doi: 10.18720/MCE.75.9

Performance characteristics of differentially quenched rails

Эксплуатационные показатели дифференцированно термоупрочненных рельсов

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Key words: rails; differential quenching; wear; rate of wear; curves of small radius

Ключевые слова: рельсы; дифференцированное термоупрочнение; износ; интенсивность износа; кривые малого радиуса

Abstract. With the development of railway transport, the train speed, the traffic intensity, and the axle load all permanently increase in magnitude. This increase adversely affects the rail operation. The quantity of rail defects and, especially, the rate of rail-head surface wear both show an increase. Such service conditions require an enhanced mechanical strength of rails, their enhanced resistance to wear, and prolonged service life. In the present study, we analyze the operation performance of modern differentially quenched rails in comparison with domestic volume-quenched rails and Nippon Steel rails (Japan). For evaluating the wear resistance of rails, in the present study we carried out measurements of their side wear at curves of small radius. As a result of the study, it was found that the resistance to wear of differentially quenched DT350 rails 1.5–1.7 times exceeded the resistance of volume-quenched T1 rails. The general-purpose DT350 rails and the advanced DT370IK rails with enhanced wear resistance and enhanced contact endurance exhibited roughly identical wear rates and therefore offered equally long service periods. The Nippon Steel rails have displayed a greater resistance to wear. The side wear of those rails was found to be 1.6 times smaller than that of DT rails, and it met the normative value for surveyed curves of small radius.

Аннотация. С развитием железнодорожного транспорта скорость, интенсивность движения и нагрузка на ось возрастают. Это неблагоприятно сказывается на рельсах. Возрастает количество дефектов и особенно износ поверхности головки рельсов. Такие эксплуатационные условия требуют увеличения прочности и износостойкости рельсов, повышения их срока службы. В настоящей работе проведен анализ эксплуатационной работы новых дифференцированно термоупрочненных рельсов в сопоставлении с рельсами объемного термоупрочнения отечественного производства и японскими рельсами компании "Ниппон Стил". Для оценки износостойкости рельсов проводились измерения бокового износа головки рельсов в кривых малого радиуса. В результате исследования было установлено, что рельсы дифференцированного термоупрочнения категории ДТ350 более износостойки, чем рельсы объемного термоупрочнения категории Т1 в 1,5–1,7 раза. Рельсы общего назначения категории ДТ350 и повышенной износостойкости и контактной выносливости ДТ370ИК имели примерно одинаковую интенсивность износа и срок службы. Большей износостойкостью обладали рельсы компании "Ниппон Стил". Их интенсивность бокового износа в 1,6 раза меньше, чему у рельсов категории ДТ и соответствовала нормативному показателю для исследуемых кривых.

Introduction

The traffic safety, and the transportation continuity and efficiency at railway transport, largely depend on the state of track structure and, in particular, on the state of rails. The capital investments in rails come as the most expensive part of infrastructure fixed assets. These factors define the necessity for strengthening the requirements to rail service properties. The latter properties are in turn defined by the service life, reliability, safety, and maintainability indexes of rails.

As early as several years ago, JSC "RZD" railroads involved no world-class rails capable of meeting the company’s increasing requirements to rails in terms of service life as well as in terms of the strategic development objectives and tasks of the industry.

Косенко С.А., Акимов С.С. Эксплуатационные показатели дифференцированно термоупрочненных рельсов // Инженерно-строительный журнал. 2017. № 7(75). С. 94–105.

The latter statement is corroborated by the annual withdrawal of more than 100 thousand defective and faulty rails from tracks. The main cause for this withdrawal was insufficiently high a contact fatigue strength (for more than 50 % of withdrawn rails) [1].

The situation has begun to change dramatically after 2013. The implemented grand-scale reconstruction, and technical re-equipment and modernization of rail production at JSC "EVRAZ ZSMK" and JSC "Mechel" have allowed the companies to master state-of-the-art technologies. A key point in the realization of the implemented technology has become the production of 100-m long differentially quenched rails. The quality and characteristics of the new rails fully meet the European requirements [2] and the Russian national standards GOST R 51685-2013 [3].

A weak point of the previous rail manufacture technology was considerable residual internal stresses occurring in the rails. The occurrence of such stresses is related with imperfect rail quenching, which process defines the mechanical and working characteristics of rails [4]. Considerable hardening strains emerge in rails during the volume quenching of rails in oil implemented in drum hardeners. Subsequent rail strengthening leads to the emergence of considerable residual stresses [1, 5].

A.D. Konyukhov and E.A. Shur [6] have shown that the increase of residual tensile stresses to 150 MPa from 0-MPa conventional level leads in R65 rails to a reduction of the number of cycles to crack formation by a factor of 2.7, and to a reduction of the number of cycles to fracture by crack development by a factor of 4.

The rail differential quenching technology using compressed air is free of this drawback. In the post-quench cooling process, there exists a possibility to regulate both the airflow rate and air pressure in the rail-head and rail-base quenches. In this way, the rail buckling can be minimized (i.e., reduced by a factor of 4.3).

The reliability indexes of rails fabricated by the new technology proved to be 50 % increased. Indeed, whereas the rails manufactured by the previous technologies were capable of ensuring an 80-% gamma resource on handling the freight volume of 500 mln gross tons, the new rails has proven to be capable of ensuring a 85-% gamma resource on handling the freight volume of 750 mln gross tons. Field tests performed by JSC "VNIIZhT" have shown that the failure-free load life of the new rails exceeded 600 mln tons, this value being 2.5 times greater than the failure-free load life of volume-quenched rails [7].

To date, more than 1.5 million tons of DT rails have been already supplied to the JSC "RZD" railroad network [8].

The laying of new DT rails, including their laying at the West-Siberian Infrastructure Directorate (WSID), began in 2014. Since then, the length of laid rails has reached 751.6 km; this value presently amounts to 8 % of the total length of main lines. The annually laid volumes of DT rails are shown in Figure 1.

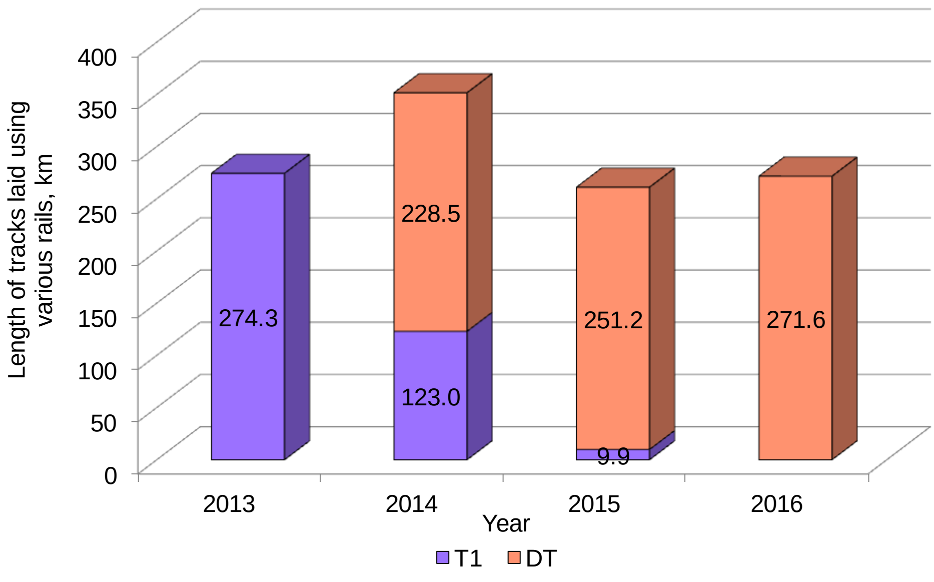

Figure 1. Annually laid volumes of T1 and DT rails at WSID

Of this volume, 646.4 km of track rails were rails replaced during track modernization and continuous rail replacement accompanied with mid-level track maintenance works. During the target replacement of high rails on curved tracks, 105.2 km of track rails were laid.

A diagram illustrating the laying of DT350 rails of total length 741.4 km at the WSID polygon with breakdown by curve radii is shown in Fig. 2. A main portion (84 %) of those rails was laid in straight track sections and curved track sections of radius 650 m and over.

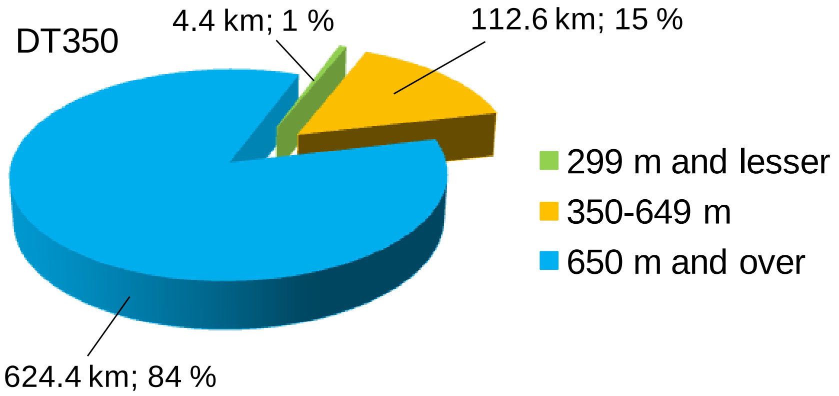

Figure 2. Laid volumes of DT350 rails versus curve radius at WSID

In 2015, the laying of DT370IK rails with enhanced resistance to wear has begun. However, a low fraction of special-purpose rails deserves mention. To date, 9.8 km of track rails was laid, this length amounting to 1.5 % of the total length of the DT rails laid. The laying of DT rails was performed by a target program in curved track sections (Fig. 3).

From Figure 3, it is seen that most of rails with enhanced resistance to wear (more than 60 %) were laid in the range of curve radii from 350 to 649 m.

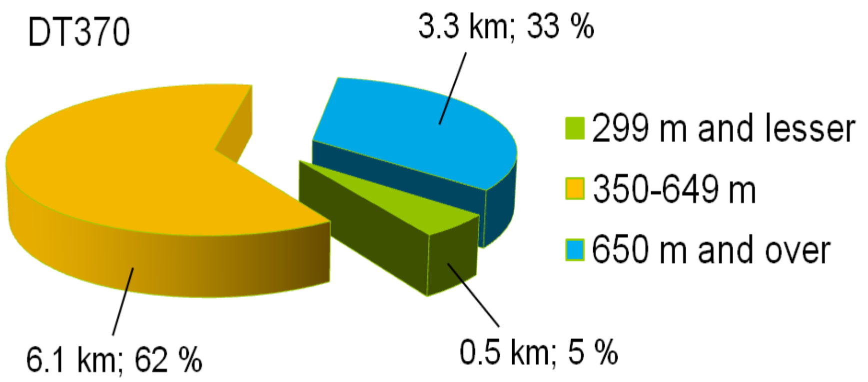

Figure 3. Laid volumes of DT370IK rails versus curve radius at WSID

With the passage from volume-quenched to differentially quenched rails, a possibility to evaluate the difference between the new rails in terms of their quality and functional reliability has emerged. The wear of the wheel–rail system is one of the most high-cost problems for railroads [9–12] and, in particular, for track facilities. This circumstance is primarily related with railway traffic safety and maintenance planning [13].

From the tribilogical standpoint, the rail wear is defined as any damage caused to rails related with the gradual loss or displacement of materials from the wheel-rail interface [14].

Numerous studies have shown that the wheel/rail wear depends on the slip along and, especially, across, the direction of wheel rolling on the rail, on the track curvature, on the load exerted on rail, on the train speed, on dynamic actions, on wheel/rail material properties, and on the environmental conditions and contaminations [5, 15–17].

In this connection, the purpose of the present study was an evaluation and performing a comparison of the operation performance of differentially quenched rails with that of volume-quenched rails and Nippon Steel rails (Japan) in curves of small radius.

The following tasks were posed:

1. Choice of reference track sections laid with rails of different types yet functioning under similar operating conditions (curve radius, track layout);

2. Measurement of rail side wear in round curves and determination of the rate of this wear;

3. Plotting the dependences of side wear values and side wear rates on the hauled gross tonnage with single-factor regression equation.

4. Prediction of the service lives of the various rails with evaluation of the service durability of differentially quenched rails.

Methods

For performing a comparison between T1, DT350, DT370IK, and Nippon Steel rails, reference track sections in curves of radii 350 to 390 m between the Izdrevaya and Sokur station, 1-st main line, were put under observation. For evaluating the rail service lives, rail-head side wear measurements were performed. The side wear comes as the main factor to limit the service life of rails at small-radius curves [18]; the mechanism of this limitation depends on many other factors [19].

The measurements were carried out over the entire length of round curves in 4-m steps along the thrust line. For excluding measurement inaccuracies, the measurement stations were marked with white paint on rail web.

For determining the rail side wear and side wear rate, initially we measured and evaluated the actual mean width of the rail head of new rails laid in curved track sections. This was made in connection with the rail production tolerance (± 0.5 mm).

The difference between the measured rail head width of a new and worn-out rail gives the rate of side wear:

$$\Delta B = B - b_1, \tag{1}$$

where ΔB is the rail side wear rate, B is the rail head width of a new rail at a distance 13 mm from the tread surface, and b_1 is the rail head width of the worn-out rail at a distance 13 mm from this surface.

From measured data, the average rail side wear over the whole length of the round curve was determined:

$$\Delta B_{avg} = \frac{\sum_{i=1}^{n} \Delta B_i}{n}, \tag{2}$$

where ΔB_{avg} is the mean rail side wear value, $\sum_{i=1}^{n} \Delta B_i$ is the sum of measured rail side wear values over the entire round curve, and n is the total number of performed measurements.

Given the tonnage hauled over the period from rail laying to the time of regular side wear measurement, we can determine the side wear rate:

$$\beta = \frac{\Delta B_{avg}}{T}, \tag{3}$$

where β is the side wear rate, T is the tonnage hauled over the period from rail laying in the curve to the side wear measurement.

The rail-head width measurements were performed with a "Puteets" sliding caliper and an SKIG-1 rail-head wear meter at a distance of 13 mm from the treed surface.

Results and Discussion

Some characteristics of the first reference track on which the operation of T1 and DT350 rails was monitored are listed in Table 1.

Table 1. Characteristics of T1- and DT350-rail reference tracks No. 1

Stage, line	**Izdrevaya – Sokur, 1-st main line**
Kilometers	17 km Hundred-Meter Mark 6 – 18 km Hundred-Meter Mark 4
Gross freight traffic, mln tons/ km per year	78.2
Curve radius, m	353
Track profile, promille	10.5
Elevation of outer rail in the curve, mm	90
Velocity of passenger/freight trains, km/hour	0/60

Based on the obtained experimental data, we have plotted diagrams of side wear (Fig. 6) and side-wear rate (Fig. 7) with their respective approximating functions.

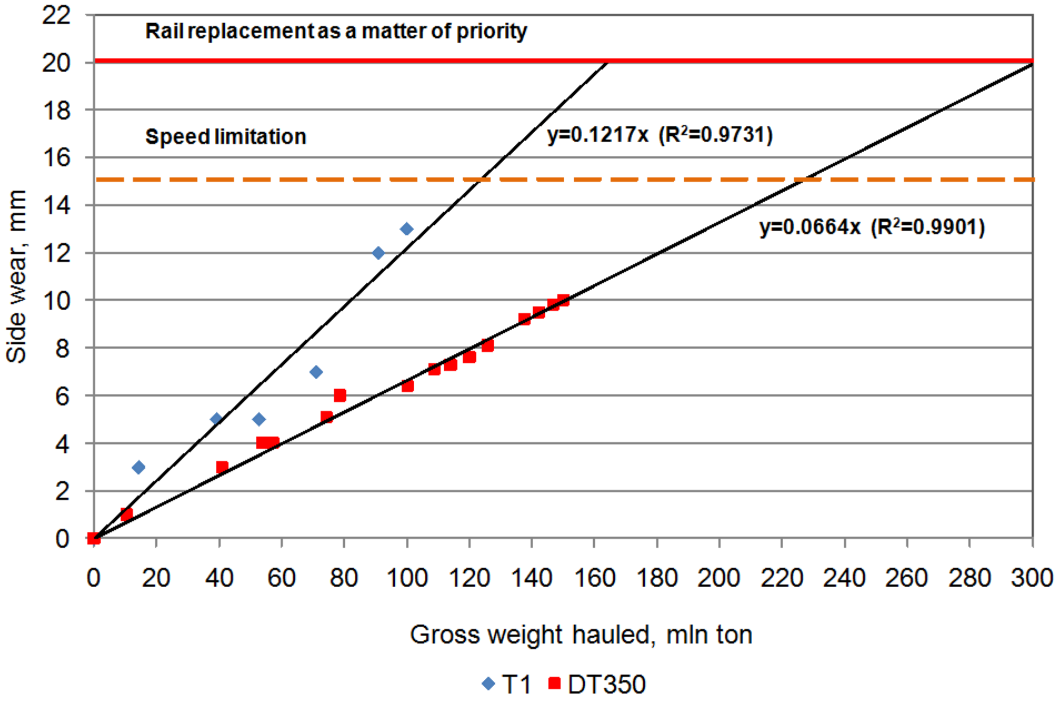

Figure 6. The side wear of T1 and DT350 rails in a curve of 353-m radius (high rails)

For the hauled gross tonnage of 100.1 mln tons, the T1 rails were found to exhibit a 13-mm side wear. After the same hauled tonnage, the wear of DT350 rails has proven to be 6.4 mm, this value being 51 % smaller than that of T1 rails.

A linear approximation to the rail side wear values yields a prediction that the load life of T1 and DT350 rails to the formation of 15-mm wear will amount respectively to 123.3 and 225.9 mln gross tons.

At rail-head side wear values of R65 rails exceeding 15 mm, the train speed is to be restricted to 70 km/hour at curve radii in excess of 350 m and to 50 km/hour at curve radii of 350 m and smaller [20]. Moreover, the re-laying of rail bars with rail edge alteration is to be made on the condition that the maximum side wear does not exceed 15 mm [21].

The rail load life to the formation of 20-mm side wear, over which the rail is to be considered defective and needing to be replaced as a matter of priority [20] is 164.3 mln gross tons for T1 rails and 301.2 mln gross tons for DT350 rails. Thus, the service life of DT350 rails in the surveyed curve is expected to be 1.8 times longer than that of T1 rails.

The mean side wear rate of T1 rails proved to be 0.113 mm/mln gross tons. The same characteristic of DT350 rails proved to be lower, equal to 0.065 mm/mln gross tons. On the average, the side wear rate of DT350 rails on the surveyed curve was 42 % lower than that of T1 rails.

The wear of DT350 rails has proven to be more uniform. The mechanisms of the wear during the breaking-in of wheel with a new rail differ from the mechanisms of wear at the main operation stage of the wheel-rail pair. Right after the laying of the rails, a high rate of their side wear is observed. After the transmission of 10–15 mln gross tons, the wear rate reaches saturation due to the breaking-in of rails with stock wheels with the formation of a conformal contact.

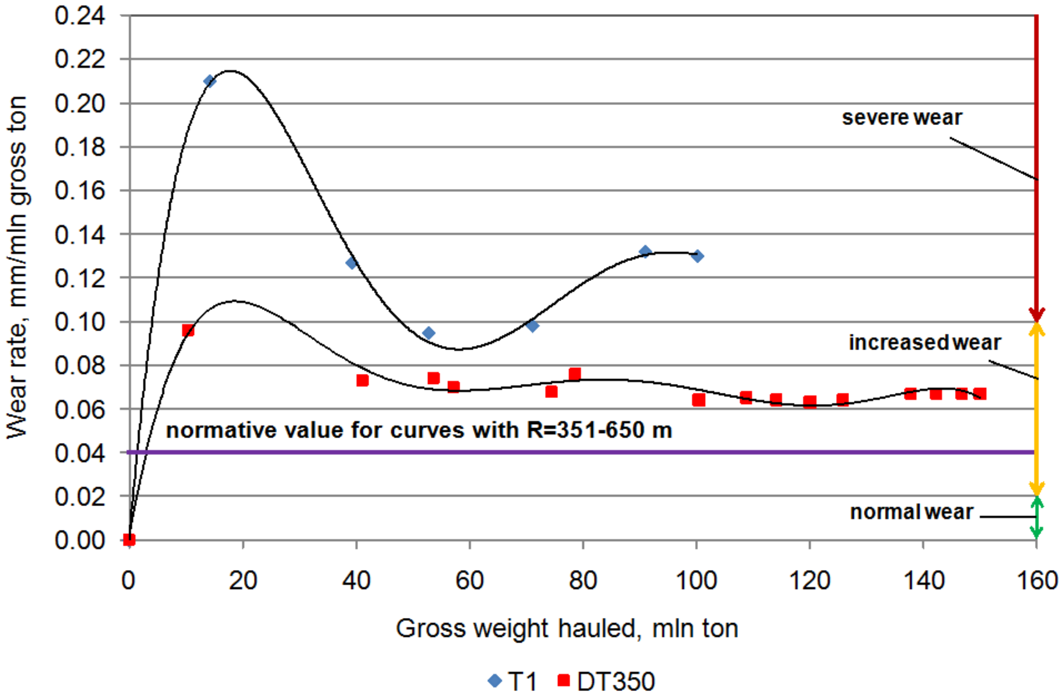

Figure 7. The side wear rate of T1 and DT350 rails in a curve of 353-m radius

The characteristics of the second reference track on which performance characteristics of T1 and DT350 rails were monitored are listed in Table 2.

Table 2. Characteristics of T1- and DT350-rail reference tracks No. 2

Stage, line	**Izdrevaya – Sokur, 1-st main line**
Kilometers	18 km Hundred-Meter Mark 6 – 19 km Hundred-Meter Mark 5
Gross freight traffic, mln tons/ km per year	78.2
Curve radius, m	390
Track profile, promille	4.7
Elevation of outer rail in the curve, mm	85
Velocity of passenger/freight trains, km/hour	0/60

On the basis of obtained data, similar diagrams of side wear and side-wear rate were plotted; those diagrams are shown in Figs. 8 and 9.

On the second curve of radius 390 m, at identical hauled tonnages the DT350 rails have also shown a side wear smaller than that of T1 rails. For instance, at a hauled gross tonnage of 123.0 mln tons a side wear of 12.0 mm was registered for T1 rails, whereas the DT350 rails have displayed a 10-mm wear, the latter value being 17 % lower than the former wear.

On this curve, the predicted load life to 15-mm rail-head side wear is 140.1 mln gross tons for T1 rails and 195.8 mln gross tons for DT350 rails. The predicted rail load life to the formation of 20-mm critical side wear is 186.7 mln gross tons for T1 rails and 261.1 mln gross tons for DT350 rails. Thus, the service life of DT350 rails in the surveyed curve is 1.4 times longer than that of T1 rails. The latter factor is somewhat smaller than the factor value obtained on the first reference curve.

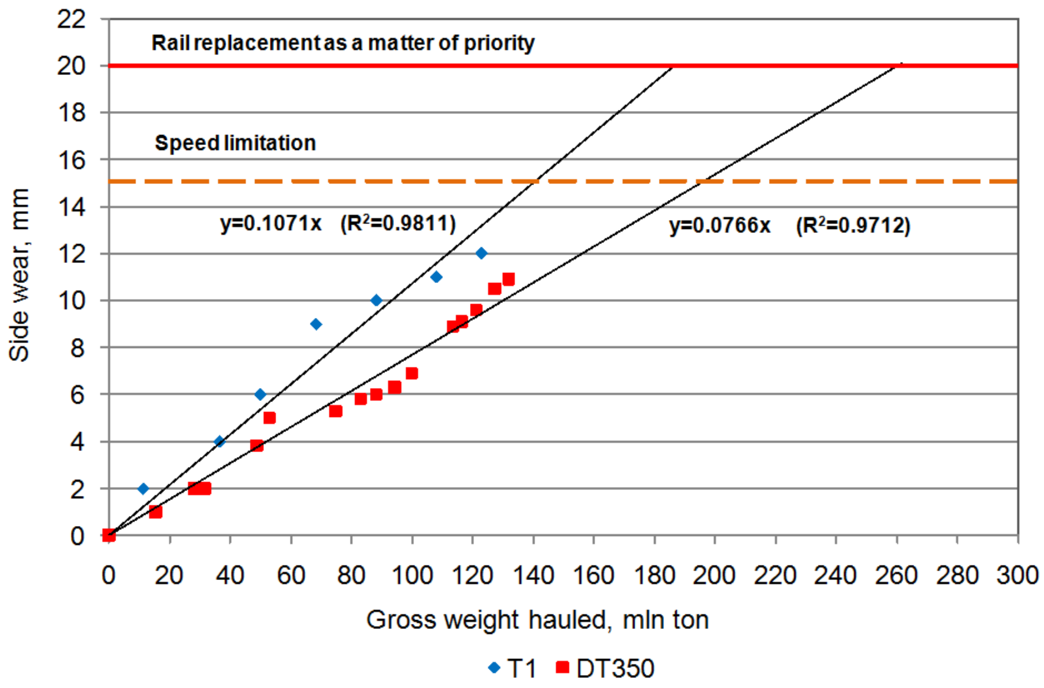

Figure 8. The side wear of T1 and DT350 rails in a curve of radius 390 m (high rails)

The mean side wear rate of T1 rails was found to be equal to 0.106 mm/mln gross tons. For DT350 rails, the same characteristic proved to be 0.070 mm/mln gross tons. The mean rate of wear of DT350 rails on the surveyed curve of radius 390 m and smaller is 34 % lower than that of T1 rails.

On both curves, of radii 353 and 390 m, the volume-quenched T1 rails exhibited a severe (by the classification of [5]) wear of the side surface of high rails. Here, the wear rate exceeds 10 mm/mln gross tons (Figs. 7 and 9). The wear of differentially quenched rails is classified as an increased one, corresponding to the interval of 2 to 10 mm/mln gross tons.

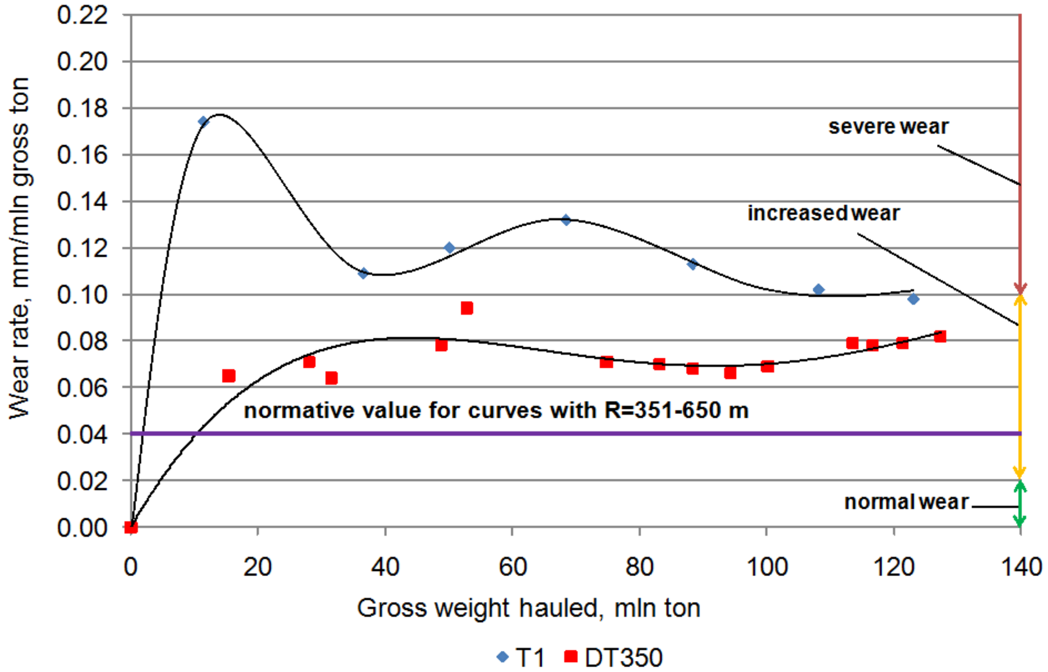

Figure 9. The side wear rate of T1 and DT350 rails in a curve of 390-m radius

For comparison of domestic general-purpose DT350 rails and domestic special-purpose DT370IK rails with Nippon Steel rails, we have monitored the operation of the rails on curved track sections with similar characteristics (Table 3).

Table 3. Characteristics of reference DT350- and DT370IK-rail tracks

Stage, line	Izdrevaya – Sokur, 1-st main line	
Kilometers	18 km Hundred-Meter Mark 6 – 19 km Hundred-Meter Mark 5	26 km Hundred-Meter Mark 6 – 27 km Hundred-Meter Mark 4
Gross freight traffic, mln tons/ km per year	78.2	
Rail category	DT350	DT370IK, Nippon Steel
Rail fastening	KB-65	
Curve radius, m	390	392
Track profile, promille	4.7	7.7
Elevation of outer rail in the curve, mm	85	87
Velocity of passenger/freight trains, km/hour	0/60	

Using the measured values of the rail-head widths for the various rails, diagrams of side wear and side-wear rate were plotted (see Figs. 10 and 11).

From the side-wear diagram of Fig. 10, it is seen that, at identical hauled tonnages, the general-purpose DT350 rails and the advanced DT370IK rails with enhanced wear resistance and enhanced contact endurance exhibited roughly identical values of side wear.

The Nippon Steel rails possess a greater resistance to wear. For the hauled tonnage of 105.8 mln gross tons, the side wear of DT370IK rails proved to be 8.30 mm. For the hauled tonnage of 107.6 mln gross tons, the side wear of Nippon Steel rails was found to be 3.97 mm, the latter value being twice smaller than the wear of DT370IK rails.

By analyzing the diagrams, one can compare the service life periods of the Russian and Japanese rails laid in the surveyed curves. The obtained values are summarized in Table 4.

The Japanese rails offer a longest service life. Before the emergence of 20-mm critical side wear, those rails can pass 413.2 mln gross tons, the latter weight being 1.6 times heavier than the weights that can be passed by DT350 and DT370IK rails.

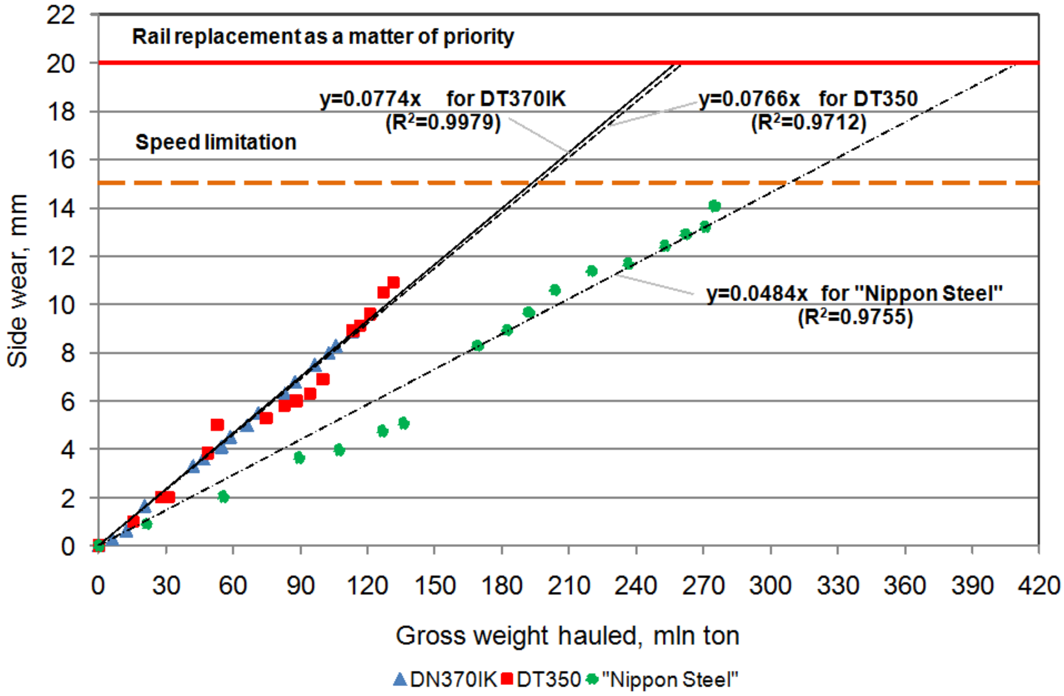

Figure 10. The side wear of DT350, DT370IK, and Nippon Steel rails on curves of 390- and 392-m radii

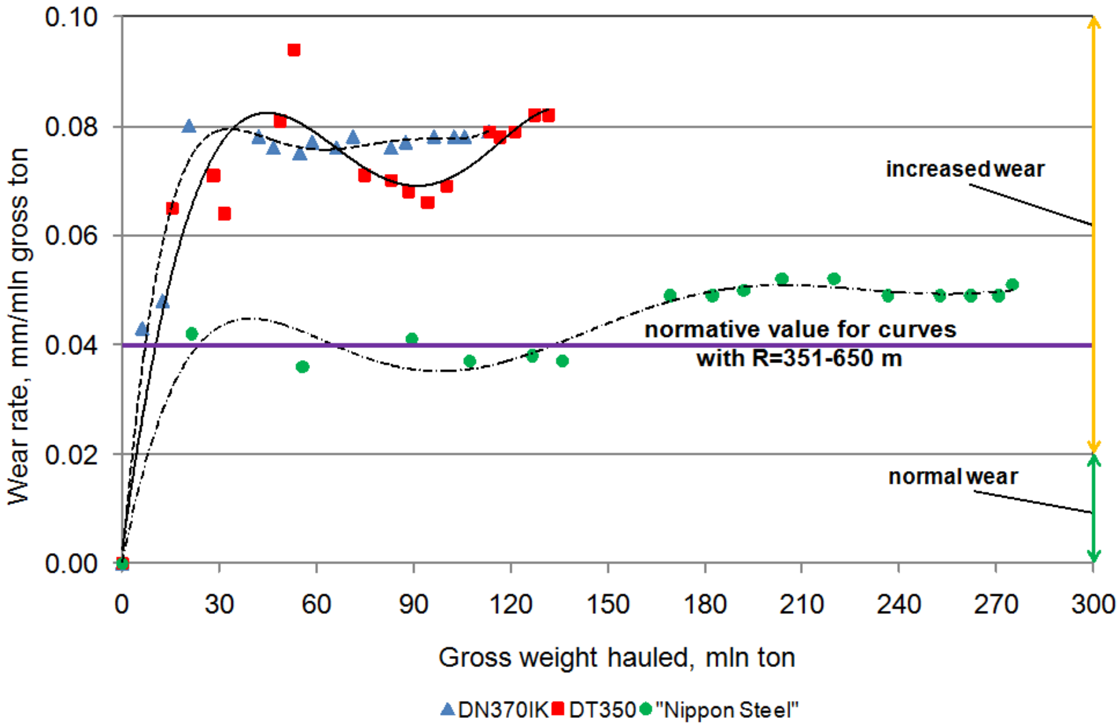

Figure 11. The side wear rate of DT350, DT370IK, and Nippon Steel rails on curves of 390- and 392-m radius

Table 4. Service life of Russian and Japanese rails for a curve of 390-m radius

Rail category	Mean side wear rate, mm/ mln gross tons	Load life, mln gross tons	
		to 15-mm side wear	to 20-mm side wear
DT350	0.070	195.8	261.1
DT370IK	0.069	193.8	258.4
Nippon Steel	0.043	309.9	413.2

The mean side wear rate of DT350 rails proved to be 0.070 mm/mln gross tons, and that of DT370IK rails, 0.069 mm/mln gross tons. It should be noted here that DT370IK rails are special-purpose ones, intended for laying heavy-traffic lines involving a multitude of small-radius curves. Following the transmission of 15 mln gross tons, those rails exhibit a more uniform rate of side wear.

The Nippon Steel rails also exhibit a uniform rate of side wear of their heads over the entire service life period. The mean side wear rate of Nippon Steel rails proved to be 0.043 mm/mln gross tons. Like for DT350 and DT370IK rails, the latter wear is classified as an increased wear. Yet, this indicator proved to be most closely meeting the rail quality standard in terms of side wear rate, 0.04 mm/mln gross tons, as recommended by JSC "RZD".

Prolongation of the service life of rails and other superstructure components presents an important strategic task for JSC "RZD" [22]. Ways toward the accomplishment of this task have been identified. This will allow prolongation of inter-repair periods and a reduction of the company operating costs.

A significant step toward the prolongation of the service life period of rail steels is the enhancement of rail-steel quality and the passage to long-length rails. Presently, the Central Infrastructure Directorate of JSC "RZD" has several times increased the order for 100-meter rails. Such rails were laid to form about five thousand kilometers of track.

For prolongation of rail service life, the current trends dictate further increase of rail resistance to wear.

Also, it is required to implement an optimal rate of rail side wear using lubrication and periodic rail grinding [23, 24]. This will exclude a necessity of early rail replacement by excessive side wear and, simultaneously, suppress the contact fatigue cracking [5, 15].

The desired value of the resistance of rails to wear can be obtained by raising the hardness of rail materials [25]. In view of the fact that the possibilities offered by pearlitic metal structure have proven to be nearly exhausted, it would be advantageous to use rails with the bainitic structure. Bainitic rail steels were examined in comparison with pearlitic rail-steel structures by E.A. Shur [5], H. Yokoyama [26], and by other workers. Bainitic rail steels exhibit higher fatigue-strength values, and they show fracture-toughness values nearly two times increased in comparison with pearlitic rail steels [10].

The use of bainitic steels in the production of rails with a load life of up to 2 bln gross tons was prospected in [22]. In combination with the differential quenching technology, this will enable the production of rails with high service durability.

Besides, a substantial contribution to the prolongation of the service life of rails and that of the whole track superstructure will be gained due to JSC "RZD" measures aimed at the improvement and prolongation of the guaranteed load life of spring rail fastening components to 1.5 bln gross tons.

Conclusions

From the performed study, the following conclusions can be drawn:

1. The modern differentially quenched rails possess a better service durability in comparison with volume-quenched rail and a lower service durability in comparison with Nippon Steel rails: the side wear rate of DT350 and DT370IK rails is 1.5 – 1.7 times lower than that of T1; yet, it is more than 1.5 times higher than the side wear rate of the Japan rails.
2. The load life of the differentially quenched rails to the formation of the maximally admissible 20-mm side wear is 29 % (in a curve of 353-m radius) and 45 % (in a curve of 390-m radius) greater than that of the T1 rails; simultaneously, it 27 % (in a curve of 353-m radius) and 36 % (in a curve of 390-m radius) lower than the load life of strings welded from the Japan rails.
3. In curved tracks, the T1 rails exhibit an extremely gross wear (in excess of 10 mm/mln gross tons), whereas the DT350, DT370IK, and Nippon Steel rails, an accelerated wear (2–10 mm/mln gross tons).
4. In a curve of 390-m radius, the general-purpose DT350 rails and the advanced DT370IK rails with enhanced wear resistance and enhanced contact endurance have demonstrated roughly identical wear rates.

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Kosenko S.A., Akimov S.S. Performance characteristics of differentially quenched rails. *Magazine of Civil Engineering*. 2017. No. 7. Pp. 94–105. doi: 10.18720/MCE.75.9.