DOI: https://doi.org/10.30932/1992-3252-2019-17-5-06-15

Mathematical Description of Wheel–Rail Wear Process

Bunkova, Tamara G., *Omsk State Transport University, Russia*.*

Tamara G. BUNKOVA

ABSTRACT

The article covers one of the most pressing challenges for the railways, namely, the identification of the optimum hardness ratio within the wheel–rail couple. The duration of the service life of wheels and rails is largely determined by the hardness of the steel used for their manufacturing. It is confirmed by rather numerous studies carried out in different countries, as well as in Russia. Nevertheless, during many studies on the dependence of the wear-resistance on hardness only specimens of wheel or rail steel were tested without a proper assessment of the influence of the one element hardness on the wear-resistance of the other within the couple simulating the wheel and rail operation.

The objective of the paper was to identify the optimum relation between strength characteristics of railway wheel and rail, considering operating conditions. The wheel–rail couple is considered as a system. A mathematical model of wheel–rail friction wear process has been developed. Mathematical simulation used the non-compositional second-order rotatable design.

The article presents the results of the study on the intensity of wear of wheels and rails and recommendations regarding choice of axle load and rolling stock speed.

Keywords: *transport, railways, wheel–rail couple, mathematical simulation, hardness ratio, wear.*

*Information about the author:
Bunkova, Tamara G. – engineer at the Department of Mechanical Engineering and Rolling Stock Maintenance Technology, lecturer at the Department of Railway Wagons and Wagon Facilities of Omsk State Transport University (OSTU), Russia, bunkovatg@mail.ru.

Article received 02.05.2019, updated 20.09.2019, accepted 17.10.2019.

For the original Russian text of the article please see p. 6.

Introduction

The problem of identification of the optimal ratio of the hardness within the wheel–rail system has existed since the very birth of railways. It is known from the engineering tribology that metals with roughly the same hardness show the best wear resistance in a friction couple. But during many years the ratio of the hardness of wheel and rail materials has been changing, e.g. in Russia. So, the experimental study in that field is still required.

As for the railway practices, the author's analysis of the current hardness of the whole-rolled wheel and rail according to domestic and foreign articles shows that maximum wheel hardness is observed in the USA, Brazil, Canada (390 HB) and the maximum rail hardness is in Russia (401 HB [Brinell hardness; hardness according to Brinell scale]). Optimum wheel and rail material hardness ratio in Russia is minimum (0,86) and in Europe it attains the maximum (1,1) [1].

Pic. 1 shows international comparisons of the wheel and rail strength properties.

Previously a series of experimental studies using the device based on the sliding-and-screw-cutting lathe 1K62 had been held to identify the efficient rail–wheel couple hardness ratio. Rollers made of the whole-rolled wheel material were used as wheel specimens and a disk made of R65 rail material was used as a rail sample. The rail specimen's hardness remained constant and equal to 401 HB corresponding thus to the upper hardness value according to GOST R51685-2013 [Russian state standard], and the wheel specimen hardness varied from 293 to 363 HB according to GOST 10791-2011 [2; 3].

The experimental studies considered three most important factors affecting the wheel–rail friction couple wear, namely: HB_w which is wheel material hardness; P_1 – vertical axle payload; P_2 – horizontal axle payload.

The experiment was made for the car operation within the curved tracks.

Experimental studies have determined HB_w, P_1 and P_2 values that provide the minimum values of wheel and rail wear. The optimum rail–wheel hardness ratio HB_w363/HB_r401 = 0,91 was also determined.

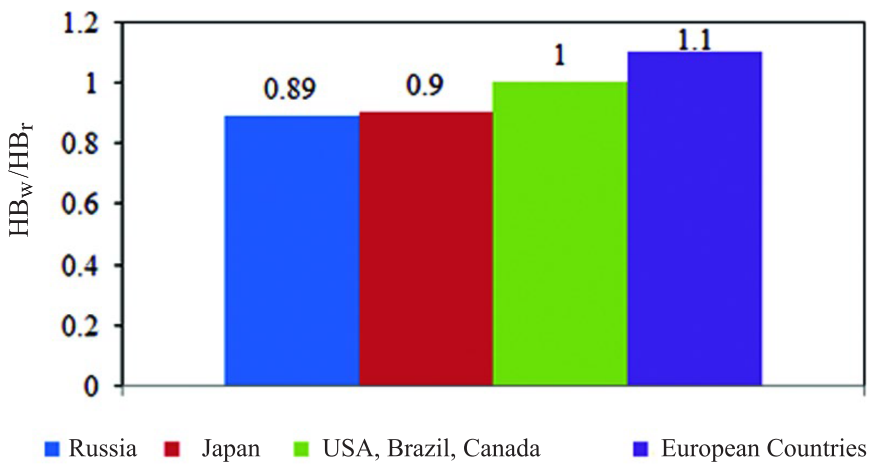
However, to clarify the results obtained, there was a need for additional experimental research [4; 5].

The objective of the research was to optimize the railway wheel and rail strength properties considering the operating conditions using the *mathematical simulation* based on the non-compositional second-order rotatable design.

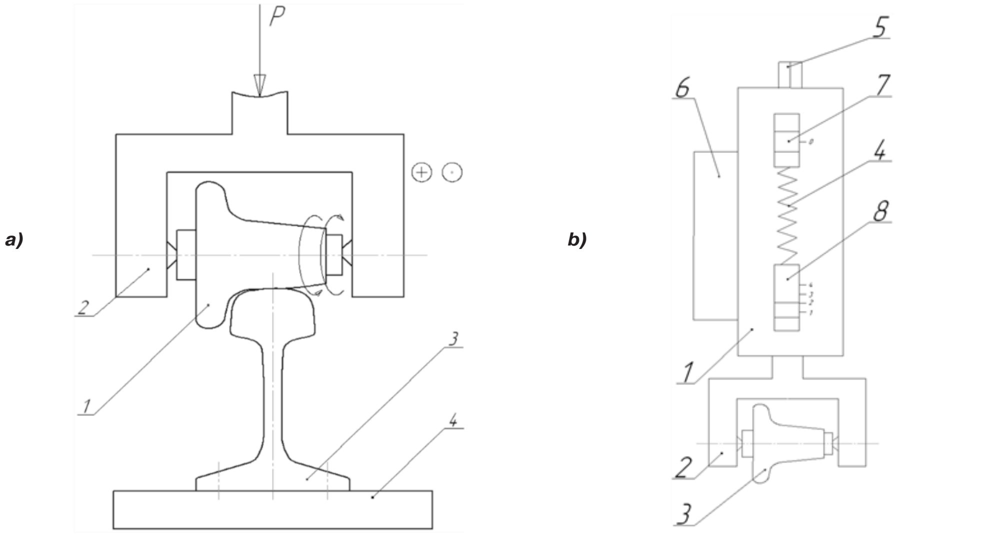
Results

Under operation conditions the wheel changes its speed from zero to maximum when moving and from maximum to zero when train is braking. To consider these features as well as conditions of jointed track, a new test unit consisting of two devices was developed [6; 7].

The experimental unit has been designed using a horizontal shaping machine (Pic. 2). The device (Pic. 2a) consists of the wheel



Pic. 1. International comparisons of the ratio of the wheel to rail strength properties [the calculations are made by the author].



1 – wheel specimen; 2 – fork-type holder; 3 – rail specimen; 4 – plate.

1 – case; 2 – folk-type holder; 3 – wheel specimen; 4 – calibrated spring; 5 – positioning screw; 6 – shelf; 7 – pin; 8 – marking pin.

Pic. 2. Device for simulating wheel motion along the rail (a) and of a wheel load on a rail (b).

specimen 1, kept in the fork-type holder 2, fixed on the device placed on the saddle of the horizontal shaping machine, and the rail specimen 3. The wheel specimen is made of wheel steel, the profile of which corresponds to the wheel rolling profile. The rail specimen is made of rail steel, mounted rigidly to the horizontal shaping machine using the plate 4. The rail specimen profile corresponds to the real rail profile. To simulate the rail joints, a saw-cut is made in the middle of the rail specimen, so that it is parallel to the rotation axis of the wheel specimen. Vertical loads can be applied to the wheel specimen (Pic. 2b) that can be relocated along the rail specimen. The dimensions of the wheel and rail specimens are reduced by a scale factor of 1/3.

Based on an analysis of global expertise and experimental studies the papers [8; 9] concluded that increasing the Brinell hardness of the wheel by one unit within the operational hardness interval increases their wear-resistance by 1–2 %. Besides, the wheel contact fatigue life increases as the square of their hardness increment [10; 11].

Using the above-designed unit, experiments were carried out based on non-compositional rotatable design to consider the wheel and rail wear provided that their hardness was equal.

In this case, the mathematical model of the process under the study is selected starting with the simple linear equation sequentially increasing the polynomial degree to obtain an adequate model. In that case the process of obtaining a mathematical model is as follows. First, a complete factorial experiment 2^k or a fractionally replicated experiment 2^{k-p} should be implemented, where p is the number of interaction effects replaced by new variables [12].

It should be noted that the process under the study can often be described by a second-order polynomial. If the second-order polynomial is inadequate, then one can proceed with the planning of the third-order polynomial and describe the process under the study using the third-degree polynomial.

The hardness of the wheel and rail specimens is assumed to be 440 Brinell units. The values of speed and load are taken considering scale factors: P_{max} = 27 tf as limits of load, V_{max} = 140 km/h as the speed.

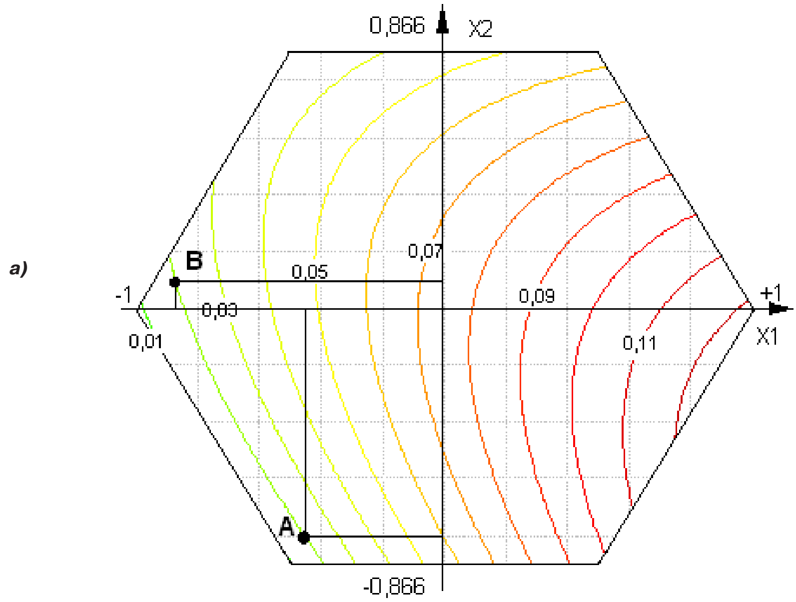
Planning matrix and test results are shown in the Table 1.

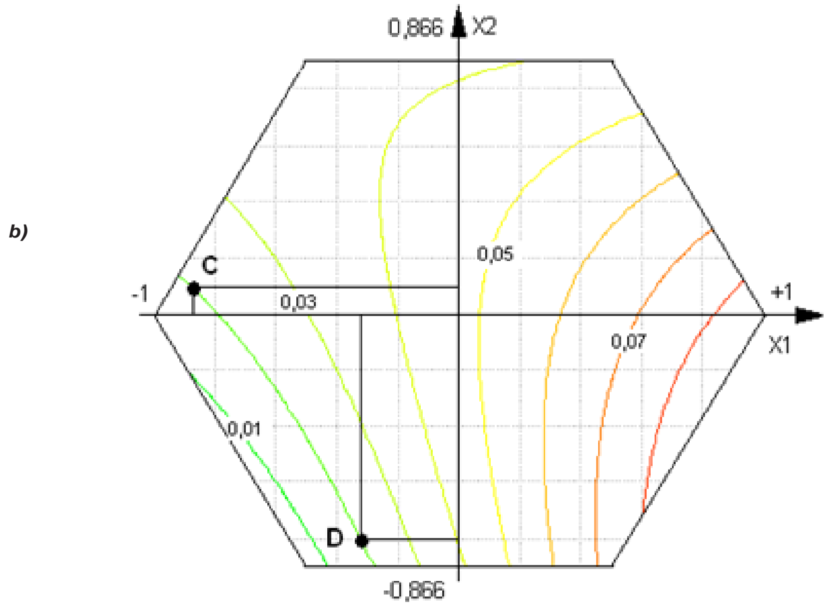
Regression equations describing the influence of load and speed on the wear resistance of the wheel Ya and of the rail Yb:

$$Ya = 0{,}075 + 0{,}0567x_1 - 0{,}0058x_2 - 0{,}01x_1^2 - 0{,}03x_2^2 - 0{,}346x_1x_2, \quad (1)$$

$$Yb = 0{,}0475 + 0{,}0367x_1 + 0{,}0025x_1^2 - 0{,}0108x_2^2 - 0{,}346x_1x_2. \quad (2)$$

Since the hypothesis of adequacy is not rejected (the condition $F_p < F_{table}$ holds), the





Pic. 3. Lines of equal distribution (response) of the wheel wear (a) and the rail wear (b).

regression equations can be used as a mathematical model to determine the wheel and rail wear resistance [12].

For a graphical interpretation of the model obtained, lines of equal distribution were built (Pic. 3a, b).

Using lines of equal distribution contour plots, it is possible to find the values of the speed and vertical load that ensure minimum wear of both the wheel and the rail.

In terms of natural values for the points A and B with corresponding wear value of 0,02 g (Pic. 3a), we get:

For the point A:

P = 841,2 H; V = 8,4 m/min.

For the point B:

P = 513,6 H; V = 19,2 m/min.

From the point of view of increase in axle load, point A is preferable since the wheel can withstand a large load at the same wear value

Table 1

Planning matrix and test results

Test No.	x_0	x_1	x_2	x_1x_2	x_1^2	x_2^2	P, H	V, m/min	Ya, g	Yb, mm
1	+1	+1	0	0	+1	0	1980	18	0,12	0,09
2	+1	-1	0	0	+1	0	420	18	0,01	0,01
3	+1	0,5	0,866	+0,433	+0,25	+0,75	1590	28,4	0,06	0,04
4	+1	0,5	-0,866	-0,433	+0,25	+0,75	1590	7,6	0,10	0,07
5	+1	-0,5	0,866	-0,433	+0,25	+0,75	810	28,4	0,03	0,04
6	+1	-0,5	-0,866	+0,433	+0,25	+0,75	810	7,6	0,01	0,01
7	0	0	0	0	0	0	1200	18	0,08	0,05
8	0	0	0	0	0	0	1200	18	0,07	0,04
9	0	0	0	0	0	0	1200	18	0,07	0,05
10	0	0	0	0	0	0	1200	18	0,08	0,05

but point B is preferable thanks to the trend of increase in freight wagon speed.

On the lines of equal distribution of response of the rail wear resistance (Pic. 3b) we can mark two points: C (-0,88; 0,1) and D (-0,33; -0,8) corresponding to the rail wear value of 0,02 mm.

For the point C we get:

P = 513,6 H; V = 19,2 m/min.

For the point D we get:

P = 942,6 H; V = 8,4 m/min.

A comparative analysis of the curved surfaces on the contour plot of the wheel and rail wear shows that decrease in the wear rate of wheel and rail steel of 440 HB is achieved at the speed values V = 7,6–28,4 m/min and with load values P = 474,6–989,4 H (wheel wear is 0,02 g, rail wear is 0,02 mm). The smallest wear is achieved with load-to-speed ratio:

For the wheel:

P_{max} = 482,4 H; P_{min} = 443,4 H;

V_{max} = 18,36 m/min; V_{min} = 16,2 m/min.

For the rail:

P_{max} = 864,6 H; P_{min} = 505,8 H;

V_{max} = 15,24 m/min; V_{min} = 7,61 m/min.

Conclusion

The study has shown practical application of the methods of non-compositional designing for mathematical representation of the wheel–rail friction couple wear rate. It has resulted in mathematical models for determining the optimum wear within wheel–rail system. The process of solution of the problem of the wheel and rail wear reduction by selecting a rational hardness ratio has thus been conducted considering the operating conditions.

REFERENCES

1. Bunkova, T G. About optimum ratio of the hardness of the whole-rolled wheel of the freight wagon and of the rail [*Ob optimalnom sootnosheniyi tverdosti tselnokatanogo kolesa gruzovogo vagona b zheleznodorozhnogo rel'sa*]. *Nauchno-tekhnicheskiy vestnik Povolzhiya* [*Povolzhye Scientific and Technical Bulletin*], 2011, Iss. 1, pp. 86–90.

2. GOST R51685-2013 [Russian state standard]. Railway rails. General Specifications. [Electronic resource]: http://docs.cntd.ru/document/1200105520. Last accessed 01.10.2019.

3. GOST 10791-2011 [Russian state standard]. Whole-rolled wheels. Specifications. [Electronic resource]: http://docs.cntd.ru/document/1200085777. Last accessed 01.10.2019.

4. Razhkovskiy, A. A. Bunkova, T. G., Petrakova, A. G., Gateluk, O. V. Optimization of hardness ratio in rail–wheel friction pair [Original version in Russian]. *Trenie i iznos [Friction and Wear]*, 2015, Iss. 4, pp. 433–442.

5. Razhkovskiy, A. A. Bunkova, T. G., Petrakova, A. G., Gateluk, O.V. Optimization of hardness ratio in rail–wheel friction pair. *Journal of Friction and Wear*, 2015, Vol. 36, Iss. 4, pp. 334–341.

6. Patent 98070 of the Russian Federation, IPC G 01 M 17/10 (17/00). Device for simulating wheel motion along the rail. Razhkovskiy, A. A., Petrakova, A. G., Bunkova, T. G.; Omsk State Transport University is an applicant and patentee. No. 2011125268; appl. 20.06.2011; publ. 20.11.2011, 2 p.

7. Patent 113839 of the Russian Federation, IPC G 01 M 17/10. Device for simulating wheel loading on the rail. Razhkovskiy, A. A., Petrakova, A. G., Bunkova, T. G.; Omsk State Transport University is an applicant and patentee. No.2011131543/11; appl. 27.07.2011; publ. 27.02.2012, Bulletin No. 6, 2 p.

8. Markov, D. P. Hardening of wheel flanges of rolling stock intended for high speed to reduce side wear [*Zakalka grebney kolyos podvizhnogo sostava na vysokuyu skorost' dlia snizheniya bokovogo iznosa*]. *VNIIZhT Bulletin*, 1997, Iss. 1, pp. 45–51.

9. Bogdanov, V. M., Markov, D. P., Penkova, T. I. Optimization of RS wheel flange tribotechnical characteristics [*Optimizatsiya tribotekhnicheskikh kharakteristik grebney kolyos podvizhnogo sostava*]. *VNIIZHT Bulletin,* 1998, Iss. 4, pp. 3–9.

10. Moreau, A. Characteristics of wheel/rail contact. *Rail Engineering International*, 1992, Iss. 3, pp 15–22.

11. Stone, D. H., Sawley, K. J., Kelly, D., Shust, W. Wheel/rail Materials and Interaction: North American Heavy Haul Practices. IHHA 1999 STS Conference on Wheel/Rail Interaction, Moscow, 1999, pp. 155–168.

12. Spiridonov, A. A, Vasiliev, N. G. Experimental design when investigating and optimizing technological processes: Study Guide [*Planirovanie experimenta pri issledovanii i optimizatsii tekhnologicheskikh protsessov*]. Sverdlovsk, Kirov UPI publ., 1975, 140 p.