Study of the influence of thermal treatment on the structure and mechanical properties of carbon rail steel

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Abstract. The article provides the results of investigation of the way various types of thermal treatment affect the microstructure parameters and mechanical properties of grade 76HF (R65) carbon rail steels produced by Russian and Japanese manufacturers and used for the production of R65 rails. We determined the optimal heat treatment conditions to provide an increased microhardness and wear resistance of rail steel.

1. Introduction
Currently, the problem of increasing the capacity of modern railways (RW) is one of the most relevant and complex tasks from a scientific and practical point of view [1-3]. Over the past decade, domestic electric railways have been actively using high-speed electric trains, the speed of which is 100-150 km/h higher than the speed of conventional railway trains. In addition, the project of creating high-speed highways (HSR) requires the creation of conditions that allow high-speed electric trains to move at a speed of 400-500 km/h. This leads to a significant tightening of the requirements for the mechanical properties of rail steels used for the manufacture of high-speed railways.

It is also important to emphasize that for the Northern and Far Eastern regions of the Russian Federation, heavily loaded container carriers remain the main type of railway transport. At the same time, specific features and complicated nature of the landscape of these regions often require railway tracks with curvatures exceeding standard limits. This imposes additional requirements on the strength, fatigue, and contact fatigue strength of rail steels [3].

The problem of developing highly reliable rail steels for HSR is limited by the lack of reliable methods for assessing the mechanical properties of steels that would be sensitive to the accumulation of microdamage during operation. Currently used traditional methods such as tensile tests or impact tests are not sensitive to the accumulation and development of failures in rail steels. Rail steels with the same strength characteristics and impact hardness often have significantly different operational reliability.

It is known [4] that a decrease in the interlamellar distance in pearlite grains (the average distance between cementite plates in pearlite) leads to an increase in hardness and strength, and, as a result, to an increase in resistance against abrasive wear. In accordance with the requirements of Russian Standard GOST R 51045-2014, the interlamellar distance in the plate pearlite in the microstructure of the head of the heat-strengthened rails should not exceed 0.6 μm. The microstructure of the head of heat-strengthened rails may contain small scattered ferrite sections with a volume fraction of not more than 5%. However, the presence of bainite is not permitted, due to its negative effect on the wear resistance of rail steels.
The aim of the work is to study the structure and properties of modern rail steels in various structural states, as well as to develop the optimal heat treatment modes that increase the mechanical properties of rail steels.

2. Materials and methods

To study the properties and structure of rail steel, we obtained the rail samples of Russian and Japanese origin (see table 1). We investigated samples cut from the rails in delivery and post-operational condition. Series 1-3 represent various casts of Russian steel. According to the chemical composition, steel samples correspond to Russian steel grade 76HF (see table 2). Samples of Russian steel grade U8 were used as the object of comparison.

| Series | Country | Tonnage, mln tons gross | Marking | No. of zone | Hv, MPa | Microstructure parameters | Microstructure type |
|--------|---------|-------------------------|---------|-------------|---------|---------------------------|---------------------|
| 1      | Russia  | 0                       | R-65, DT370 | 1           | 3455 ± 120 | Sorbite + coarse-lamellar pearlite | 12.2±1.4 185±36 7.4±1.2 |
|        |         |                         |         | 2           | 3550 ± 145 | Sorbite + coarse-lamellar pearlite | 10.8±1.2 174±20 6.7±2.6 |
| 3      | Russia  | 0                       | R-65, DT370 | 1           | 3470 ± 145 | Sorbite + coarse-lamellar pearlite | 10.8±1.6 150±18 4.2±1.4 |
|        |         |                         |         | 2           |          | Sorbite                  | 7.8±0.7 125±21 5.7±1.1 |
| 4      | Japan   | 100                     | R-65, NSC | 1           | 3815 ± 145 | Sorbite                  | 9.6±1.3 108±13 7.1±0.9 |
|        |         |                         |         | 2           | 3995 ± 70  | Sorbite                  | 9.6±1.1 129±10 5.2±1.4 |
| 5      | Japan   | 0                       | R-65, NSC | 1           | 3875 ± 145 | Sorbite                  | 10.2±1.1 115±59 7.9±2.2 |
|        |         |                         |         | 2           | 3685 ± 105 | Sorbite                  |  - 118±17 6.4±2.1 |
| 6      | Japan   | 20                      | R-65, NSC | 1           | 3730 ± 135 | Sorbite + fine-grained pearlite | - 135±34 4.5±1.5 |
|        |         |                         |         | 2           | 3810 ± 75  | Sorbite + fine-grained pearlite | - 117±25 7.2±1.3 |

| Series | Country | Tonnage, mln tons gross | Marking | No. of zone | Hv, MPa | Microstructure parameters | Microstructure type |
|--------|---------|-------------------------|---------|-------------|---------|---------------------------|---------------------|
| 7      | Russia  | 160                     | R-65, T1 | 1           | 3730 ± 135 | Sorbite + fine-grained pearlite | - 135±34 4.5±1.5 |
|        |         |                         |         | 2           | 3810 ± 75  | Sorbite + fine-grained pearlite | - 117±25 7.2±1.3 |

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|--------|---------|-------------------------|---------|-------------|---------|---------------------------|---------------------|
| 6      | Japan   | 20                      | R-65, NSC | 1           | 3730 ± 135 | Sorbite + fine-grained pearlite | - 135±34 4.5±1.5 |
|        |         |                         |         | 2           | 3810 ± 75  | Sorbite + fine-grained pearlite | - 117±25 7.2±1.3 |

Table 1. Test samples of rail steels

Table 2. Chemical composition of steels
To conduct research on an EDM machine, we cut 5×6×10 mm samples from the rail head - sample No. 1 was cut out of the rolling area, which undergoes the most intensive wear and stress during operation, sample No. 2 was cut out from the central part of the rail head.

To conduct metallographic studies and hardness measurements, we applied mechanical and chemical treatment to the surface of each sample. A 0.5% solution of nitric acid (HNO₃) in alcohol was used to reveal the microstructure. The research was conducted on a LEICA DM IRM metallographic microscope and a Jeol JSM-6490 scanning electron microscope. Pearlite grain size (d), interlamellar spacing (h), and volume fraction of bainite (f) were determined using the GoodGrains software (see figure 1).

![Figure 1. Analysis of microstructure parameters using the GoodGrains software: (a) determining the interlamellar spacing in pearlite using the intercept method; (b) determining the volume fraction of bainite using shading. Scanning electron microscopy](image)

An HVS-1000 hardness tester was used to measure the microhardness of the samples.

To conduct abrasion tests using an EDM machine, we cut five cylindrical samples from the rail head. The tests were carried out on a Buehler AutoMet 250 polishing grinder. The following parameters were set for the experiment: experiment time, loading force, speed of movement (rotation) of the sample and base, direction of rotation, and type of force. KK19XW 16-H abrasive paper attached to the surface of a metal disk was used as a wear surface. To reduce the effect of abrasive paper wear, we studied the rate of its wear depending on time and applied load. During the test, the sample moved along the surface of abrasive paper in a circle with a radius of ~ 50 mm. The parameter characterizing the wear rate was the loss of mass of samples ∆m. Mass measurements were carried out on a Startorius CPA 225D weights.

To conduct annealing of rail steel samples, we used the SNOL-1 and EKPS-10 muffle furnaces.

3. Experimental results

3.1. Study of the structure of steels in the initial state
Samples of series No. 1 and No. 3 were cut from various melts of R65 rail steel produced in Russia. Analysis of the results presented in Table 3 shows that the hardness of samples of series No. 1 and No. 3 coincides within confidence intervals, which indicates the stability of the strength properties of the products and, as a consequence, the high reproducibility of the modes of technological processes for the production of such type of rail steel. It is also evident that used samples have a greater hardness. We should note that the microhardness of Russian R65 steel in zone No. 1 (the zone in which the most intense wear and destruction of rail steel occurs) is ~100 MPa lower than the hardness of steel in zone No. 2.

Analysis of the results presented in Table 3 shows that the microhardness of Japanese steel in supply condition (series No. 5) is greater than the microhardness of Russian R65 steel (series No. 1) by ~150 MPa in zone No. 1 and by ~300-320 MPa in zone No. 2. We should also note that the hardness of Japanese rail steel increases after operation - the microhardness in zone No. 1 increases from 3595-3600 MPa to 3815 MPa, and the microhardness in zone No. 2 increases from 3875 MPa to 3995-4000 MPa. Microhardness measurements also showed that the hardness of Russian and Japanese steel increases
towards the middle of the head – the microhardness of Japanese and Russian rail steel in Zone 2 is greater than the microhardness in Zone 1.

Studies of the microstructure showed that Japanese and Russian steels have a pearlite structure, with a small volume fraction of bainite and ferrite (see Table 3). The lamellar structure of most pearlite grains is practically undiscernable during metallographic examination, which indicates a small interlamellar distance (the distance between cementite plates in pearlite). The structure of the Russian rail steel contains single grains of coarse-lamellar pearlite, in which, upon metallographic examination, individual cementite plates are visible. Japanese steel has a slightly smaller grain size, a smaller Fe-Fe₃C interplate spacing, and a smaller volume fraction of bainite (see Table 3). In accordance with Table 4, GOST 8233-56, it can be concluded that pearlite can be classified as sorbite-like compound for all steels.

![Figure 2](image1.png)
**Figure 2.** Microstructure of a sample of Russian rail steel. Series 3 and Series 7. Zone 1

![Figure 3](image2.png)
**Figure 3.** Microstructure of a sample of Japanese rail steel before operation (series 5) and after operation (series 4)

Table 3 demonstrates that the interlamellar distance for Japanese-made steels decreases after operation (see also Figure 3), which may indicate fragmentation of pearlite particles during operation.

### 3.2. Effect of heat treatment on the structure and microhardness of steel

Steels were subjected to three types of heat treatment:

(i) quenching (hardening at high rate cooling) from a temperature of 860 °C into water or oil;

(ii) normalization from a temperature of 860 °C at various rates (cooling together with the furnace (average cooling rate 0.2–0.5 °C/min), controlled cooling of the sample in an Nabertherm RHTC 80-230/15 air oven at a rate of 3 and 10 °C/min; uncontrolled cooling in air with an average cooling rate of 50-100 °C/min);
(iii) two-stage heat treatment, in which the temperature $T_2$ and the duration of the second annealing stage were varied (see Figure 4). At the first stage, the sample was placed in a furnace heated to a temperature of 860 °C and held there for 10 minutes; next, the sample was moved (as fast as possible - in less than 5 sec.) from furnace No. 1 to furnace No. 2, where temperature ($T_2$) varied from 400 to 660 °C. After exposure in an oven at a temperature of $T_2$, the sample was cooled in air.

Figure 4. Diagram of a two-stage heat treatment of rail steel

Table 3 shows the results of studying the effect of temperature ($T_2$) and time ($t_2$) of isothermal exposure at the second stage of annealing of Japanese NSC steel (see Figure 4).

Table 3. The effect of heat treatment on the parameters of the microstructure and microhardness of NSC rail steel (Japan)

| Annealing No. | $T_2$, °C | $t_2$, min | Steel microstructure parameters | Hv, MPa   |
|---------------|------------|------------|--------------------------------|-----------|
|               |            |            | Microstructure type | h, nm | f, %     |
| Initial state | -          | -          | Sorbite                  | 112±16  | 15.5±6.3 | 3780 ± 75 |
| 1             | 660        | 10         | Sorbite                  | 160±42  | 16.7±7.4 | 3570±11  |
| 2             | 630        | 30         | Pearlite                 | 208±19  | 9.3±4.7  | 2980±70  |
| 3             | 600        | 30         | Sorbite                  | 168±24  | 4.1±2.3  | 2950±65  |
| 4             | 570        | 30         | Pearlite                 | 278±36  | 1.9±0.9  | 2570±50  |
| 5             | 500        | 30         | Sorbite                  | 234±24  | 2.9±1.3  | 3000±85  |
| 6             | 400        | 30         | Pearlite                 | 223±26  | 2.6±2.0  | 3165±85  |
| 7             | 300        | 30         | Sorbite                  | 168±20  | 2.6±1.5  | 3175±70  |
| 8             | 200        | 30         | Sorbite                  | 173±20  | 4.2±1.8  | 3365±80  |
| 9             | 100        | 30         | Sorbite                  | 139±21  | 5.7±2.2  | 3430±14  |
| Normalization (50-100 °C/min) |            |            | Pearlite                 | 133±9   | 4.5±1.5  | 3835±65  |
| Normalization (0.2-0.5 °C/min) |            |            | Sorbite                  | 201±21  | 2.4±1.1  | 2950±10  |

Table 4. The effect of heat treatment on the parameters of the microstructure and microhardness of T-1 rail steel (Russia)

| Annealing No. | $T_2$, °C | $t_2$, min | Steel microstructure parameters | Hv, MPa |
|---------------|------------|------------|---------------------------------|---------|
|               |            |            | Microstructure type | h, nm | f, %  |
| Initial state | -          | -          | Sorbite                        |         |
| 1             | 660        | 10         | Sorbite                        | 201±11  | 2.5±1.1 | 2950±10  |
| 2             | 630        | 30         | Pearlite                       | 168±20  | 2.6±1.5 | 3175±70  |
| 3             | 600        | 30         | Sorbite                        | 173±20  | 4.2±1.8 | 3365±80  |
| Initial state | Sorbite + coarse-lamellar pearlite | Sorbite + single grains of coarse-lamellar pearlite | Sorbite + single grains of coarse-lamellar pearlite | Sorbite + single grains of coarse-lamellar pearlite | Sorbite + spheroidized pearlite | Sorbite + coarse-lamellar pearlite | Sorbite + coarse-lamellar pearlite | Pearlite + coarse-lamellar pearlite | Pearlite + coarse-lamellar pearlite |
|--------------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| 1 660 1      | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 2 660 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 3 660 120    | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 4 630 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 5 600 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 6 570 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 7 500 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| 8 400 30     | -                                 | -                                             | -                                             | -                                             | -                             | -                             | -                             | -                             | -                             |
| Normalization (50-100 °C/min) | - | - | - | - | - | - | - | 133±9 | 4.5±1.5 |
| Normalization (0.2-0.5 °C/min) | - | - | - | - | - | - | - | 201±21 | 2.4±1.1 |
| Hardening at high rate cooling | Martensite | - | - | - | - | - | - | 9185±200 |

An analysis of the results shows that the hardness of steel decreases with increasing exposure time at temperature T2, while a decrease in temperature T2 leads to an increase in hardness. The maximum value of hardness and the minimum interlamellar distances in steels are achieved during normalization with a cooling rate of 50-100 °C/min. An analysis of the results in Tables 3-4 shows that an increase in the isothermal holding time t2 leads to an increase in the interlamellar distance, as well as to a decrease in the volume fraction of bainite. Most of the experiments indicate that a decrease in the temperature of isothermal decomposition (temperature T2) leads to a decrease in the interlamellar distance.

Quenching leads to a sharp increase in hardness and the formation of a brittle martensitic structure with particles of residual austenite.

**Figure 5.** The effect of normalization at a rate of 50-100 °C/min on the microstructure of NSC rail steel (Japan): a) before normalization; b) after normalization
3.3. Wear test

At the first stage of testing, we studied the influence of test modes on the abrasive wear rate of rail steel in various structural states. Figure 7 shows the dependences of mass loss on test time at various loads for normalized (Figure 7a) and quenched (Figure 7b) steel. The tests showed that the dependence of the mass loss on the test time is close to parabolic in nature. This is obviously due to the gradual chipping of sandpaper and its clogging with wear products. The linear plot of the dependence $\Delta m(t)$ is observed only for small test times (no more than 1-2 min), which allows with a sufficient degree of accuracy to determine the rate of mass loss in the linear approximation $V_m = \Delta m/\Delta t$. An increase in the voltage applied to the sample leads to a noticeable increase in the wear rate, while an increase in the hardness of steel leads to an increase in the wear resistance of steel (see Fig 7). The dependences of the mass loss on the hardness of the samples are close to linear (Figure 7), which proves the correctness of the selected test modes (see tab. 5). It is interesting to note that in the region of low values of hardness $H_v$, close to the hardness of rail steels in the delivery condition, a maximum is observed in the dependence $\Delta m(H_v)$, the scale of which depends on the magnitude of the load applied to the sample during abrasion tests. Thus, as follows from the obtained graphs (Figure 7), for rail steel, a decrease in hardness below a certain value can lead to a certain change in the wear rate of the surface of the sample.

Figure 7. Dependence of mass loss on test time for different loads (a) and dependence of mass loss on the hardness (b). Normalized Russian grade U8 steel

Table 5. Test modes for wear resistance of rail steels

| Experiment time, min | Load, N | Stress, kPa | Sample speed, rpm | Base speed, rpm | Direction of rotation | Type of load |
|----------------------|---------|-------------|-------------------|----------------|----------------------|--------------|
| 0                    | 5N      | 0,1         | 3000              | 0              | 15N                  | 100          |
| 1                    | 15N     | 0,2         | 6000              | 0              | 30N                  | 200          |
| 2                    | 30N     | 0,3         | 9000              | 0              | 45N                  | 300          |
| 3                    | 45N     | 0,4         | 12000             | 0              | 15N                  | 400          |

R² = 0,9655
R² = 0,9699
R² = 0,9863

Figure 6. The effect of normalization at a rate of 10 °C/min on the microstructure of DT-370 rail steel (Russia): a) before normalization; b) after normalization
Tests for abrasive wear of samples of Russian and Japanese rail steels after various types of heat treatment made it possible to plot the degree of wear (mass loss) against hardness. The obtained dependences $\Delta m(H_v)$ are presented in Figures 8-9. The obtained graphs show that, in general, as the steel hardness increases, the general dependence of reduced intensity of abrasive wear for rail steel remains unchanged. It is interesting to note that the linear correlation coefficient (0.96-0.97) for Russian steels is higher than that for Japanese steels (0.79-0.89). Lower values of the linear correlation coefficient are associated with a large scatter of experimental data in the hardness range $H_v < 3500$ MPa.

We should also note that if the hardness values remain in the low zone ($H_v < 3500$ MPa), corresponding to the region of formation of the pearlite-sorbite structure in Japanese NSC steels, we can distinguish three stages in the dependence $\Delta m(H_v)$, indicating a high “sensitivity” of the degree of wear to the structural state of steel – the size of the interlamellar distance, the volume fraction of bainite, and the size of the pearlite grain.

In conclusion, it is interesting to note that the nature of surface failure during wear tests of NSC hardened steel samples (Figure 10) differs from the nature of fracture during wear of samples of normalized steel (Figure 11). As can be seen from a comparison of the presented figures, the average size of the scratches on the surface of normalized steel is much smaller, and the scratches themselves are unidirectional. The surface of normalized steel may have single large scratches with a width of ~10
μm, which are apparently formed when the sample rotation is stopped by large abrasives “torn out” from sandpaper.

We should also note that the surface of hardened NSC steel has scratches of two different sizes with different directions of propagation – along with very small submicron scratches aligned along the axis of rotation of the sample, we can see large scratches, several microns wide (up to 10-15 μm), aligned quite randomly. This may indicate multiple brittle fractures of the surface of the test sample – a chipped particle of abrasive or martensite is being affected by a force perpendicular to the rotation line, which tries to “pull” it from under the abrasive sample.

A significant number of large scratches, the orientation of which is close to micron slip lines, indicates the formation of a large number of such particles during the destruction of the surface and, as a result, the brittle destruction of the surface of the sample of hardened steel during its wear test. Thus, it can be argued that the wear mechanisms of rail steel with ferrite-pearlite and martensitic structures are different.

Figure 10. The surface of a sample of hardened and normalized NSC steel after abrasion testing

Figure 11. The surface of the sample hardened and normalized DT370 steel after abrasion testing

4. Conclusions
Our study established that the structure of modern rail steel 76HF (R65) has a pearlite structure. Pearlite in the central part of the head of the rail of steel manufactured by NSC (Japan) has a smaller distance between the cementite plates than in the structure of pearlite in the region of rolling of the rail head, which results in its higher hardness.

The isothermal decomposition of austenite and cooling rate in the range from 1 to 100 °C/min do not allow achieving high microhardness and the required values of the inter-plate distance, but allow for the disappearance of zones with bainitic microstructures. The best rail steel characteristics (maximum hardness, minimum interlamellar distance) are achieved in the case of uncontrolled cooling in air at a
rate of more than 100 °C/min. We also established that an increase in the hardness leads to an increase in the wear resistance of rail steels.

Our study shows that Japanese rail steels have higher wear resistance compared to Russian rail steels. An increase in the hardness of steel leads to a change in the nature of surface fracture – in steels with low hardness, there is a co-directional arrangement of micron scratches, in steels with high hardness - brittle fracture of the surface.

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