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Advanced Manufacturing Technology of Rails Intended for Operation in the High-Speed or Heavy-Haul Traffic Environment

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Abstract. Expanding the railway domain fit for train operation at speeds up to 200–250 kph, construction of high-speed lines intended for train operation at speeds up to 400 kph and setting heavy-haul traffic pattern on the main routes of the JSC RZD network suppose introduction of new generation rails, manufactured with use of innovative production procedures.

The paper contains technical requirements to straightness and profile fidelity of rails intended for operation in the high-speed traffic environment.

Relying on evaluation experience of metallic matrix structure and service durability of railway rails, acquired through the semicentennial period, there have been formulated requirements to rail structure and residual stresses aimed at extending the rails' service life.

As related to 800 m long CWRs it was proposed to turn from traditional production pattern represented as "hardening of 25-m or 100-m rails — cold straightening — welding — local heat treatment of welded rail joints" to an innovative one which may be described as "cold straightening of hot-rolled 100-m rails — welding — heat treatment throughout the CWR length". The new production pattern will allow for gaining such advantages as:

More favourable diagram of residual stresses in the rail head

Lesser length of "soft" portions with lower wear resistance and crushing strength in the weld adjacent zones ranging from 60 to 6 mm, eliminating at those portions the possibility of increased vehicle wheels dynamic impact and emergence of irregularities

Higher impact hardness/crack strength and larger critical fatigue crack size as compared with direct quenching pattern

In the technological context realization of the desired structural condition in the course of rail heat treatment is achieved through sequential induction volume heating of every cross-sectional area of the processed rail (inclusive of welds' cross-sections) and subsequent cooling performed so as to obtain highly dispersed sorbite structure in the 20-mm deep rail head surface layer. Rail straightness is retained due to controlled cooling-down treatment of its base. The developed humidity control procedure of the cooling air medium allows to omit (due to increase in the air flow cooling rate) chromium alloying of steels thus contributing to higher economic efficiency of the process.

Thuswise produced heat treated CWRs will have interrepair resource of no less than 1,500–2,000 MGT in terms of regular preventive grinding and milling.

Keywords: heat treatment; welded rail joints; microtexture uniformity; hardness

Extension of the high-speed traffic domain to be operated at train speeds up to 200–250 kph, construction of high-speed lines permitting train running at speeds up to 400 kph, setting operations of speeded-up container trains and extending the total length of high-freight-density sections with heavy-haul traffic operations pattern implying high axle and per-unit-length loads form the strategic development area of Russian railways.

Fig. 1. Trace of the wheel-rail contact, characterizing geometric parameters of home-made (*a*) and Japanese (*b*) rails

Achievement of the listed goals is impossible while using the existing 25-m volumetrically-thermostrengthened Category OT350 rails with hardness slightly exceeding HB 350 and poor geometric quality, which are welded by electric resistance (electrocontact) method widely practiced on the Russian railways. Such rails are incompatible with high-speed traffic operation pattern primarily because of their low straightness (especially at the ends) and too wide profile size tolerance.

Fig. 1 represents photos of contact traces resulting from interaction of rolling stock wheels with home-made and imported rails [1]. Such traces may be treated as comprehensive indicator of the rails' geometric quality (especially in the starting period of their service). It's evident from the photo that there exists a rather notable difference between

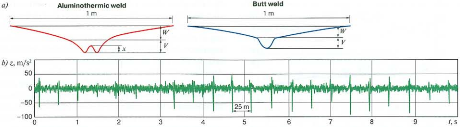

Fig. 2. An example of accelerations on the axle-box, recorded in the high speed train Sapsan movement over a tangent track segment at a speed of 200 kph [3]

the home-made and imported rails when it comes to continuity of the traces under consideration along the rail length.

While comparing geometric quality of existing home-made rails and welds, it becomes evident that in the latter case things are even in a worse way. Manual grinding at the welds' locations leads to emerging various combinations of tuberosity and stains. In the course of operation, changes in microstructure uniformity within the weld-adjacent and heat-affected zones resulting from welding and subsequent local heat treatment causes increased wear rate as well as saddling and shelling and in the weld area.

In Fig. 2 there are represented typical examples of irregularities in the weld joint zone (*a*) [2] and an example of accelerations on the axle-box, recorded in the high speed train Sapsan movement over a tangent track segment at a speed of 200 kph (*b*) [3]. In the record one can see acceleration bursts due to geometric irregularities at all the weld joints spaced at a distance of 25 m. These result in increase of dynamic impact on railway track on the one hand, causing its deterioration, and on rolling stock on the other hand, reducing its durability. Also such an impact leads to worsening of passenger comfort conditions in trains.

The use of Category OT350 rails on high-freight-density sections with heavy-haul traffic operations pattern implying high axle and per-unit-length loads is hindered with the rails' insufficient service resource measured in gross tonnage throughput. In remains insufficient even with improved purity of rail steel due to introduction at metallurgical complexes of secondary refining, degassing, continuous casting and other innovations. As a rule, at the RZD network rails' tonnage throughput before complete replacement ranges from 300 to 1,000 mln gross tonnes depending primarily on curvature of corresponding track segment and on the volume of reconstruction/overhaul wherein new rails are laid in track. The more is repair volume on the new rails, the less may be tonnage throughput at which these rails are removed (Fig. 3). Average tonnage throughput at railway sections knowing overhaul and reconstruction is slightly more than 600 mln gross tonnes. Such a resource of the rails, intended for high-freight-density sections with heavy-haul traffic operations pattern implying high axle and per-unit-length loads, must be 1.5–2 times higher.

Rails' service resource is limited by their incapacitation with increase in the tonnage throughput due to various defects and wear. And in this context situation with weld joints is much less favourable than it is with rails themselves. During the recent ten-year period annual rails' removal as a whole has been kept nearly constant. However annual rails' removal by the weld joint zone defects has been increasing steadily (Fig. 4). In 2002 such defects amounted to only 4.1% of the total rail defects, but in 2012 their respective share reached 6.4%. This may be explained with increase in the CWR track length by about 30,000 km for the period under consideration on the one hand and with the fact that welds remain trouble spot of railway track (weld breakages share in the rail breakages total is more than 33%, exceeding 90% in the tonnage throughput interval up to 100 mln gross tonnes).

Basic technical requirements to rails intended for operation in the high-speed traffic environment relate to their straightness and profile accuracy. Home-made rails meet these requirements for the most part [4]. Permitted for Class X rail profile deviations of cross-section dimensions and shape may be listed as follows:

- Rail height: ± 0.6 mm,
- Rail web height: ±0.5 mm,
- Rail head width: ±0.5 mm,

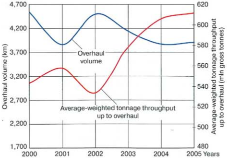

Fig. 3. Scope of overhaul and the rails' overhaul life in terms of tonnage throughput

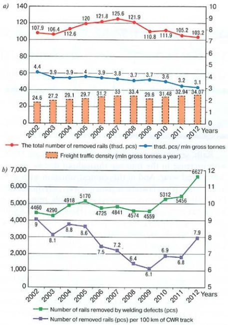

Fig. 4. General rails removal dynamics (*a*) and dynamics of rails removal by welding defects in the period of 2002 – 2012 (*b*)

- Rail web width: +1.0 – 0.5 mm,
- Rail base blade height: +0.75 – 0.5 mm,
- Wheel thread form deviation from the rated shape: +0.6 – 0.3 mm,
- Rail dissymmetry: ±1.2 mm,
- Rail base seating protuberance: 0.3 mm.

Admissible straightness errors of Class A rails amount to:

- For the rail's main part in vertical plane: 0.30 mm per 3 m and 0.20 mm per 1 m,
- For the rail's main part in horizontal plane: 0.45 mm per 1.5 m,
- For the rail's tail part up the vertical plane: 0.40 mm per 2 m and 0.30 mm per 1 m,
- For the rail's tail part down the vertical plane: 0.20 mm at the distance from the end butt to the downward bias beginning point of the rail's tail part: 0.6 m,
- For the rail's tail part in horizontal plane: 0.60 mm at 2 m and 0.40 mm per 1 m,
- For the whole rail: curvature at the ends 10 mm,
- For the whole rail: torsion twisting 2.5 mm.

On completing the construction of new rail-and-structural steel mills at the West-Siberian Metallurgical Plant in Novokuznetsk (JSC EVRAZ ZSMK) and Chelyabinsk Metallurgical Plant (JSC ChMK) with versatile mills, such technical requirements to rails operated in the high-speed traffic environment will be met as related to rolling of rails of the length 100 m. Technical requirements stipulated in [5] to the weld joints' geometry at railway sections with high-speed traffic pattern, require maximum deviation of 0.20 mm per 1 m in vertical and horizontal planes. Capability of fulfilling such a requirement gives rise to doubts even with zero tonnage throughput, appearing absolutely unreal when it reaches the level of several hundreds of millions gross tonnes. Thus weld joint adjacent zones are weak spots of rail track whether it be railway section with high-speed or heavy-haul traffic pattern. The reasons lay in changes of the microstructure uniformity in the weld adjacent and heat-affected zones, formation of unfavourable residual internal stress diagram, development of welding process-instigated defects becoming stress concentrators and weakening rail segment with a weld as well as in rail warping in the weld adjacent zone followed with formation of "saddles" in the course of rail operation.

Manufacturing rails with service resource amounting to 1,500 – 2,000 mln gross tonnes is possible only in terms of comprehensive optimization of their metallurgical quality, metal matrix structure, residual stress diagram and straightness (rectilinearity) [6,7]. High metallurgical quality of rails is primarily associated with the absence in them of clustered or large individual brittle-fractured oxidic non-metallic inclusions due to low content in rail steel of aluminium (less than 0.004%) and oxygen (less than 20 ppm of the total and less than 10 ppm of the fixed one bound into the oxidic high-aluminous inclusions).

Based on the experience in estimation of metal matrix structure and service durability of railway rails [7], accumulated for the late 50 years, there have been laid down the following qualitative principles of specifying requirements to structure aimed at maximum service resource extension of the rails:

- Rail head structure shall be single-type and to the great possible extent uniform throughout the stress effect depth with allowance for wear tolerance
- Pearlite interlamellar distances shall be minimal, not exceeding 0.1 μm
- Occurrence of carbides in pseudo-eutectoid shall be maximal
- Occurrence in perlitic structure of grain boundary hypereutectoid cementite and bainite constituents is inadmissible and presence of free ferrite constituent — undesirable
- The size of actual austenitic grain in the matrix structure shall be minimal, not exceeding 20 – 60 μm

Requirements to residual stresses in rails, which must be compressive at all the rail head zones subject to contact-fatigue crack development, are imperative so far as initiation and proliferation of cracks is hindered with compressive residual stresses [8].

Of all the rails manufactured by the world leaders and subject to full-scale laboratory, rig and field tests at the VNIIZhT's Testing Center most closely met the aforementioned requirements production of Japanese company Nippon Steel mill in Yawata and Indian company Tata Steel mill in Hayange, North-East France. Conducted field tests demonstrated that 80-percent resource of these rails laid in the curve with radius about 600 m and operated under 27-t axle-load conditions accounted to 1,000 – 1,290 mln t, being larger by half than the same indice of the home-made rails.

Now under field tests at the VNIIZhT's Testing Center are Austrian rails rolled by Voestalpine Schienen mill (Leoben), US-manufactured rails of EVRAZ Rocky Mountain Steel Mill (Pueblo, Colorado) and Russian rails of the EVRAZ ZSMK. All of them belong to Category DT350, manufactured of high metallurgical quality vacuum degassed steel, rolled on versatile mills and subject to quenching from rolling heat. Their production procedures differ only by post-heat-treatment cooling methods. However in spite of employing all the world best solutions of rail rolling technology it's difficult to expect that service resource of these rails as determined in the course of the indicated field tests may be more than 1,000 mln of passed tonnes. There remain the following major drawbacks, contributing to reduction in the service life of these rails:

- Presence of residual stresses in the rail head, induced by the terminal technological operation of the production flow, namely by cold straightening on multiroller machines.
- Formation of "soft" areas with lowered wear resistance and crushing strength in the heat-affected zones after welding and subsequent local induction heat treatment of the welds leading to emergence in these areas of irregularities and increased vehicle dynamic impact exercised by wheels.
- Notable decrease in impact strength, cracking resistance and critical size of fatigue cracks under quenching from rolling heat (as compared with quenching from separated recrystallization heat).

It's possible to overcome all the listed drawbacks through developing and mastering CWR products of the length of 800 m fabricated by welding 100-m long solid-rolled rails and subsequent heat treatment through progressive feed heating of the whole rail's cross-section followed by differential cooling aimed at obtaining in the rail head sorbitic and fine-perlitic-sorbitic structure which must be maximum homogeneous as related to both solid-rolled rail and weld joint as in the absence of heat-affected zones thereof. Thus fabricated heat-treated CWR products must have inter-repair service resource no less than 1,500 – 2,000 mln gross tonnage throughput in terms of properly scheduled preventive grinding and shaping.

Such an approach is capable to ensure maximum possible strength uniformity of welded joints and solid-rolled rails, paving the way to obtaining long CWRs with uniform in-service wear resistance and crushing strength and thus contributing to risk elimination of emergence of CWR local irregularities throughout the rails' service life.

Besides it will make possible to obtain advantageous internal residual stress diagram, contributing to maximum increase in the resistance to contact-fatigue cracking in the rail head, corrosion-fatigue cracking in the rail base and longitudinal cracking in the rail web in both rolled and welded parts of CWRs.

Proper adjustment of differential CWR heat strengthening schedule and parameters allows to minimize post-heat treatment smelting process and retain internal residual compressive stresses. It's known that rails subject to progressive-feed inductive through heating and post-heat treatment differential compressed-air cooling on the side of the rail head and base at one of the Canadian enterprises (by now closed down) and Tata Steel mill in Hayange had residual compressive stresses in the head (ranging from 100 to 200 MPa) and in the base (from 100 to 150 MPa). Tensile stresses in the heads and bases of rails, heat-strengthened from rolling heat by way of differential quenching or bulk oil hardening from separated heat and further on exposed to cold straightening on multiroller machines, range from 150 to 200 MPa [9].

The results of the VNIIZhT's investigations [10] have shown that increase in residual tensile stresses in the R65 rail up to 150 MPa above the reference zero level leads to:

- 2.7-fold reduction in the number of loading cycles preceding crack initiation
- 4-fold reduction in the number of loading cycles preceding the rail fracture caused by crack development

These results also have indicated that application of separate hardening heat leads to growth of impact strength (1.4 – 2.0-fold), impact bending strength as determined on the impact testing machines (2-fold) cracking resistance (1.5 – 1.8-fold) and critical size of fatigue cracks (2.3 – 2.5-fold) due to obtaining fine grain and its recrystallization in the course of reheating.

Requited structural state of standard steel rail in the course of its heat treatment is achieved through successive heating of its every cross-section, inclusive of welds, up to the temperature level exceeding the finishing temperature of at-heat crystalline transformations and up to obtaining homogeneous austenite structure followed with successive post-heat treatment cooling of each indicated cross-section, inclusive of welds, to temperature level lower than the perlitic transformation finishing temperature of the given steel exercised in such manner as to obtain resulting 15 – 20 mm highly dispersed sorbitic structure within the rail head surface level.

Limited cooling capacity of air flow causes the necessity of rail steels slight alloying with chrome contributing to better hardness penetration. And this results in deterioration of the rail steel welding properties and undesirable rise in its price.

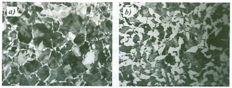

Fig. 5. Weld microstructure after differential heat treatment applied throughout the rail's length employing TEC-DTO technology (from separated induction heat) (*a*) and after local heat treatment (*b*) (× 500)

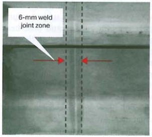

Fig. 6. Full-scale rail specimen with a weld joint after differentiated heat treatment applied throughout the rail's length

Research and production enterprise "Tomsk Electronic Company" (RPE TEC) developed humidity control technique of the cooling air contributing to acceleration of air flow cooling process and thus allowing to give up on chrome alloying of rail steels [10]. Codeveloping of induction plant TEC-DTO-13.6 by RPE TEC and Magnit-M, LLC was intended for differentiated heat treatment of rails with a separate induction heater allowed the manufacturers to implement throughout-the-length strengthening of welded rails. Therewith post-heat treatment cooling was carried out employing compressed air with controllable humidity.

The study under consideration employed rails manufactured by EVRAZ ZSMK of steel E76F, containing 0.79% C, 0.97% Mn, 0.39% Si, 0.08% V, 0.11% Cr, 0.015% P, 0.010% S, 0.004% Al, 0.0015% O and 0.014% N, with welded joints. Welding of specimens was carried out by a standard welding technique at the Rail-Welding Plant No 29 of Zapadno-Sibirskaya Railway.

Examination of hardness, macrostructure and microstructure within the welded joint zone in succession to heat treatment by the TEC-DTO technique demonstrated that the width of deferred hardness zone with changed microstructure abruptly diminished as compared with local heat treatment of welds. After local heat treatment weld adjacent zone is characterized with hypoeutectoid steel structure consisting of ferrite and perlite grains by virtue of burning-out of carbon and alloying agents in the course of welding. After throughout-the-length heat treatment this zone represents quasi-eutectoid structure with ferrite network (Fig. 5). After local heat treatment the width of such zone with changed microstructure and hardness amounted to 60 mm in the rail head and to 130 mm in the rail base, while after throughout-the-length heat treatment it was no more than 6 mm (Figures 6 and 7). Such reduction in lengths of welded joints' "soft" zones must lead to extinction of saddles' initiation over here in operation. At that hardness reduction value decreased from 110 to 20 HV. Reduction in hardness stems from decrease in carbon content straight in the narrow weld zone by virtue of its burning-out in the course of welding. Technological sample (cut along the web by the length of 400 mm in the sample as long as 600 mm) being rather sensitive to the value and distribution of residual stresses indicated closure of the slot instead of its traditional separation. This is a qualitative evidence of obtaining advantageous residual stress diagram under such heat treatment procedure. Optimization of residual stresses as well as achievement of the rails' sufficient straightness represents a wide field of further research activities.

Conclusion. Transition from traditional production pattern of 800 m long CWRs represented as "quenching of 100 m long rails — cold straightening — welding — local heat treatment of welds" to the new one described as "cold straightening of hot-rolled rails — welding — throughout-the —length heat treatment of CWRs" contributes to:

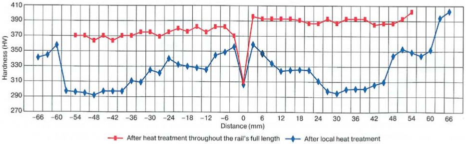

Fig. 7. Hardness distribution in the weld adjacent zone

- Obtaining advantageous diagram of residual stresses within the rail head
- Eliminating emergence of "soft" areas with reduced wear resistance and crushing strength in the weld adjacent zones prevents the initiation in such areas of irregularities and dynamic overimpact on the side of railway vehicles.
- Improving the CWR impact hardness, resistance to cracking and critical size of fatigue cracks as compared with quenching from rolling heat.

Thus fabricated heat-treated CWR products must have inter-repair service resource no less than 1,500 – 2,000 mln gross tonnage throughput in terms of properly scheduled predictive grinding and shaping.

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