Issue VII, November 2024
e-ISSN 2707-9481
ISBN 978-601-80473-3-6
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https://doi.org/10.31643/2024.01

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On the optimal ratio of the hardness of wheel and rail steel, ensuring minimal wear of the wheel-rail friction pair

Abstract: In this work, to identify the optimum between the hardness of the wheel and the rail, which ensures minimal wear, methods were used to determine wear by mass loss (volumetric wear) and by micrometric measurement of the size of the imprint (linear wear). It has been shown that the optimal range of wheel and rail hardness, determined by measuring (reducing) the size of the indentation, is in the range of 1.38-1.55. This interval practically confirms the wear identified by mass loss of 1.41-1.58. Based on these data, it is recommended to use the average value of the ratio between them, namely, 1.39-1.56 (HVк556-655, HVр400-420), which does not violate the objectivity and accuracy of measurements, both when determining volumetric and linear wear. It is noted that there is no magic relationship between the hardness of a wheel and a rail; there is only an optimal hardness for wheels and rails, determined by several internal (chemical composition, structure, properties, etc.) and external (friction coefficient, degree of slippage, presence or absence of lubrication, axle loads, etc.) factors.

Keywords: wheel, rail, hardness ratio, friction pair, wear, weighing, sample mass, measurement, print size.

Introduction

One of the determining factors in the development of the economy of Kazakhstan is railway transport, which, according to experts, accounts for up to 70-75% of freight turnover and 50% of passenger traffic in the republic. Under these conditions, increasing the operational wear resistance and durability of wheel pairs, the main element of which are solid-rolled wheels, is an urgent task of great practical importance (Bogdanov & Zakharov, 2014; Balanovsky, 2016). Analysis of the operational resistance of the "wheel-rail" friction pair shows that the cause of wear of such joints is friction, which results in repeated deformation of the contacting areas of the surfaces, their strengthening and softening, heat release, changes in micro- and substructure, development of adhesion processes, fatigue, corrosion and other physical and chemical processes.

The complexity of the processes in the contact zone has led to the emergence of different theories of external friction and wear. A unified theory explaining the wear mechanism in the "wheel–rail" friction pair has not yet been created (Samotugin et al., 2016; Kuksenkova & Polyakov, 2021).

Many factors simultaneously influencing the wear of wheels and rails have led to the hypothesis that the main reason for intense wear and a significant reduction in the service life of wheelsets is a violation of the optimal ratio of hardness of the materials of wheels and rails. However, practice shows that there is no strictly established optimal ratio of the hardness of wheels and rails (their obligatory equality or excess of the hardness of one of the elements by a strictly fixed percentage, etc.) (Larin, 1986).

Based on special laboratory tests of roller samples, taking into account slippage equal to 2%, a ratio of at least 1.2 was established (20% excess of the hardness of the wheels relative to the hardness of the rails). The results of these tests, which determine the required hardness ratio of the "wheel-rail" friction pair, and the proposed idea of the causes of intense wear of wheel pairs (violation of the required hardness ratio), do not agree well with the actual results during operation. Therefore, at present, the question of the ratio of hardnesses of the "wheel-rail" friction pair remains the subject of discussion among researchers and production workers, and debate continues about the optimal level of hardness of the wheel and rail (Vorobyov & Benkova, 2015).

Note that in real production conditions, obtaining direct experimental data on optimizing the hardness of rails and wheels is a complex technical and economic task. This is due to the long duration and labour intensity of industrial tests, due to the need to exhaust the service life of the unit under study, its periodic disassembly, and the difficulty of measuring the wear of products (parts).

Materials and research methods

To identify the optimum between the hardness of the wheel and the rail, two methods were used in this work: a) determination of wear by weight loss (volumetric wear); and b) determination of wear by micrometric measurement of the size of the print (linear wear).

a) Determination of wear by weight loss (volumetric wear);

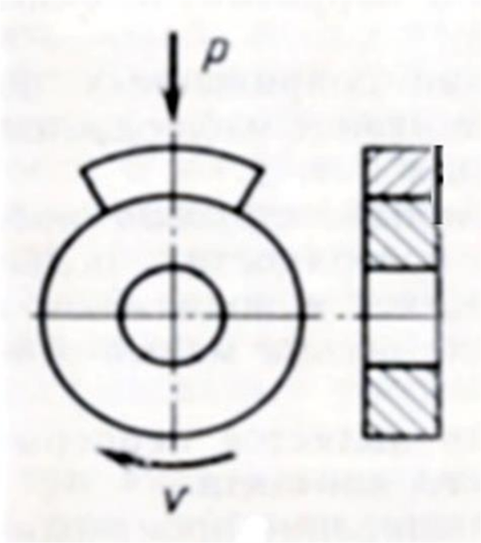

Figure 1. Roller wear test diagram and liner when the roller rotates (Lakhtin, 1984)

We used roller samples with a diameter of 40 mm and a width of 8 mm from wheel steel containing 0.64% C, cut from the rim of a solid-rolled wheel, and hardened by plasma hardening. As a counter-body, we used liners 5 mm thick and 10 mm wide made of rail steel containing 0.81% C (Fig. 1).

Wear resistance was determined by weighing the mass of the sample before and after testing. The measure of wear was the loss of mass of the sample, for which the sample was weighed before and after testing with an accuracy of 0.0002 g after thoroughly rubbing with felt with gasoline, and then with technical alcohol. Weight loss g*m^2/h, where g is the weight loss in grams, m2 is the wear surface; h – is wear time.

The surface hardness of the rail samples varied in the range of 345-455 HV (Table 1). This is justified by the fact that this range of hardness covers possible fluctuations in hardness (350-405HV) of P65-type length rails. The hardness of the wheel samples varied from 275 HVk to 900 HVk. The depth of the hardened layer for wheel steel samples is ~1.5 mm.

Table 1. Influence of the ratio of wheel and rail hardness on the wear resistance of the “wheel metal – rail metal” pair

Option No.	**Wheel hardness HVk,**	**Hardness rail, HVp**	**Attitude HVк / HVp**	**Volumetric wear, g.**		
				sample wheel steel	**sample rail steel**	**total wear and tear**
1	263	430	0,61	1,10	0,21	1.31(original state)
2	275	345	0,80	0,95	0,24	1.19
3	380	362	1,05	0,73	0,26	0.99
4	505	377	1.35	0,58	0,22	0.80
5	**560**	**397**	**1.41**	**0,37**	**0,23**	**0.60**
6	**615**	**410**	**1,50**	**0,33**	**0,25**	**0.58**

7	**675**	**425**	**1,58**	**0,29**	**0,21**	**0.50**
8	860	440	1,95	0,48	0,44	0.92
9	900	455	1,98	0,51	0,49	1.00

From Table 1 it is clear that the minimum total wear falls on the ratio 1.41-1.58 [hardness of the wheel HVk / HVr (560/675), rail (397/425)]. The wear of wheel samples in the hardness range 275-505 (HVк/HVр) is 0.95+0.73+0.58 = 2.26 g, the rail in the hardness range 345-377 (HVк/HVр) is 0.24+0.26+0.22 = 0.72 g, which is 3. 1 time more than with a ratio of 1.41-1.58. Note that the experiments used samples with hardness beyond the limits established by the standard, which is explained by the need to obtain a complete picture of the wear resistance of the wheel and rail.

The total wear of wheel and rail steel samples increases when the wheel is hardened to high hardness (over 860-900HV), which can cause spalling of the hardened layer and cracking. Hardening a wheel to a relatively low hardness (275-505HV) leads to an increase in total wear, mainly, as noted, due to wheel wear (Table 1). Thus, the experiments carried out show that the optimal ratio of wheel and rail hardness, ensuring minimal wear in terms of mass loss, is the ratio of 1.41-1.58.

Selected hardness ratios of wheel samples can be obtained by plasma hardening (by changing the current strength, the length of the plasma arc, the flow rate of the plasma-forming gas (argon), the diameter of the gas ceramic nozzle and other technological parameters) in real operating conditions of the rolling stock, which brings laboratory tests closer to production ones and is of great practical importance.

Table 2 shows changes in microhardness and emerging structures during plasma hardening. It can be seen that in the surface layer 1.55 mm thick, a mixed-layer structure is formed with a decreasing microhardness during the transition from martensite with acicular morphology to a ferrite-pearlite structure in the central layers.

Table 2. Changes in microhardness and structure of the strengthened layer

Distance from top ness, mm	Microhardness, HV 02	Microstruk tour	Distance from top ness, mm	Microhardness, HV 02	Microstruk tour
0,25	850	Martensite	1,00	585	Sorbitol + perlite
0,40	802		0,80	557	
0,70	685	Martensito-troostite	1.25	427	Perlite
0,95	615	Troosto-sorbitol	1.55	372	Pearlite + ferrite
0,97	613		1.70	345	Pearlite + ferrite

b) Determination of wear by measuring the size of the print (linear wear)

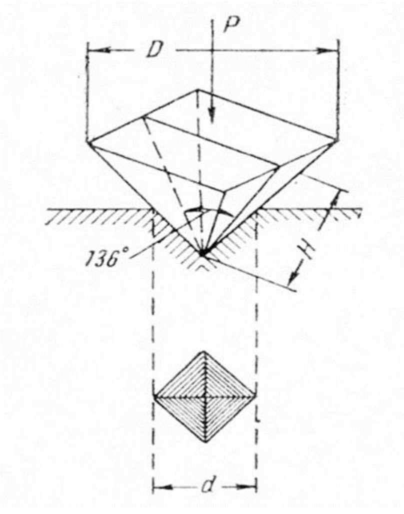

Figure 2. Scheme imprinting with a diamond pyramid

As noted above, measuring wear by weight loss is a complex task that requires a long time, which is a disadvantage of this method. Therefore, in the experiments we used the micrometric measurement method, which is successfully used to determine linear wear. This method is based on precise micrometric measurements of the size of the print using instrumental microscopes before and after the wear of the test samples (Metal Science and Heat Treatment of Steel. Directory, 1983).

To measure hardness, the Vickers method (HV) was used, in which a diamond tip in the shape of a tetrahedral pyramid is pressed into the surface under study, giving a more objective and accurate assessment of the hardness of metallic materials (Fig. 2).

The essence of the method is that depressions in the form of an imprint are applied to the working surface, and by reducing the size of the imprint, the amount of linear wear is judged. The prints were made using a four-fold diamond pyramid with a square base and an apex angle of 1360 between opposing faces. To obtain such pyramids, a PMT-3 microhardness tester was used, on which the reduction in the size of the print was measured.

The indentation depth h was determined by the formula:

$$h = d / 2 \sqrt{2}\ \mathrm{tg}\ (\alpha / 2), \qquad (1)$$

where α is the angle at the top of the pyramid between opposite faces; d is the length of the print diagonal.$d = 0{,}5\ (d_1+d_2)$. At $\alpha = 1360$ the value is $h=0.143d$. Linear wear is defined as the difference between the indentation depth before and after the test $\Delta h = h1 – h2 = 0.143(d1–d2)$ at $\alpha = 1360$, where h1 is the indentation depth before the test, h2 is the same after the test. The accuracy of measuring linear wear by micrometric measurements before and after wear using fingerprints is 0.3 µm. The diagonal dimensions of the applied prints are in the range of 1-10 microns.

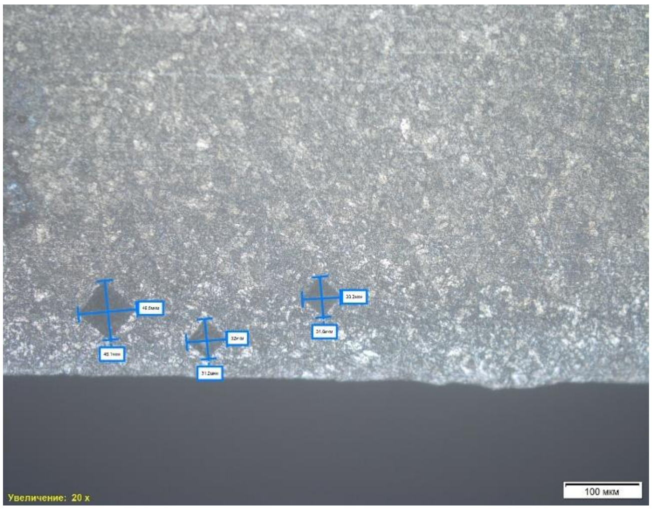

Figure 3. Measuring the length of diagonal prints using Thixomet

The amount of linear wear was determined using the Thixomet program - a computer image analyzer, which allows you to obtain the necessary information automatically, which increases the objectivity and accuracy of the assessment (Fig.3). The wear test mode, the test steel samples, and their geometric dimensions are taken to be the same as in the method of determining wear by weight loss.

Table 3. Determination of linear wear by micrometric measurements before and after wear of samples

Option No.	Wheel hardness HVk,	Rail hardness, HVp	Attitude HVк / HVp	Linear wear, µm		
				wheel steel sample	sample rail steel	Totalny
1	271	427	0,.63	10,0	3,2	13,2 (original state)
2	370	395	0,94	9, 6	3,5	13.1
3	394	375	1,05	8, 7	3,5	12.2

4	450	380	1,18	7, 8	3,6	11.4
5	**555**	**400**	**1,38**	**3,5**	**3,1**	**6.6**
6	**604**	**411**	**1,47**	**3,1**	**3,3**	**6.4**
7	**655**	**420**	**1,55**	**3,8**	**3,5**	**7.3**
8	868	445	1,95	5,1	4,6	9.7

The data obtained (Table 3) show that the optimal ratio of wheel hardness (HVk555 / HVr655 and rail HVk400 / HVr420) is in the range of 1.38-1.55. With this ratio, linear wear of both wheel and rail samples has a minimum value (3.1-3.8 µm). It can be seen that hardening the wheel to high hardness (over 868HV) leads to intense wear of both elements of the friction pair (wheel -5.1 microns, rail -4.6 microns); When the wheel rim is hardened to a relatively low hardness of 370-450HV, wheel wear increases up to 2.3 times than in the optimal hardness range of 555-565HV. (9.6+7.7+6.8=24.1 µm versus 3.5+3.1+3.8= 10.4 µm). It is also noteworthy that the wear of wheel and rail steel samples increases, respectively, to 5.1 microns and 4.6 microns with a wheel-to-rail hardness ratio of 1.95 (HVk 868/HVp445).

Thus, the optimal range of wheel and rail hardness, determined by reducing the indentation size, is in the range of 1.38-1.55. This interval practically confirms the wear identified by the mass loss of 1.41-1.58. Based on these data, it is recommended to use the average value of the ratio between them, namely 1.39-1.56 (HVк556-655, HVр400-420), which does not violate the objectivity and accuracy of measurements, both when determining volumetric and linear wear.

A comparative analysis of these results with known methods (where the ratio of the hardness of the wheel and the rail is assumed to be equal to unity) shows that to ensure minimal wear in this work, a range of hardness ratios is recommended. Let us note that the recommended range of hardness ratios practically coincides both when determining volumetric and linear wear. It would not be a great exaggeration to note that there is no magic relationship between the hardness of a wheel and a rail; there is only an optimal hardness for wheels and rails, determined by several internal (chemical composition, structure, properties, etc.) and external (friction coefficient, degree of slippage), presence or absence of lubrication, axle load, etc.) factors (Kanaev, 2020; Kanaev et al., 2023).

It is also important to note that the technical result of the proposed method for determining the optimal ratio of the hardness of wheel and rail steel is to obtain a rational range of wheel and rail hardness, in which the total wear of the wheel and rail is reduced by up to 2 times. Analysis of the experimental data obtained shows that the indicated reduction in the total wear of the wheel and rail is realized mainly due to a decrease in wheel wear by 2.3 times with practically unchanged rail wear in the studied range of surface hardness.

Conclusions

The optimal range of wheel and rail hardness, determined by reducing the size of the indentation, is in the range of 1.38-1.55. This interval practically confirms the wear identified by the mass loss of 1.41-1.58. Based on these data, it is recommended to use the average value of the ratio between them, namely 1.39-1.56 (HVк556-655, HVр400-420), which does not violate the objectivity and accuracy of measurements, both when determining volumetric and linear wear.

Research results show that an increase in wheel hardness during plasma treatment above 860÷900 HV under real operating conditions leads to chipping of the hardened layer of the wheel and intense wear of the rail. Hardening the rim and wheel flanges to a relatively low hardness of 275÷505 HV is ineffective since wear resistance improves slightly.

The results of laboratory tests presented in the article and the ideas expressed on the optimal ratio of the hardness of the wheel-rail friction pair should be tested in production operating conditions using the artificial base method based on micrometric measurements before and after wear.

Cite this article: Moldakhmetova, A., Kanaev, A. (2024). On the optimal ratio of the hardness of wheel and rail steel, ensuring minimal wear of the wheel-rail friction pair. *Challenges of Science*. Issue VII, 2024, pp. 5-10. https://doi.org/10.31643/2024.01

References

Balanovsky, A.E. (2016). Basic questions of the theory of plasma surface hardening of metals. *Strengthening technologies and* *coatings*, No.2 (134), 20-30.

Bogdanov, V.M., & Zakharov S.M. (2014). Modern problems of the wheel-rail system. *Railways of the world*, No.1, 57-62.

Kanaev, A.T. (2020). Plasma hardening of heavily loaded parts and components of transport engineering. Astana, Master-PO LLP, p.173.

Kanaev, A.T., Moldakhmetova, A.E., Kanaev, A. A., Ramazanova, Zh.M., Sarsembaeva T.E. (2023). About the Optimal Range of Hardnessof Wheel and Rail Steel. *Steel in Translation*, 53(7), 648-653.

Kuksenkova, L.I., & Polyakov S.A. (2021). Problems of materials science and *methodological features of their solution in the science of friction and wear. Metallurgy and heat treatment of metals*, No.3(789), 3-12.

Lakhtin, Yu.M. (1984). Metallurgy and heat treatment of metals. Moscow, *Metallurgy*, 360.

Larin, T.V. (1986). On the optimal hardness of the elements of the wheel-rail friction pair. *News of universities, Ferrous metallurgy*, No. 10, 4-9

Metal science and heat treatment of steel. Directory. 3rd ed., Vol. 1 Test methods and research. M.: Metallurgy, 1983, p. 352.

Samotugin, S.S., Gagarin, V.A., Samotugina, Yu.S. (2016). Technological basis of plasma gradient hardening of parts. *Strengthening technologies and coatings*, No. 9,15-19.

Vorobyov, A.A., & Benkova, T.G. (2015). On the question of the method of relating the hardness of the wheel-rail friction pair. Friction and wear. *International technical journal*. Vol.36(4), 433-442.