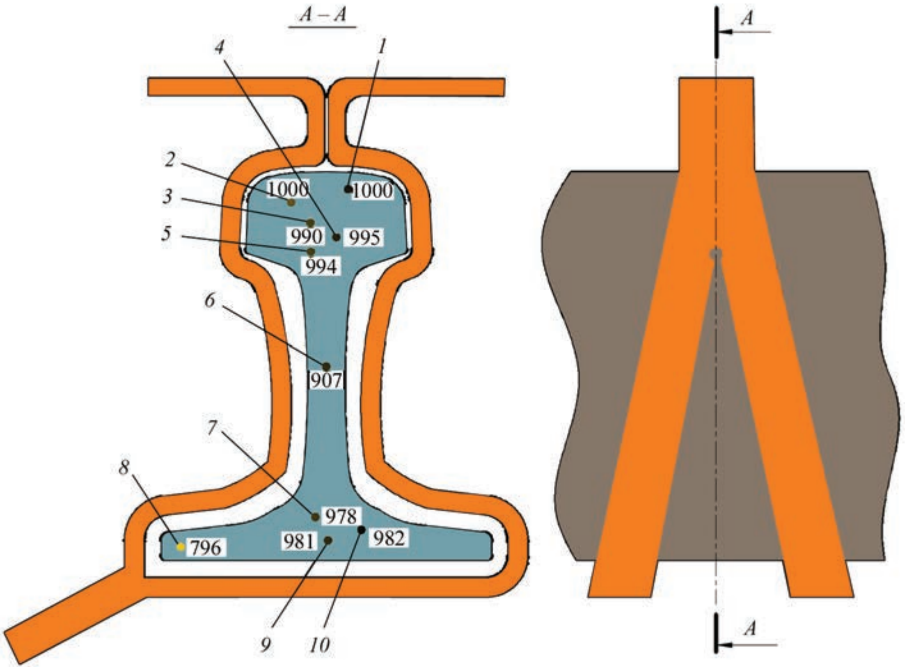

**Figure 6.** Scheme of location of 10 thermocouples in the conditional cross-section of the rail

**Figure 7.** Heating of welded butt joint of R65 rail by a test split inductor without magnetic circuit

UT70V and Velleman DMV1090; phase meter F2-1; Rogowski belt.

Measurement of temperature field in the rail weld was performed by sensors in the form of chromel-alumel thermoelectric converters (thermocouples) of K type of 0.75 mm diameter. Thermocouples were welded to the rail, using low-power capacitor welding source. Four thermocouples *1–4* were placed in the rail head (Figure 6), at the depth of 6, 12, 19 and 25 mm from the rolling surface, respectively; thermocouple *5* was installed in the place of head transition to the web; *6* — at 9 mm depth in the narrowest part of the weld; *7* — at the depth of 22 mm in the place of the web transition to the foot; *8* — at 10 mm depth at the end of the rail base point; *9* and *10* — in the rail foot at the depth of 10 and 14 mm, respectively.

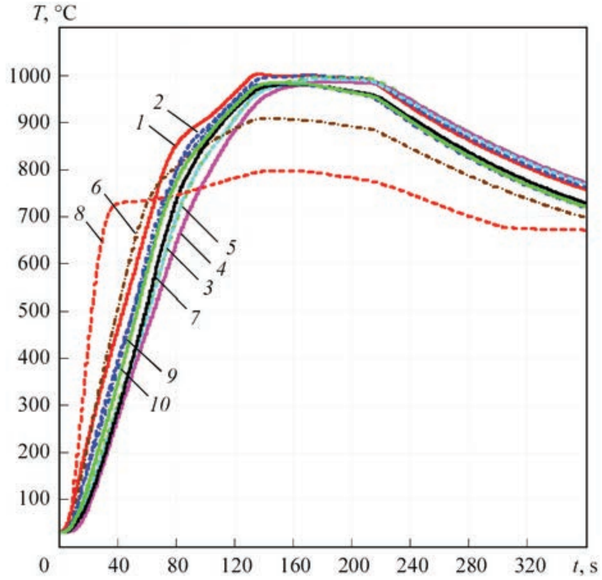

**Figure 8.** Dependencies of temperature $T$ on time $t$ in points *1–10* (thermocouple numbers) in the conditional cross-section of the rail

Conversion of the thermocouple signal took place due to connection of 10-channel ADC ISP-DAS M-7018 and galvanic decoupling block ISP-DAS i-7561U. Visualization of the results of temperature measurement in time was performed on the computer monitor, using a special program of measured data processing.

Figure 7 showed the welded butt joint of R65 rail heated by a test split inductor without magnetic circuit.

Dependencies of temperature $T$ (°C) in points 1–10 of the conditional cross-section of the rail on time $t$(s) are given in Figure 8, and the numerical temperature values in these points are given in Table 2.

Experimental data show the ability of the developed inductor to heat the surface layers of the rail head up to the temperature of 1000 °C, which is even higher than metal normalizing temperature of 825–875 °C, at relatively uniform distribution of the temperature field in the main working areas of the rail volume.

Maximum temperature of 1000 °C was reached during time $t_1$ = 135 s, which was taken as the start of the process of soaking at this temperature up to $t_2$ = 215 s and was continued $\Delta t = t_2 - t_1$ = 80 s. Then the inductor was switched off and the heating process stopped. Rail cooling occurred under natural conditions.

In the temperature curves (Figure 6), their smooth inflection can be observed from the start of heating up to time $t_{1,}$ when the temperature in different sections of the rail rises abruptly at the rate $v_{mg}$ = 7.3–20.1 °C/s (mean value of 10.5 °C/s) (Table 2), and then its increase slows down and the heating rate drops to $v_{nmg\text{-}t1}$ = 0.8–4.1 °C/s (mean value of 3.1 °C/s). Abrupt temperature rise is observed at the start of heating, when the rail metal is in the magnetic state, and the depth of magnetic field penetration into the surface layers is minimum, and the density of eddy currents, which heat the metal, is maximum. After the temperature has passed through the Curie point (phase transition point $A_{c3}$, approximately 770 °C for steel), the metal layers by the depth are gradually becoming nonmagnetic, depth of magnetic field penetration into the metal becomes greater, and the density of eddy currents in it smoothly becomes smaller, that leads to slowing down of the heating process and, usually, to the need to increase the power from the source. In different areas and in different volumes of the rail this process proceeds in different ways, depending on the state of the magnetic and nonmagnetic metal, during the heating process.

**Table 2.** Temperature values in points 1–10 of the conditional cross-section of the rail

| Thermocouple numbers (Figure 6) | | | | | | | | | | Mean value |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Temperature $T_1$, °C of the start of the soaking process, reached during heating time $t_1$ = 135 s | | | | | | | | | | |
| 1000 | 990 | 962 | 943 | 962 | 906 | 970 | 794 | 979 | 977 | 948 |
| Temperature $T_2$, °C at the end of the soaking process, which is achieved during heating time $t_2$ = 215 s | | | | | | | | | | |
| 985 | 985 | 984 | 981 | 985 | 882 | 955 | 772 | 950 | 951 | 943 |
| Temperature difference $\Delta T = \|T_2 - T_1\|$, °C on the boundaries $t_1$ and $t_2$ of range $\Delta t$ of soaking time ($\Delta t = t_2 - t_1$ = 80 s) | | | | | | | | | | |
| 15 | 5 | 22 | 38 | 23 | 24 | 15 | 22 | 29 | 26 | 22 |
| Maximum temperature $T_{max}$, °C in soaking time range $\Delta t$ | | | | | | | | | | |
| 1000 | 1000 | 990 | 995 | 994 | 907 | 978 | 796 | 981 | 982 | 962 |
| Minimum temperature $T_{min}$, °C in soaking time range $\Delta t$ | | | | | | | | | | |
| 985 | 985 | 962 | 943 | 962 | 882 | 955 | 772 | 950 | 951 | 935 |
| Difference between the maximum and minimum temperature $\Delta T_{max\text{-}min} = \|T_{max} - T_{min}\|$, °C, in soaking time range $\Delta t$ | | | | | | | | | | |
| 8 | 8 | 28 | 45 | 27 | 23 | 23 | 21 | 30 | 27 | 24 |
| Temperature difference $\Delta T_{1000\,°C\text{-}max} = \|T_{1000\,°C} - T_{max}\|$, °C in soaking time range $\Delta t$ | | | | | | | | | | |
| 0 | 0 | 10 | 5 | 6 | 93 | 22 | 204 | 19 | 18 | 38 |
| Temperature difference $\Delta T_{1000\,°C\text{-}min} = \|T_{1000\,°C} - T_{min}\|$, °C, in soaking time range $\Delta t$ | | | | | | | | | | |
| 15 | 15 | 38 | 57 | 38 | 118 | 45 | 228 | 50 | 49 | 65 |
| Metal heating rate in the magnetic state $v_{mg}$, °C/s | | | | | | | | | | |
| 10.8 | 9.5 | 8.5 | 7.3 | 8.5 | 11.5 | 9.0 | 20.1 | 9.9 | 9.7 | 10.5 |
| Metal heating rate under the impact of the nonmagnetic state up to the start of the soaking process $v_{nmg\text{-}t1}$, °C/s | | | | | | | | | | |
| 2.7 | 3.0 | 4.1 | 3.6 | 4.1 | 2.0 | 3.7 | 0.8 | 3.4 | 3.6 | 3.1 |
| Rate of temperature change during soaking, $v_{\Delta t}$, °C/s | | | | | | | | | | |
| 0.2 | 0.1 | 0.3 | 0.5 | 0.3 | 0.3 | 0.2 | 0.3 | 0.4 | 0.3 | 0.3 |

In massive parts of the rail, such as the head, the foot and places of the web transition to the head and the foot, the heating process occurs smoothly at rates $v_{mg}$ = 7.3–11.5 °C/s and $v_{nmg\text{-}t1}$ = 2.0–4.1 °C/s (Table 2), without any significant inflections of the temperature curves, which during the entire duration of heating are located in clusters, that is the consequence of correctly determined geometrical parameters of the inductor. The rate of temperature change during soaking is equal to $v_{\Delta 1}$ = 0.1–0.5 °C/s (mean value of 0.3 °C/s).

The rail base points are thin and heat the fastest at the beginning, but at their complete heating above the Curie point, the rise of temperature in them becomes considerably slower, as the depth of magnetic field penetration coincides with base point thickness, current density becomes smaller, as does the power consumed in their heating. Slowing down of the heating is observed also in the rail web center. More over, these areas, more than others, are affected by the cooling process due to convection and radiation, in connection with the larger cooling area per a unit of metal mass.

During soaking at the temperature, the difference in the temperatures in different areas of the rail is small (Table 2), that is the difference between the temperatures at the start $T_1$ and at the end $T_2$ of the soaking range is $\Delta T = |T_2 - T_1|$ = 5–38 °C (mean value of 22 °C), between their maximum $T_{max}$ and minimum $T_{min}$ values it is $\Delta T_{max\text{-}min} = |T_{max} - T_{min}|$ = 8–45 °C (mean value of 24 °C), and between limit temperature of 1000 °C and maximum and minimum temperature values it is $\Delta T_{1000\,°C\text{-}max} = |T_{1000\,°C} - T_{max}|$ = 0–204 °C (mean value of 38 °C), $\Delta T_{1000\,°C\text{-}min} = |T_{1000\,°C} - T_{min}|$ = = 15–228 °C (mean value of 65 °C). If we ignore the temperature in the rail base points, then the upper limit values of temperature difference will be even smaller.

Thus, the developed split inductor without the magnetic circuits, ensures the temperature in the main rail areas, acceptable for bulk heating of the rail welded butt joints.

Further studies should focus on producing a split inductor without the magnetic circuits for surface HT of incomplete recrystallization zones that form after performance of bulk HT.

## Conclusions

1. Modern development of railway transportation is going along the path of construction of continuous track with application of new high-strength rails from alloyed steels of higher strength and wear resistance. Stringent requirements are made also of welded butt joints of the rails as an integral part of the continuous track. Achieving metal normalizing, reducing unfavourable residual stresses in the welded joint zone due to performance of HT and improvement of its quality is an urgent task.

2. Implementation of the proposed concept of bulk and surface induction heat treatment of the HAZ of welded butt joints of the rails will allow producing normalized metal structures, which will promote improvement of metal characteristics.

3. Based on the conducted calculations and experiments, analysis of the features of the geometrical forms and weights of the rail in its different areas was the basis for development of split inductors without magnetic circuits for the possibility of conducting bulk and surface induction heat treatment.

4. Conducted experiments on performance of heating of a welded butt joint of rail of R65 type by a test sample of the developed split inductor of a complex shape without magnetic circuits at current frequency of 2.4 kHz showed acceptable for bulk heat treatment of rails values of heating uniformity, limit temperatures and rates of heating the main working areas of the rail, both on the surface, and in-depth of the narrow heating zone of 40 mm.

5. Development of a test sample of a complex-shaped split inductor without magnetic circuits by the performed calculations and the conducted experiments on heating the welded butt joint of rail of R65 type, confirmed the correctness of the calculation model of the «inductor–workpiece» induction system.

1. Gubatyuk, R.S. (2019) Heat treatment of welded joints of high-strength railway rails (Review). *The Paton Welding J.*, **2**, 41–48.
2. Taras, P., Fireteanu, V. (2010) Inductors for continuous induction heating of rails. *Induktsionnyj Nagrev*, 14(**4**), 21–26 [in Russian].
3. Skoblo, T.S., Sapozhkov, V.E., Aleksandrova, N.M., Sidashenko, A.I. (2014) *Quality of thermally-hardened rails and rail bases. Investigations. Theory. Equipment. Technology. Operation.* Ed. by T.S. Skoblo. Kharkov, LLC Shchedra Sadyba Plus [in Russian].
4. Pantelejmonov, E.A., Pismenny, A.A. (2015) Inductor for continuous heating in hardening of railway rail head. *The Paton Welding J.*, **3–4**, 74–76.
5. Panov, V.I. (2018) Evaluation of technological heredity of metal of solid structures before their repair welding. *Svarshchik*, **1**, 9–11 [in Russian].
6. (2005) *DSTU 4344:2004*: Normal rails for full-gauge railway. General specifications. Kyiv, Gospotrebstandart Ukrainy [in Ukrainian].
7. (2013) http://magnit-m.ru/catalog/ustanovki-induktsionnogo-nagreva-tvch/termoobrabotka-svarnykh-relsovykh-stykov/uin-001-100-rt-p
8. (2013) http://magnit-m.ru/catalog/ustanovki-induktsionnogo-nagreva-tvch/termoobrabotka-svarnykh-relsovykh-stykov/uin-001-100-r-tsm
9. *Zhan* Xinwei, Wang Shuqing, Shao Yangdao, at. al. (2015) *Non-contact type opening/closing split induction heating device for rail welded joints*. China Pat. CN 201510540567.
10. *Ding* Wei, Song Hongtu, Li Li, at. al (2012) *Heat treatment device of welding joint of steel rail.* China Pat. CN 201120285569.
11. Pysmennyi, O.S., Pysmennyi, P.O., Prokofiev, O.S., Yukhymenko, R.V., Gubatyuk, R.S. (2012) *Induction installation for heat treatment of rail welded joints*. Ukraine Pat. on utility model UA 75027 [in Ukrainian].
12. Panteleimonov, E.O. (2017) *Complex for heat treatment of railway rail welded joints in situ*. Ukraine Pat. on utility model 114593 [in Ukrainian].
13. Pysmennyi, O.S., Panteleimonov, E.O., Rymar, S.V., Gubatyuk, R.S. (2017) *Induction device for heat treatment of railway rail welded joints.* Ukraine Pat. on utility model 116086 [in Ukrainian].
14. Panteleimonov, E.O., Gubatyuk, R.S. (2016) *Induction device for heat treatment of railway rail welded joints.* Ukraine Pat. On utility model 109123 [in Ukrainian].
15. Zhan, X., Wang, S. (2005) Research on the improvement of rail head hardening. Technology on railway. *Proc. of the Eastern Asia Society for Transportation Studies*, **5**, 263–271.
16. Slukhotsky, A.A., Ryskin, S.G. (1974) *Inductors for induction heating*. Leningrad, Energiya [in Russian].
17. Rezanov, V.M., Fedin, A.V., Bashlykov, A.V. ((2013) Differential hardening of rail welded joints. *Vestnik VNIIZhT*, **2**, 28–34 [ in Russian].
18. Shamov, A.N., Bodazhkov, V.A. (1963) *Design and operation of high-frequency installations*. Moscow, Leningrad, Mashgiz [in Russian].
19. Bar, I.G., Polevoj, S.V. (1989) *Repair of live overhead power lines*. Moscow, Energoatomizdat [in Russian].

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