Features of restoring the rolling profile of wheels coming into turning during repair

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Abstract. The main objective of the performed studies was to improve the durability and operability of railroad wheels and make lower the costs of acquiring new ones by means of an innovative technology development for wheel profile rehabilitation and further restoration of physical and mechanical properties of the rim metal and improvement its structure. The information consists the facts about the nature of wheel pairs damage in operation, machine-tool equipment and cutting tools, used to restore the surface, based on the analysis of which a new rational technology for repair of wheel pairs on the rolling surface profile with subsequent restoration of the original operational properties is collected. A new method of wheel rolling surface profile restoration has been developed, which includes high-performance plunge grinding and subsequent induction heating (thermocycling), resulting in the formation of structures that lead to increasing of hardness and formation of compressive stresses, which has a positive effect on the efficiency of wheel rolling surface operation. This increases wheel life and safe operation of rail rolling stock. The implementation of the wheel profile recovery method with the help of high-performance plunge grinding and induction heating of wheels will lead to increased efficiency of railway rolling stock and reduce the need for the purchase of new wheelsets.

1 Introduction

In the process of operation, the wheelsets of wagons are worn out on the wheel rolling surface. At present, their repairs involve the restoration of the wheel profile rolling pattern on wheel lathes or wheelshaping machines, which is not rational, in view of the value of wheel life, and has a lack of efficiency at this operation. At the same time, the issue of restoring the physical and mechanical properties of wheel rim metal (its hardness and structure) has never been a priority at railroad repair enterprises. In terms of science, the issues of research in improving the physical and mechanical properties of wheel rim metal during repair and increase their service life have been being addressed for a long time. The results of these studies are reflected in the works of domestic scientists: T.V. Larina, V.A. Kislika, M.M. Mashnev, I.G. Uzlova, I.A. Ivanova, A.F. Bogdanova, N.S. Prodana, S.I. Gubenko and other authors, including foreign ones.

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As the wheel rolling surface wears, the physical and mechanical properties of the rim metal in depth decrease. Consequently, when repairing wheelsets, the removed layer of metal reduces the thickness of the wheel rim, that leads to decreasing of its physical and technical properties, as well as the life of the wheel. Therefore, the solution of this problem can increase the wheels life under the rolling stock, and also reduce the cost of acquiring new ones. The cost of new wheels, which have passed all stages of the technological process, significantly exceeds the costs related to the restoration of the wheel profile, its physical and mechanical properties. This becomes more and more important due to the significant prices rising in the ferrous metals industry.

In other words, the essence of the problem is that the repair of railway wheels to restore the rolling surface, cutting-edge technologies are not used, thought they allow to make a rational mechanical treatment of the surface profile of the wheels and restore the mechanical and physical properties of the metal rim. Today, both foreign and domestic scientists working in the field of rail transport pay a serious attention to this problem, that is reflected in their studies, the results of which are reflected in numerous literary sources, including the works of Emperor Alexander I St. Petersburg State Transport University (SPSTU) [1-15].

2 The analysis of the nature of wear and damage to wheels that come in for turning during repair

In order to find some ways of increasing the service life of wheels, and their operational reliability, it is essential to know the overall picture of the state of the wheels of rolling stock in operation and, where possible, the trends in damageability, wear resistance, performance failures and service life. Any damage to the wheel rolling surface negatively affects the cutting modes (CM) of machining when restoring its profile.

Wheels of rail transport are usually excluded from service, first and foremost, for safety reasons, that is, to prevent their failure (damage) in operation. They include: wear and tear of the tread surface and comb; defects formed during operation or manifested in the presence of defects in their manufacture. And they are mainly cracks in the solid-rolled wheel disc in the wheel center; thermomechanical damage (TMD) and other defects on the surface of the solid-rolled wheel or locomotive wheel tire rim.

Wearing on the skating surface can occur for several reasons at once. This phenomenon can be caused by the action of both tangential forces and crushing of the metal by forces normal to the rolling surface. There is also a uniform fatigue wear process on the skating surface. The surface operational abrasion profile is generally irregular and depends primarily on how the wheel-rail contact surface is positioned in relation to the location of the rolling circle. According to this feature, the following types of wear are distinguished, which are represented in Fig. 1: rolling (Fig. 1.a), ridge wear (Fig. 1.b), undercutting of the ridge vertical, significantly ahead of wear on the rolling circle (Fig. 1.c) and rolling on the rolling surface, which can be shifted to one or another side from the wheel rolling circle (Fig. 1.d). Two types of defects are formed on the wheel surface in most cases, the first being fatigue processes in the steel and the second being high-temperature events.

The emergence of these injuries is due to a number of primary causes related to both the manufacturing technology of wheels (the use of low-quality steel and failure to comply with the technology of volume hardening), and the conditions of operation of the rolling stock (it is, primarily, poorly executed regulation of the spread of wheelsets and position of the bogie from the body of the rolling stock). The choice of brake pads (construction, materials) and the quality of the railroad track (its layout and profile, etc.) also influence the occurrence of these damages.
It should also be noted that the condition (property) of the surface layer of the rim metal of wheelsets, coming after the operation for the restoration of the profile of the wheels rolling surface, significantly differs from its original (new wheels). The hardness change along the rolling surface profile of the solid rolled wheel rim after operation is shown in Fig. 2.

The nature of the possible changes in hardness and the area of its change is limited to zone 1. The location of the possible sticking is reflected in zone 2. The characteristic of wheel rim hardness before operation is reflected in zone 3.

As a result of studies of the condition of the rim metal in places of formation of TMD (Fig. 3), it was found that in the zone of their formation, areas ("white layer") with hardness that exceeds the initial one by three or more times (from 7 to 10 GPa) are formed. The structure of the metal has a pronounced fine grain structure with a grain size of the order of
0.002 to 0.003 mm. The phase composition of the structure is martensite and carbides with sizes ranging from 0.001 to 0.00015 mm.

Fig. 3. Character of metal microhardness change along the depth of the rim h from its rolling surface: 1, 2 - change in the formation of a slurry; 3, 4 - change in the formation of a light spot; 5, 6 - in the formation of a crawl

One-piece wheels of modern rolling stock of freight cars are taken out of operation mainly not because of wear, but because of wheel rolling surface damage through local displacement of surface areas at the points of contact with the rails. These defects are the main reason for the unscheduled withdrawal of wheelsets at technical inspection points.

During scheduled repairing of cars at the depot, another picture is appeared. The greatest number of wheels about 50% are turned in the depot because of differences in wheel diameters in the wheel set, 25% of wheels on the marginal rolling, 10% of wheels due to local displacements and 4% on sliders with fatigue-type pitting and pitting of hard layers with chips on the outer edge of the rim comes to 6% accordingly. In northbound trains, there is increased wheel wear because of the impact of the brake pads. The highest percentage of rejected wear and tear trains in the Trans-Siberian direction (up to 90%). On the same wheelsets are seldom encountered ramps, sliders and scrapes. The increased ridge wear (undercutting of the ridge) is mainly found on the wheels of cars running on the routes with a large number of small radius curves.

A large number of wheel rolling surface defects are also confirmed by other sources. The dynamics of wheel damage over a thirty-year period of service, performed by Rostov State University of Transport and Railway Transport, shows that the character of operational damage has changed significantly in the side of a significant reduction of wear and contact fatigue damage. At the same time, the number of defects of braking origin, the number of which is the same for cars of different types, has increased. Thus, during the current uncoupling repair the defects of braking origin are 75-90%. In case of planned repairs, wear-related faults account for 58%, brake-related faults account for 15.8%, and a significant increase in undercutting of the ridge has been in recent years.

According to the research performed by the SPSTU research laboratory, the number of failures according to the set parameters of wheels (codes) in operation for the last 50 years has not changed fundamentally, and for the last decade in Russia this value has remained stable around 500000 failures per year. For example, the table shows the data on uncoupling of freight cars due to failure of wheel pairs on the Russian railroads for 2019-2020.
The distribution of wheel failures by damage, magnitude and type of deterioration are directly related to the physical and mechanical characteristics of the wheel steel and the operating conditions of the rolling stock. Improvement in wheel quality invariably entail a change in the percentages of defects for which the wheelsets are removed from operation. Increased strength properties of wheel steels allowed to practically exclude such type of defects as pitting of fatigue and thermomechanical origin. At the present stage, JSC "Russian Railways" is constantly conducting comprehensive research, with the involvement of research institutes, transport universities and manufacturing plants to create wheels that meet the requirements of future operation.

### Table 1. Main defects of wheel pairs detected during uncoupling of freight cars on Russian roads in 2019-2020.

<table>
<thead>
<tr>
<th>No. n/a</th>
<th>Malfunction</th>
<th>Code</th>
<th>Number of uncouplings, wheel sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thin comb</td>
<td>102</td>
<td>296178</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>377640</td>
</tr>
<tr>
<td>2</td>
<td>Rolling circle skating above the norm</td>
<td>103</td>
<td>815</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2192</td>
</tr>
<tr>
<td>3</td>
<td>SMT (slips and sliders)</td>
<td>105,106</td>
<td>4625</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4053</td>
</tr>
<tr>
<td>4</td>
<td>Uneven rolling</td>
<td>117</td>
<td>34097</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28649</td>
</tr>
<tr>
<td>5</td>
<td>The rims are scraped.</td>
<td>107</td>
<td>163942</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>176961</td>
</tr>
<tr>
<td>6</td>
<td>Sharp ridge roll</td>
<td>109</td>
<td>1934</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2858</td>
</tr>
</tbody>
</table>

In order to increase the surface contact strength of the wheel rolling surfaces, we can basically advise four ways: the first is to increase the contact area between the wheel and the rail; the second is to use the elastic elements in wheel set and track structures; the third is the use of new materials that allow high contact and thermal stress; the fourth is the improvement of heat treatment (HT) in their production and repair of wheel sets, in order to form the specified physical and mechanical characteristics of the metal in the area of the appearance of the limit of operational rolling in the surface layers of the rim.

### 3 Analysis of methods to restore the specified profile of the wheels, used at the repair enterprises of railway transport

During the repair of wheelsets in the shops of the repair enterprises of JSC "Russian Railways", defects arising during operation, are eliminated by turning on the wheel lathes and milling on wheel milling machines, both with rolling out and without rolling out from under the rolling stock (RS). The treatment includes the skating surfaces, chamfers, ridge and inner sides of the wheel rim. The outer edges can also be ground as needed. Parameters of the surface of the wheels, restored during repair, must comply with GOST10791-2011, and
the dimensions and accuracy of the norms given in GD VNIIZhT 27.05.01-2017 (for freight cars).

Russian and foreign railway companies have known a number of methods to reconstruct the rolling surfaces of rail transport wheels. The advantages and effectiveness of recovery methods are primarily characterized by its economic parameters and the productivity of the equipment on which they are implemented. First of all, it should be noted that we are talking about the minimum layer of metal of the rim of the wheel, which is technologically required for the repair. At the repair enterprises of JSC "Russian Railways" for the repair of wheel pairs (restoration of the rolling surface) currently apply only 2 methods - copy turning and shaped milling. During machining, the required geometric shape of the profile is achieved by removing part of the rim metal into chips. Turning has a number of peculiarities arising from the condition of the rolling surfaces of the wheelsets that come in for repair.

While turning along the profile of used wheels, there is a considerable variation in the amount of the allowance to be removed - up to 15 mm. Figure 4 shows the profile of the worn wheel and the magnitude of the removed metal layer depending on the method of restoration. Turning is accompanied by shock loads on the cutting tool and machine, due to the uneven mechanical properties of the rim metal caused by local thermomechanical damage. This leads to premature failure of machines and cutting tools. Especially high consumption, for which an expensive hard alloy is used (from 1x10^{-3} to 20x10^{-3} kg per one sharpened wheelset).

Most wheelsets are ground "under the crust", that is, in addition to the defective layer of metal in the places of SMT removed and a significant serviceable layer (2-4 mm). Frequently, defect-free gears are also machined under the crust in the case of a surface layer of the metal that has been toughened by the operational hardening of the hardening. Studies have found that, on average, 3-4 mm of useful metal from each defective wheel goes into chips per turning, which is equivalent to about 100,000 km of extra mileage.

As a result, for example, during the repair of wheel pairs of high-speed trains, metal wheel rim thickness up to 27 mm is consumed in chips, while the working thickness of the rim is 43 mm. When repairing non high-speed passenger trains up to 17 mm, with a thickness of the working part of the rim of 48 mm. Consequently, only 16 mm (37%) and 31 mm (64%) are subject to wear in operation, respectively. This is due to the fact that turners have to "under the crust" and reduce cutting modes parameters in order to reduce the effect of impact loads during turning on cutting tools and machines. That is why they are set, usually by testing on the wheel lathes, taking account of the actual wheel wear and rolling surface.

![Fig. 4. Results of wheel profile restoration when implementing the existing repair methods (turning "under the crust"): 1 - original, 2 - worn out, 3 - optimally restored, 4 - restored after 1st trimming, 5 - restored after 2nd turning, 6 - thermomechanical damage](image)

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condition (damage), the difference in wheel diameters on the wheels of one wheel set and the
distance between the inner faces of the wheels. The model of the machine, its technical
condition and the characteristics of the cutting tools influence on the cutting modes. At
present, machining of wheelset rolling surface is carried out at different, set by a machine
operator of a particular enterprise CM, and the cutting speed can vary from 0.6 to 2 m/s. Feed
at rough turning ranges from 0.8 to 4 mm/rev, and at finishing - from 0.5 to 3.2 mm/rev.
Machine time at these processing modes is from 11 to 40 minutes.

To grind the rolling surface of wheel pairs during their repair, different wheel turning
machines in design and in their technological capabilities are used, which are the basic
equipment. A large number of machines of this type have been developed and nowadays they
are used both in our country and abroad. Russian wagon repair shops use wheel turning
machines of Russian and foreign models. The machine park of Russian Railways' repair
enterprises consists of machines of the Kramatorsk Heavy Engineering Plant (KZTS,
Ukraine), machines of the Polish company Rafamet, the German company Hegenscheidt, etc.

To restore the specified rolling profile the grinding process is also used, but it is currently
not as widespread as turning, and is only used to repair wheelsets without rolling out from
under the high-speed rolling stock. The major advantage of sanding is the ability to process
wheelsets with SMT while maintaining a useful workable layer of rim metal, as well as
achieving a low surface roughness of the machined surface. Wheelset profile grinding
machines are used to repair high-speed rolling stock at the Osaka depot (Japan). In the United
States, there are two companies that manufacture wheelset grinders: "Belt Railway Co." and
"Withing Corporation". The major disadvantage that deters the use of grinding to restore the
rolling profile of railway wheels is the rather low productivity of existing machines - from a
half an hour to 2 hours to process one wheel set.

The productivity and cost of wheel rolling profile restoration depend not only on the
technical condition of the machine and the machining scheme, but also to a large extent on
the quality of the applied RP and the cutting modes. Quality of a RI is characterized mainly
by its durability, which depends on the design of the tool, the shape and material, the cutting
inserts used, the quality of its workmanship. Due to the fact that wheel turning machines are
designed for intensive cutting modes (CM), the normal course of the technological process
can only be ensured by the use of a special cutting tool (CT). A significant influence on the
service life of a tool has geometry parameters of the cutters and the used carbide grades. In
domestic practice, for turning the wheel rolling surface profile, different designs are currently
used, using a whole range of tool materials and plate shapes. The greatest application is found
in prismatic inserts of domestic and foreign manufacture with almost the same sharpening
geometry and form, made of double-carbide hard alloys of different chemical compositions
without wear-resistant coatings or with coatings TiC, TiNc.

Today, it is not possible to completely abandon cup cutters (GOST 19072-80) because of
the availability of previous generations of wheel turning machines at repair plants. However,
it should be noted that these cup cutters have their own positive qualities when turning
wheels. The advantage of all cup cutters compared to straight cutters (prismatic plates) is that
they achieve a higher surface quality. Maximum radius of used cutters is limited by the radius
of curvature within the wheel fillets, as the cup cutter must fit within the wheel fillet when
processing. The advantages of working with prismatic plates in wheel machining include the
reduction of the cutting width by 1.5-5 times compared with cup cutters (Fig. 5), a larger
contact area with the tool holder (shell), increased thickness of prismatic plates. When
machining wheels with such inserts, the cutting force is reduced due to the decrease of shear
width compared to the force that arises in processing with cup cutters, and the heat dissipation
is improved. Therefore, the use of prismatic tangential inserts with a large height is the most
appropriate for heavy cutting conditions when machining wheel sets.
Increasing the machining productivity of wheel profiles can be achieved by creating more favorable machining conditions, such as the part heating during cutting or using special types of heat treatment before turning.

Fig. 5. Wheel machining schemes with cup and tangential cutters

At present, methods of processing of metal with cutting are very widespread, especially those ones, in which pretreatment of hard-to-machine steels and alloys is carried out, which improves their machinability. However, not all of them can be used in the repair of wheelsets, and specifically - in the restoration of the rolling profile. The most effective and advanced current solution to the problem of thermal treatment, in our view, is the heat treatment of the wheel rolling surface with high frequency currents (HFC) prior to treatment.

Induction heating has the following main advantages over the other methods listed above: high labor productivity; strict repeatability of results; no metal loss on scale; possibility of applying the heat treatment operation in the repair flow. There is a positive experience of using high-frequency currents accumulated at Oktyabrsky Electric Railway Car Repair Plant (OERCRP), in Wagon part of the depot-5 of Oktyabrskaya railroad and depot "Dachnoye" of St. Petersburg subway, when restoring hard-to-process surfaces of solid rolled wheels, as passenger, as freight and subway cars. There is such an experience in some CIS countries as well. In this case, the heating was carried out in a continuous-sequential way on a one or two-stage induction machine, which includes a high-frequency generator, control equipment and pumping station of hydraulic drives.

Research carried out at the Department of "Metal Technology" of PSUPS to improve the wheel pairs restoration process using an induction installation has shown that the application of preliminary heat treatment HFC of the rolling surfaces, reduces wheel rim material losses to chips when turning wheels and provides increased labor efficiency due to higher processing modes. That is why the induction heating HFC method was proposed to be recommended by the Department of Metal Technology for application in restoration of the roll profile.

4 Formulation of general requirements for methods of rolling wheel surface profile reconstruction

Analysis of the methods used at the repair enterprises of railway transport to restore the profile of the wheel rolling surface shows that these methods become insufficiently effective. They do not meet today's requirements and have significant shortcomings. It is determined
by an increased resistance characteristics of wheel steel due to the loads growing on the axle and wheel, the need to implement a higher level of mechanization and automation of the process, increasing technology flexibility and labor efficiency, the increasing complexity of problems with labor resources. As mentioned above, the machining of the wheel rolling surface profile has several features: uneven allowance for machining, the presence of local thermal and mechanical damage and, as a result, low durability of the cutting tool, the use of mostly old-type wheel lathes, which are difficult to automate and integrate into the production line.

Therefore, turning is not cost-effective (up to 44% of the working layer of the rim metal is converted to chips on average) and is a low-productive process (the average productivity of the turning process during repair is 12 wheel pairs per shift). Furthermore, the wheels' performance worsens with repeated sharpening, as the underlying layers of the rim metal with lower hardness are included in the process. Therefore, the issue of developing the cost-effective and highly productive ways to restore the rolling surface profile of wheel pairs remains very relevant. Currently, the general demands to the designed methods of production, repairs and technological procedures are known: they include a high productivity, cost-effectiveness, fulfillment of technical requirements to the product, improving the quality of the product. The designed method must be based on the modern and foreseeable scientific and technological advances, improve the existing level of technology, satisfy safety requirements and ensure the environmental system's stability.

Based on the studies of the rolled surface condition of wheel pairs, when they enter the repair and the current requirements for wheel pairs, issued from the repair, it is able to specify a number of the above general provisions in relation to the optimal method of restoring the rolling surfaces of wheel pairs.

5 The optimal method for restoring the rolling surfaces of wheel sets must meet the following requirements:

1) To provide the desired accuracy of geometric shape, size and relative positioning of the machined surfaces;
2) To provide the serviceability of the surface layer of the rim metal after the restoration, which is sufficient for subsequent long-term operation;
3) Do not affect the residual stress pattern in the rim and disc or distribute it in a favorable way;
4) Do not deteriorate the performance of repeated restoration of their rolling surfaces;
5) Do not affect the strength of the press connection of the wheels to the axle;
6) To repair rolling surfaces of most types of wheelsets with rim thicker than the allowable limits;
7) To let restore the wheel set rolling surfaces profile both with removed roller axles and without their prior dismantling;
8) To make sure that the removed chips are easily transported and disposed of (for cutting-based methods);
9) To ensure minimal loss of rim metal during rebuilding;
10) To correspond the productivity requirements resulting from the needs of companies of different capacities;
11) To be economically feasible for most repair facilities;
12) Provide the ability of creating flexible production units, automated production lines and sites on its basis.

6 Analysis of results
Based on the results obtained by the Department of Metal Technology SPSTU in the course of a number of studies, including production as the most optimal method to restore the profile of the wheelset rolling surface during repair, we can recommend the method of high performance plunge grinding (plunge cut profile high-speed grinding), which provides an optimal restoration of the geometry of the wheelset profile with subsequent heat treatment by high frequency, which forms the desired physical and mechanical properties of the rim metal to a depth exceeding the great A technical specification was developed for a grinding machine that restores the profile of the wheel rolling surface by the plunge cut profile high-speed grinding method. HFC unit for two types of wheel pairs maintenance during repair (annealing and thermal cycling) was tested in the railcar depot Wagon part of the depot-5 of the October railway, which allowed to develop the "Temporary technological instructions for induction annealing and thermal hardening (thermal cycling) of the rolling surface of wheel pairs of railcars”.

The economic parameters of the methods of wheel pairs repair were also calculated by calculating the present costs to restore the serviceability of the wheels in the conventional wheel shop for a variety of programs. In addition, the industry economic effect of increasing the service life of wheels due to the economic restoration of the profile geometry by the plunge cut profile high-speed grinding method and the restoration (improvement) of physical and mechanical properties (hardness and structure) due to the subsequent maintenance of the rim was determined.

7 Conclusion

The realization of the method of restoring the rolling surface profile designed at the department "Metal Technology" of PGUPS enables, in case of its implementation at the repair enterprises of JSC "Russian Railways" to increase the technical life of the wheel block in comparison with the existing used life by 1.9 times due to cost-effective restoration of geometric parameters of the wheel rim, and restoration of its physical and mechanical metal properties. Russia's need for railroad wheels could be reduced by the same factor, and, as a result, the safety of rolling stock operation could be improved.

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