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Determination of the filler concentration of the composite material to reduce the wear of the central bowl of the rail truck bolster

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ABSTRACT

During the operation of freight cars, uneven wear occurs in the central bowl of the rail truck bolster. This article aims to determine the concentration of the filler of the composite material to reduce the wear of the central bowl of the rail truck bolster. In this work, for the first time, a mathematical model of the distribution of the filler concentration in the projected composite tape was obtained. To reduce the wear of the working surface of the central bowl of the rail truck bolster, as well as to ensure uniform wear distribution, it is proposed to weld a composite tape with variable tribomechanical properties using contact welding. The wear value of the working surface of the central bowl of the bolster of the rail truck bolster when using composite tapes of compositions Fe-Cr-Ni-Cr_3C_2 and Fe-Cr-Ni-TiC with contact welding was 0.15–0.18 mm per 10,000 km - for a loaded freight car and 0.08–0.10 mm per 10,000 km for an empty freight car. According to the amount of wear, the value of the service life of the center plate assembly is predicted, which is 320,000–420,000 km.

1. Introduction

The safety of train traffic and the technical and economic indicators of the operation of rail transport is particularly influenced by the technical condition of freight cars [23,24,29]. An increase in the service life of freight rolling stock will lead to an improvement in the main technical indicators, as well as to a reduction in financial costs [23,24]. At the same time, the value of the risk of the current state of traffic safety should not be increased [1,5,9]. There are mathematical models and algorithms to reduce risks [10–12]. In addition, there are models and design developments that make it possible to increase the technical and economic performance of freight rolling stock [4,5,7].

The resource-determining part of a freight car is the central bowl of the rail truck bolster (Fig. 1). The wear of the central bowl of the rail truck bolster determines the turnaround time of the freight car. In connection with the intensive operation of freight cars and their movement along the tracks in curves, the wear of the central bowl of the rail truck bolster is intensified. The nature of wear is uneven on the working surface of the central bowl of the rail truck bolster. Occurring uneven wear leads to premature repair of the entire freight car. This causes additional economic waste and increases the number of technical impacts in the car depot.

When performing technical inspections of the central bowl of the rail truck bolster, an increase in the amount of wear of the working side surface was observed. Presumably, the increase in wear may be associated with an increase in the speed of the rolling stock [6], as well as with the load mode. The load-speed mode affects the uneven distribution of the amount of wear on the working side surface of the central bowl of the rail truck bolster. As is known [26,27,30,31,38], freight car the rail truck bolster parts are made of 20GL, 20FL, and 20GFL steels. These are low alloy steels. Such steels can be classified as ferritic or pearlitic [35,36]. Since the interacting elements of the rail truck bolster operate in the dry friction mode and at the same time there are high alternating contact-shock loads, the result is an increase in the wear of the interacting surfaces by 1.2–2.0 mm, and sometimes by 3.0 mm per 100,000 km of freight car mileage. Today, in the process of repairing the central bowl of the rail truck bolster, it is known about the use of welding or fusing technology. Commonly used [37] are low-alloy surfacing and welding consumables. Welding or fusing repair technology allows you to extend the mileage until

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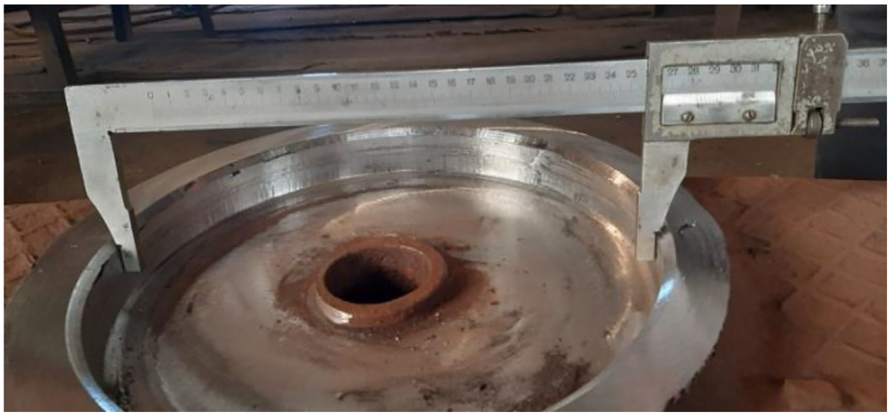


Fig. 1. General view of the central bowl of the rail truck bolster.

the next repair up to 160,000 km. Such an service life can approximately correspond to two years of operation [26]. During the life cycle of a freight car, the working side surface of the central bowl of the rail truck bolster is welded 10–14 times during the repair process.

There are various ways to reduce the amount of wear on the central bowl of the rail truck bolster. These can include modern deposition technologies (for example, laser deposition) [35,36]. Gaskets may also be used during the repair process [3,31]. These gaskets are made of more wear-resistant steel than the material of the central bowl of the rail truck bolster.

The operation and repair of the rail truck bolster and the use of wear-resistant elements [3,26,31] indicate that there is no single solution to reduce frictional wear. The use of high-strength materials in the bolster is impossible because of their increased brittleness.

However, no studies have been conducted that would suggest the use of composite materials or tapes in the repair of the central bowl of the rail truck bolster.

Increasing the service life of the central bowl of the rail truck bolster using various composite materials or tapes is a topical issue. This problem can be solved by using structural materials with higher tribomechanical properties.

In addition, it is possible to manufacture a tape from composite materials with predetermined tribomechanical properties. Furthermore, during repair, the composite material tape is welded to the working part of the central bowl of the rail truck bolster. Contact welding can be used as welding the tape with the central bowl of the rail truck bolster. When repairing the central bowl of the rail truck bolster, contact welding was not used earlier. This type of welding is easy to use and requires a transformer and devices to press the electrode. To manufacture a tape from composite materials, it is necessary to establish the quantitative ratio between the materials of the matrix and its filler.

Next, we will analyze the articles, the studies of which are aimed at establishing the amount of the composite material of the matrix and the filler material.

An overview of various composite materials is presented in many articles [2,8,13,19,32–34,39].

At the limit of a defective weld, in the work [15] in a composite material, the matrix and its filler was found based on a linear approximation of the magnitude of the displacement field. However, this publication does not include the optimal distribution of the matrix and filler in the composite material.

Liu & Huang [25] investigated the strength of a composite material with the assertion that strength can be estimated from a theoretical approach and without the use of experimental results.

The prediction of woven composite fractures [20] is based on synergistic modeling. The resulting model structure is intended for the study of composite materials in the aviation industry.

Using the properties of the filler and matrix of the composite material [18], a prediction of its destruction was made. However, the model presented includes only a composite analysis.

The effect of the morphology and spatial distribution of TiAl3 particles on the hardness, tensile behavior, and wear resistance of a functionally graded Al-TiAl3 composite (FGC) is given in the article [40]. Finally, the relationship between the mechanical properties, wear resistance, and microstructure of the FGC was discussed.

Kanaoun [21] calculated the physical and mechanical characteristics of composite materials based on the effective field method. Isolated inclusions and a homogeneous matrix constituted a composite material. However, the method used in the work only allowed us to refine the predictions of the properties of composite materials. Also, this method is applicable only for high concentrations of isolated inclusions in a composite material.

Huang & Liu [16] predicted the strength of a composite material based on changes in the physical and mechanical properties of its components. The paper presents a methodology for the design of a composite material and lacks the results of experimental studies.

Huang & Xin [17] based on information about the components of a composite material, its strength was predicted. The experiments performed to determine the strength, as well as the initial physical and mechanical properties, were input information for the prediction. However, there is no information on the dependence of properties between the matrix and the filler of the composite material in the work.

An experimental study of the relationship between the filler concentration in the matrix of a composite material and Young's modulus of elasticity was performed by Lapčík, et al. [22]. With an increase in the filler concentration, an increase in Young's modulus of elasticity of the composite material occurs. It should be noted that there is no theoretical relationship in the work.

Experimental studies of the mechanical properties of a composite material are carried out based on the selection of the range of ratios of matrix and filler concentrations [14,28,41,42].

As a result of the analysis of the literature, we can conclude that there is no existing model for calculating the concentration of the filler in the matrix in the manufacture of a composite material. In this regard, it seems necessary to carry out a theoretical study in order to establish a quantitative relationship between the filler concentration and the matrix concentration of the composite material. In addition, it is necessary to conduct experimental studies of physical and mechanical properties to confirm the adequacy of the dependence obtained.

The scientific novelty of this work lies in the fact that, for the first time in a composite material (tape), the filler concentration was determined.

When conducting theoretical studies, theories were used: logic, physics, dimension and wear.

The theoretical model obtained for a composite tape, which allows determining the concentration of the filler, opens up the possibility of reducing the wear of the interacting parts. The results of the performed research can be widely applied in the rail car depots in the process of repairing the central bowl of the rail truck bolster.

This article aims to determine the concentration of the filler of the composite material to reduce the wear of the central bowl of the rail truck bolster.

2. Materials and methods

To determine the nature of the wear of the central bowl of the rail truck bolster, wear diagrams were plotted. A general view of the average wear diagram of the central bowl of the rail truck bolster is shown in Fig. 2.

As a result of the study of the operational wear of the central bowl of the rail truck bolster of the freight car, diagrams of the wear of the working side surface were constructed. The data obtained were typical for 95% of the cases of the studied generation of freight cars. Five typical freight cars were not assigned to any of the subgroups, since they did not have the above distribution of the wear value of the central bowl of the rail truck bolster. The wear graphs of the central bowl of the rail truck bolster of the experimental subgroups of freight cars are shown in Fig. 3.

As can be seen in Fig. 3, the central bowl of the rail truck bolster of freight cars in two cases is characterized by a variable amount of wear. In this case, there is a decrease in the service life of a freight car, which causes additional financial costs for premature repairs.

Uneven wear of the working surface of the central bowl of the rail truck bolster occurs due to the acceleration and deceleration of the train. Therefore, higher values of acting forces and pressures arise along the OX axis than along the OY axis.

Fig. 4 shows a picture of the uneven wear of the central bowl of the rail truck bolster and the center plate of the body. They mechanically interact with each other.

Since uniform wear was manifested on the center plate of the body, the wear dependences are not given in the work.

As appears from the results of studies of the operational wear of the central bowl of the rail truck bolster, it seems necessary to use a material that is variable in terms of wear resistance on the working surface area to ensure uniform wear in operation.

Upon reaching uniform wear of the central bowl of the rail truck bolster, it is possible to ensure the planned mileage before repair of more than 300,000 km, which will improve the technical and economic indicators both during repair and in the operation of freight cars.

The wear diagrams (Fig. 3) of the central bowl of the rail truck bolster confirm the feasibility of using a composite material that will have variable-distributed physical and mechanical properties on the working surface to further obtain uniform wear of both interacting parts during operation.

That is, to increase the service life of the central bowl of the rail truck bolster during manufacture or during the repair process, it is necessary to distribute, for example, the hardness of the composite material over the working surface.

The authors believe that the amount of wear is affected by the amount of hardness. In accordance with this, if the hardness is distributed along the length of the composite tape, then uniform wear can be expected.

In this work, during the manufacturing process or during the repair of the central bowl of the rail truck bolster, it is proposed to set a variable-distributed hardness value according to Fig. 5.

The variable-distributed value of the hardness of the central bowl of the rail truck bolster on the working surface is similar to the given wear diagrams (Fig. 3).

Such a variable-distributed value of hardness over the working surface of the central bowl of the rail truck bolster of the rotation angle can be achieved using modern technologies, however, the technological process will be greatly complicated, which will lead to an increase in the time of both manufacturing technology and repair.

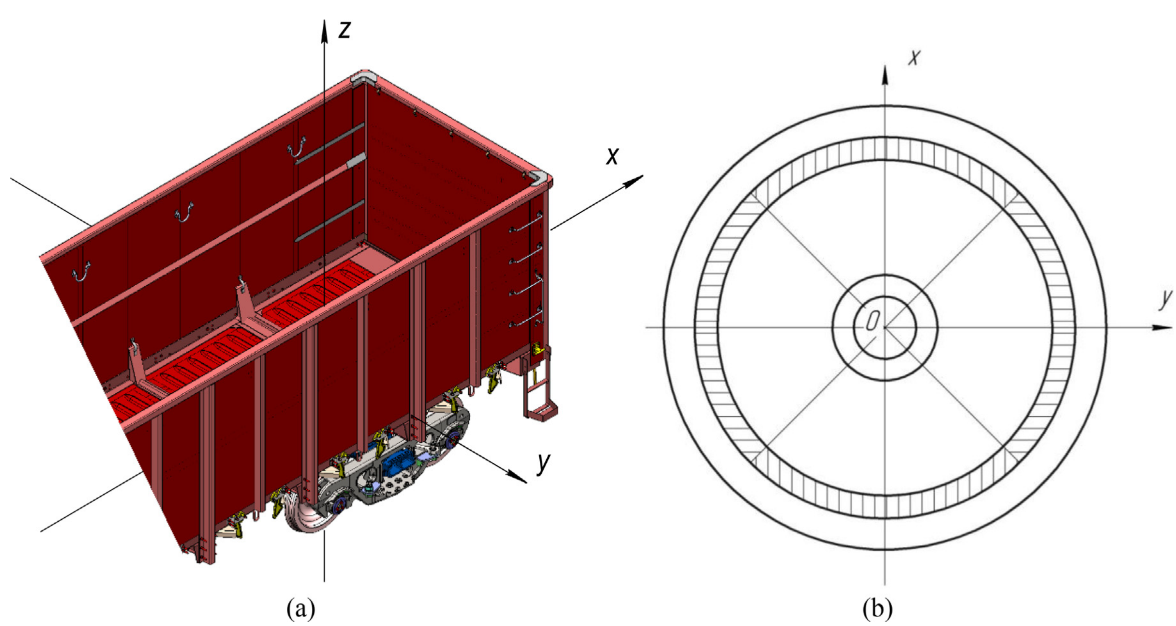


Fig. 2. General view of the direction of the axles in the freight car (a) and the diagram of the average wear of the central bowl of the rail truck bolster (b).

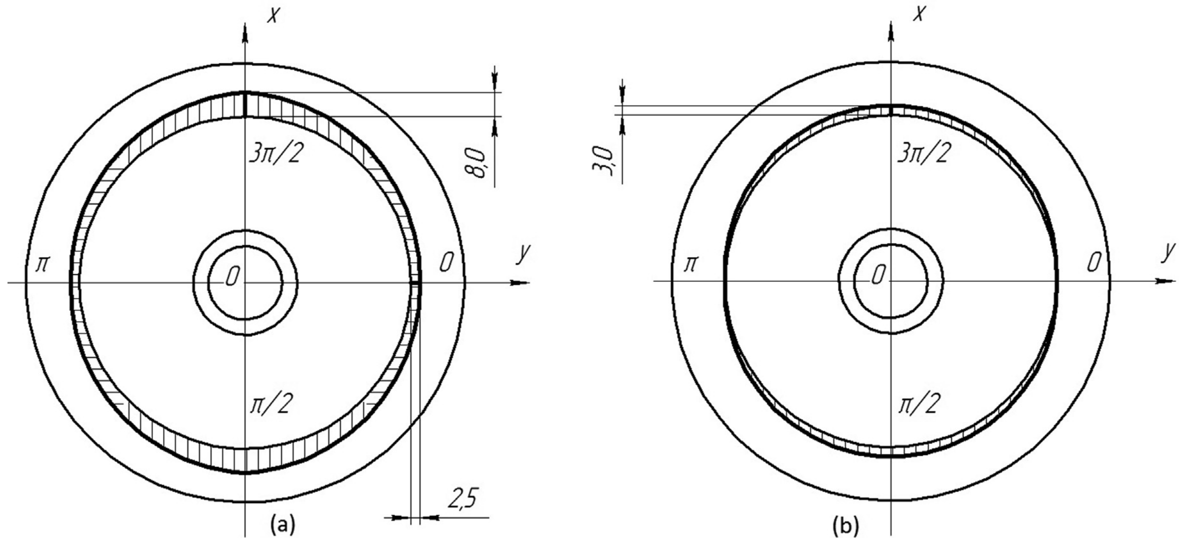


Fig. 3. Diagrams of wear of the central bowl of the rail truck bolster in operation: (a) Full load; (b) Empty mileage.

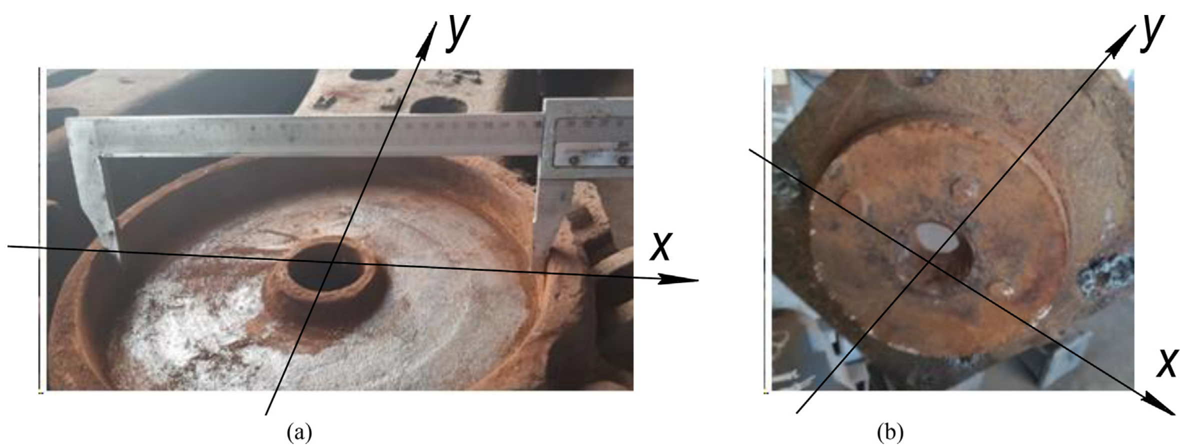


Fig. 4. Some pictures of the uneven wear of the central bowl of the rail truck bolster (a) after interaction with the center plate of the body (b).

In work, when using a composite tape with a variable-distributed hardness value, it seems possible to use contact welding technology. At the same time, the composition of the composite material does not affect the possibility of using contact welding.

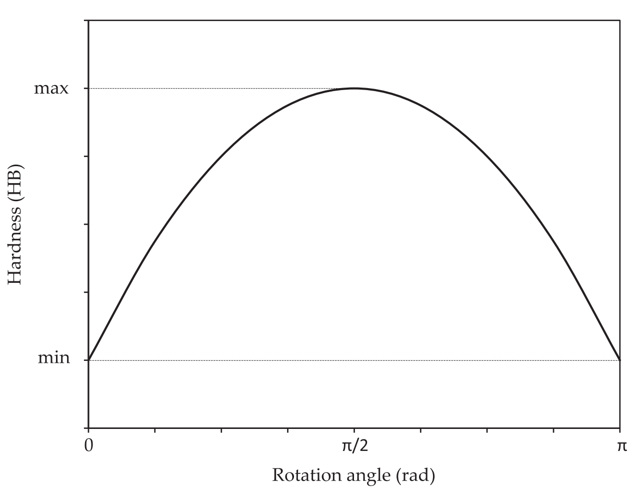


Fig. 5. The dependence of the variable-distributed value of hardness on the working surface of the central bowl of the rail truck bolster of the rotation angle, corresponding to the wear curves shown in Fig. 3.

When using contact welding, the repaired parts do not heat up, and the consumption of 3–4 times less material used can be ensured compared to arc welding technologies. In addition, it is possible to regulate the layer being welded within the range of 0.1–5.5 mm. Contact welding does not affect the atmosphere and is widely used in the repair of parts of the 'shaft' type. The use of contact welding and composite tape for bushings, which is the central bowl of the rail truck bolster, has not been found in the literature.

In this regard, the work assumes the use of contact welding for welding a composite tape with a variable-distributed hardness value. This is done to increase the service life of the central bowl of the rail truck bolster.

To weld the composite tape to the cylindrical surface of the central bowl of the rail truck bolster, a technological scheme was developed (Fig. 6).

When conducting experimental studies in the contact welding of composite tapes to the central bowl of the rail truck bolster, the following technological values were taken: pressure on the roller – 60–80 MPa, roller feed speed – 5–8 mm/min, amperage – 350–400 A.

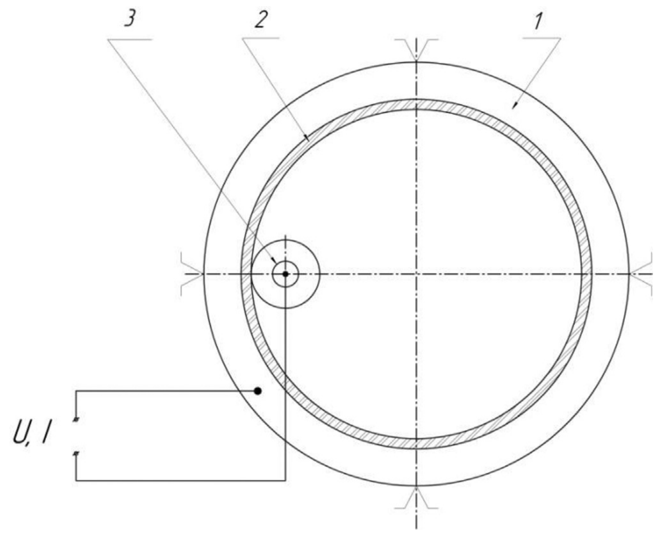


Fig. 6. Technological scheme for welding a composite tape (2) with a roller electrode (3) onto the cylindrical surface of the central bowl of the rail truck bolster (1).

To ensure the necessary physical and mechanical properties of the composite tape, it is necessary to ensure that the hardness of the matrix is not lower than 300 HB and not higher than 400 HB. The austenitic or martensitic structure of the composite tape matrix makes it possible to provide such hardness.

High physical and mechanical properties, namely hardness, can be achieved with the help of carbides. Chromium (Cr_3C_2) and titanium (TiC) carbides were chosen as fillers in the composite tape. It was assumed that these materials would provide the required hardness of the composite tape. In addition, the presence of electrical conductivity of these carbides allows for the use of resistance welding to repair the central bowl of the rail truck bolster. The following powders were used: chromium carbide 12012-35-0 (VWR) and titanium carbide 12070-08-5 (VWR).

Iron powder grade 7439-89-6, VWR, was used as the matrix of its composite tape, whose properties are high and allow the use of resistance welding in the process of welding the composite tape to the working side surface of the central bowl of the rail truck bolster.

The manufacturing process of composite tapes is quite complicated. Because complex thermomechanical reactions occur. In this regard, it is proposed to add chromium and nickel powders to the matrix material. These chemical elements will make it possible to form sufficiently strong bonds, as well as provide the necessary electrical conductivity and high plasticity, which affects the process of contact welding of the composite tape to the working side surface of the central bowl of the rail truck bolster. As a result, the matrix of the designed composite tape includes materials in the form of iron, chromium and nickel powders. A preliminary study allowed us to carry out the incoming powder distribution of the the concentrations of incoming powders in the following ratio: 70% Fe, 20% Cr and 10% Ni.

The process of contact welding of the composite tape to the working side surface of the central bowl of the rail truck bolster is a thermomechanical interaction. The process of manufacturing and forming a composite tape includes the process of rolling a mixture of powders; then the sintering takes place in an inert gas in a furnace. Therefore, in the process of manufacturing and forming a composite tape, the thermomechanical interaction process proceeds. In this regard, the above two processes can be considered jointly in the form of a thermomechanical impact process.

Next, consider the rational distribution of the filler concentration in the composite tape.

3. Results

3.1. Determination of the filler concentration in the composite tape

It is necessary to provide a different hardness value along the working side surface of the central bowl of the rail truck bolster. To do this, it is necessary to establish the theoretical distribution of changes in the concentration of the filler in the composite tape. To obtain a wear-resistant composite coating, evenly distributed over the working side surface of the central bowl of the rail truck bolster and ensuring the same wear, the following equation can be written:

$$\frac{dC}{dl} = kC \tag{1}$$

where

C is the filler concentration.
k is the property difference coefficient, which includes the influence of two different friction materials. The property difference coefficient is proposed to be determined taking into account the main tribomechanical properties of the interacting materials:

$$k = f\frac{K_1 \cdot H_1}{K_2 \cdot H_2} \tag{2}$$

where

f is the value of the friction coefficient of the interacting materials;
H_1, H_2 are the hardness values of interacting materials;
K_1, K_2 are coefficients of elasticity of interacting materials. These coefficients can be determined using the following expressions:

$$K_1 = \frac{1-\mu_1^2}{E_1}; K_2 = \frac{1-\mu_2^2}{E_2} \tag{3}$$

where

μ_1, μ_2 are Poisson's ratios of interacting materials;
E_1, E_2 are the elastic moduli of the interacting materials.

Then the property difference coefficient (2) will take the following form:

$$k = f\frac{E_2(1-\mu_1^2)H_1}{E_1(1-\mu_2^2)H_2} \tag{4}$$

Determine the modulus of elasticity of the designed composite tape:

$$E_2 = E_M(1 - C_F) + E_F C_F \tag{5}$$

where

C_F is the filler concentration value;
E_M is the value of the matrix elasticity modulus;
E_F is the value of the filler elasticity modulus.

The value of the hardness of the designed composite tape:

$$H_2 = H_F\frac{H_M + H_F - C_F(H_F - H_M)}{H_M + H_F + C_F(H_F + H_M)} \tag{6}$$

where

H_M is the hardness value of the matrix of the designed composite tape;
H_F is the value of the filler hardness of the designed composite tape.

Then the property difference coefficient (4) will look like:

$$k = f\frac{(E_M(1-C_F)+E_FC_F)(1-\mu_1^2)H_1}{E_1(1-\mu_2^2)H_F} \times \frac{(H_M+H_F+C_F(H_F+H_M))}{(H_M+H_F-C_F(H_F-H_M))} \tag{7}$$

Let us integrate equation (1) by setting the following initial conditions (point 1, Fig. 3):

$$l = 0,\ C_F = C_{F0}$$

and get:

$$ln\frac{C_{F0}}{C_F} = kl \tag{8}$$

where

C_{F0} is the value of the initial minimum filler concentration;
l is the circumference of the working side surface of the central bowl of the rail truck bolster. This value can be defined as:

$$l = \varphi\frac{d}{2} \tag{9}$$

where

d is the diameter of the circumference of the working side surface of the central bowl of the rail truck bolster;
φ is the value of the angle of rotation of the point located on the circumference of the working side surface of the central bowl of the rail truck bolster.

Then the concentration value of the filler of the designed composite tape of (8), taking into account expression (7), will take the form:

$$C = C_{F0}\cdot\exp[-f\frac{(E_M(1-C_F)+E_FC_F)(1-\mu_1^2)H_1}{E_1(1-\mu_2^2)H_F} \times \frac{(H_M+H_F+C_F(H_F+H_M))}{(H_M+H_F-C_F(H_F-H_M))}\frac{d}{2}\varphi] \tag{10}$$

The theoretical dependence (10) of the distribution of the filler concentration C on the angle of rotation φ of a point located on the circumference of the working side surface of the central bowl of the rail truck bolster takes into account the tribomechanical properties of the interacting materials.

Next, we find the value C_{F0} in expression (10). To find this value, the hardness of the designed composite tapes was studied depending on the concentration of the filler.

3.2. Hardness test

The study of the hardness of composite tapes on prepared samples was carried out according to the PN-EN ISO 6506-1: 2014-12 standard. The results were processed using mathematical statistics methods. The average value of the hardness of the composite tapes depending on the value of the concentration of the filler is represented in Table 1.

An increase in the hardness of the Fe-Cr-Ni-Cr_3C_2 material from 335 to 395 HB occurs with an increase in the filler concentration from 10 to 25%; also chromium due to chemical interaction. With an increase in the filler concentration of more than 25%, the hardness of the composite tape decreases to 382 HB. This decrease is associated with an increase in the porosity of the composite material.

An increase in the hardness of the Fe-Cr-Ni-TiC material from 359 to 397 HB occurs with an increase in the filler concentration from 10 to 20%. As in the previous case, such an increase in hardness occurs when titanium carbide is dissolved and the matrix of the composite material is saturated with carbon and titanium as a result of chemical interaction. With an increase in the concentration of the TiC filler, starting from 25%, there is a sharp decrease in the hardness of the composite tape to 366 HB at a filler concentration of 35%. In this case, also a decrease in the hardness value is associated with the formation of a higher porosity of the composite material.

The results obtained by studying the hardness of composite tapes indicate that the optimal filler concentration, both for Cr_3C_2 and TiC, is a concentration equal to 10%. This ensures low porosity of the composite material and sufficient hardness of the working side surface of the central bowl of the rail truck bolster.

3.3. Theoretical dependence of the filler concentration

Accordaning to the model obtained (10), for the value of the filler concentration based on the angle of rotation of the point located on the circumference of the working side surface of the central bowl of the rail truck bolster, a theoretical concentration distribution was constructed (Fig. 7). In the theoretical model (10), we make a sign change for each next value of $\pi/4$ under the exponent.

3.4. Composite tape wear. Theoretical aspect

To determine the wear of the central bowl of the rail truck bolster, the following dependence was applied:

$$\delta = fk\frac{\omega d}{hd_0}\frac{QL}{v} \tag{11}$$

where

ω is the value of the circular sign-variable speed of rotation;
h is the height of the shoulder of the central bowl of the rail truck bolster;
Q is the effective average load (25 t/axle);
L is the mileage;
d_0 is the diameter of the counterbody;
v is the average train speed (100 km/h).

Substituting the values of the quantities into expression (11), we obtained wear graphs on the working side surface of the central bowl of the rail truck bolster on the mileage (Fig. 8).

3.5. Bond strength test

To control the quality of contact welding between the composite tape and the surface of the central bowl of the rail truck bolster, the bond strength was studied using the pin break method (Fig. 9).

As a result of the contact welding tests performed on composite tapes and a sample base material of steel 20GL, bond strength values were obtained (Table 2).

The tests performed on the bond strength of contact welding of composite tapes and a sample base material from steel 20GL allow us to state (Table 2) that the bond strength is more than sufficient. This is manifested for two compositions of composite tapes. For the case of composite tapes with chromium carbide, a higher bond

Table 1
The average value of the hardness of the composite tapes (HB) depending on the value of the concentration of the filler.

Matrix	Filler concentration (Cr_3C_2/TiC), %					
	10	15	20	25	30	35
Fe-Cr-Ni	335/359	344/374	372/397	395/387	390/378	382/366

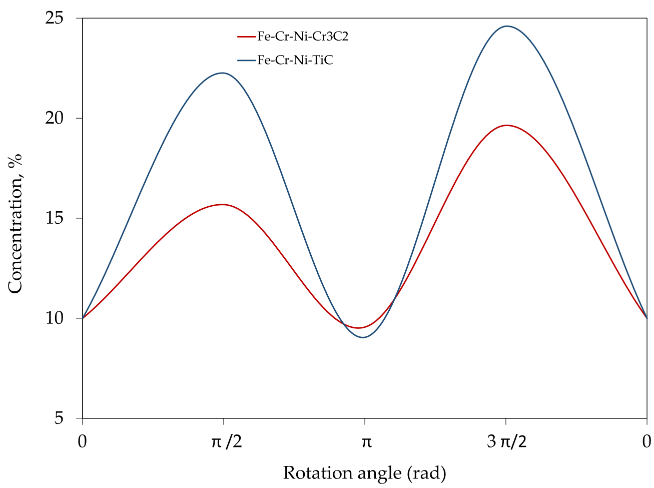


Fig. 7. Theoretical distribution of the filler concentration value depending on the angle of rotation of the point located on the circumference of the working side surface of the central bowl of the rail truck bolster.

strength value of 6.5% can be traced compared to composite tapes with titanium carbide filler.

3.6. Experimental results of wear of the central bowl of the rail truck bolster

Bench tests were carried out to determine the amount of wear on the working side surface of the central bowl of the rail truck bolster. The study of wear was carried out on the repaired working side surface of the central bowl of the rail truck bolster using contact welding of two options for the designed composite tapes. In addition, bench tests were also performed to determine the amount of wear of the working side surface of the central bowl of the rail truck bolster for the following repair options.

– Repair option, which provides for the installation of wear-resistant steel elements;
– A repair option in which the method of automatic surfacing under a layer of flux is used.

The mode was modeled with load-speed characteristics, which are similar to the operating conditions of freight trains. The freight wagon (25.0 t/axle) was presented empty and loaded. The composition of the freight cars consisted of 60 units.

The experimental results of the wear of the working side surface of the central bowl of the rail truck bolster during bench tests of loaded freight cars are shown in Fig. 10. The determination of the amount of wear and its statistical processing were carried out in the Ukrainian car depot.

The experimental results of the wear of the working side surface of the central bowl of the rail truck bolster during the bench tests of empty freight cars are shown in Fig. 11.

The results of the wear on the working side surface of the central bowl of the rail truck bolster indicate the feasibility of using contact welding of composite tapes. At the same time, the amount of wear is more than twice the amount. Therefore, the task was set to determine the value of the wear center plate to obtain a certain picture of the wear of the interacting parts. It does not make sense to present the wear of the results of the center plate wear separately. Therefore, in Fig. 12 shows the experimental results of the total wear value of the working side surfaces of the center plate assembly, depending on the mileage of the loaded freight car.

Experimental results of the value of the total wear of the working side surfaces of the center plate assembly indicate that the burn-in process lasts for 8,000 km. After 8,000 km, the burn-in process ends. The total wear of the working side surfaces of the center plate assembly with welded composite tapes is more than 2–4 times lower compared to traditional repair methods. This confirms the feasibility of using two composite tapes compositions welded by contact welding to the working side surface of the central bowl of the rail truck bolster.

In addition, the total amount of wear of the center plate assembly was studied depending on the mileage of an empty freight car. The results are shown in Fig. 13.

In the case of an empty freight car (Fig. 13), the total wear value of the working side surfaces of the center plate assembly is more than 2–3 times lower for the repair option with composite tapes welded by contact welding compared to the total wear value, where wear-resistant elements were used in the repair process and technology of surfacing under a layer of flux. And in this case, we get confirmation of the feasibility of using composite tapes of the Fe-Cr-Ni-Cr3C2 and Fe-Cr-Ni-TiC composition to repair the the central bowl of the rail truck bolster. It should be noted that for bench tests of an empty freight car, the burn-in process continued after 10,000 km of mileage.

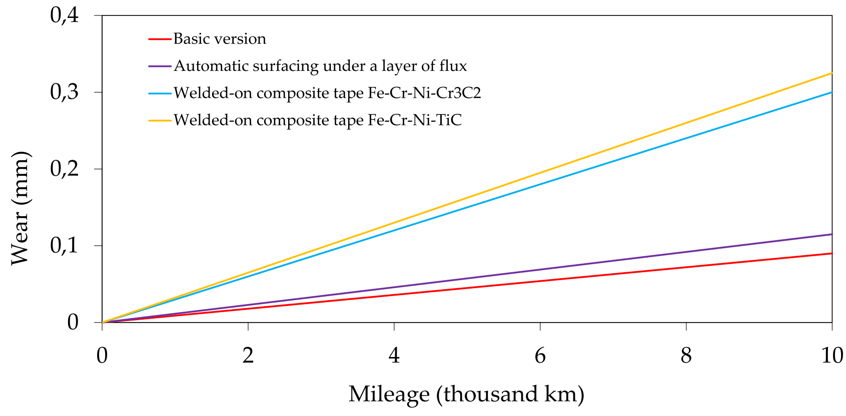
The given data of the total wear of the center plate assembly with welded composite tapes indicate the processes of uniform wear of both parts (Figs. 12, 13).

4. Discussion

In the article, to reduce the wear of the central bowl of the rail truck bolster, the use of composite tapes is proposed, which are welded by contact welding to the working surface. The theoretical study made it possible to develop a mathematical model for the distribution of the filler concentration in the composite tape depending on the angle of rotation of the point, which is located on the circumference of the working side surface of the central bowl of the rail truck bolster. The resulting mathematical model of the filler concentration distribution includes the main characteristics of the tribomechanical properties of the composite material and the counterbody.

The results of experimental studies made it possible to establish the magnitude and nature of the wear of the central bowl of the rail truck bolster during bench tests. Four groups of center plates were tested, which included repair with composite tapes of two compositions with contact welding, repair using the installation of wear-resistant elements and repair technology under a flux layer.

The highest wear of the working side surface of the central bowl of the rail truck bolster both for a loaded freight car (Fig. 10) (0.50 mm per 10,000 km) and for an empty freight car (Fig. 11) (0.24 mm per 10,000 km) was observed during repair using submerged flux repair technology. In second place was the case of using wear-resistant elements. At the same time, the wear rate



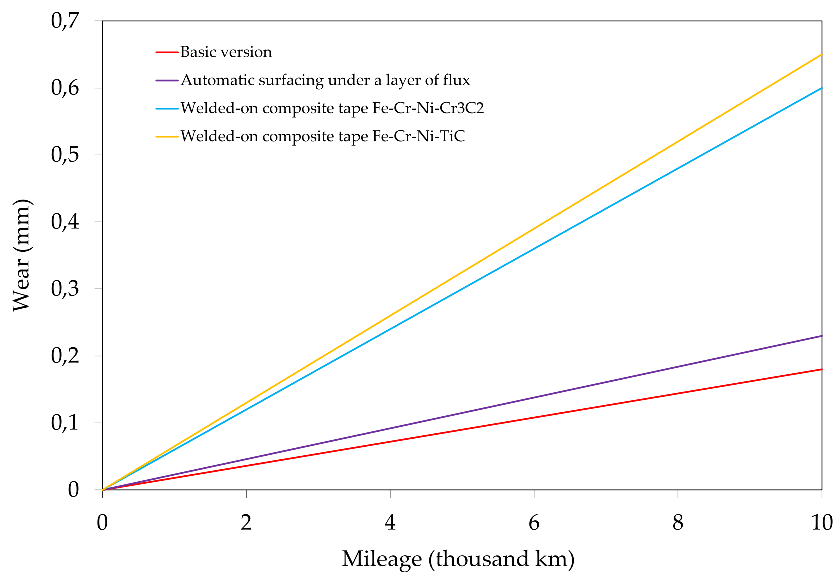


Fig. 8. Wear graphs on the working side surface of the central bowl of the rail truck bolster on the mileage: (a) Full load; (b) Empty mileage.

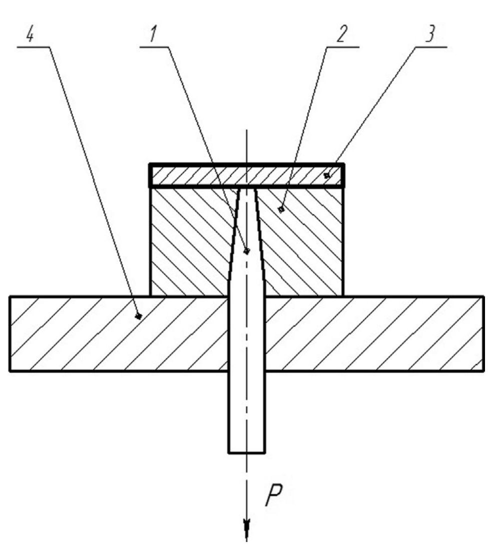


Fig. 9. Bond strength study scheme: **(1)** Pin; **(2)** Sample base material; **(3)** Composite tape; **(4)** Support.

was 0.28 mm per 10,000 km for a loaded freight car and 0.20 mm per 10,000 km for an empty freight car. The smallest amount of wear of the working side surface of the central bowl of the rail truck bolster is observed when using composite tapes of compositions Fe-Cr-Ni-Cr_3C_2 and Fe-Cr-Ni-TiC with contact welding. This value is 0.15–0.18 mm per 10,000 km for a loaded freight car and 0.08–0.10 mm per 10,000 km for an empty freight car. The amount of wear of the working side surface of the central bowl of the rail truck bolster is observed during contact welding of composite tapes of the compositions Fe-Cr-Ni-Cr_3C_2 and Fe-Cr-Ni-TiC 2.7–5.6 times less compared to the amount of wear when applying surfacing under a layer of flux and 1.6–4.3 times less compared to the method of installing wear-resistant elements.

The nature of the wear of the working side surface of the central bowl of the rail truck bolster with composite tapes has a linear relationship, which indicates the absence of the burn-in process of this surface.

Confirmation of the adequacy of theoretical studies of the wear of the working side surface of the central bowl of the rail truck bolster (Fig. 8) was made in comparison with the experimental results shown in Figs. 10, 11. The error of the compared theoretical and experimental results does not exceed 6.25%.

Table 2
The results of the bond strength test (MPa) of composite tapes and a sample base material of 20GL steel welded by contact welding.

Composite tape	Pin no.										
	1	2	3	4	5	6	7	8	9	10	Mean
Fe-Cr-Ni-TiC	287	290	297	305	295	308	307	301	303	298	299.2
Fe-Cr-Ni-Cr_3C_2	308	309	329	315	322	328	320	308	306	312	315.7

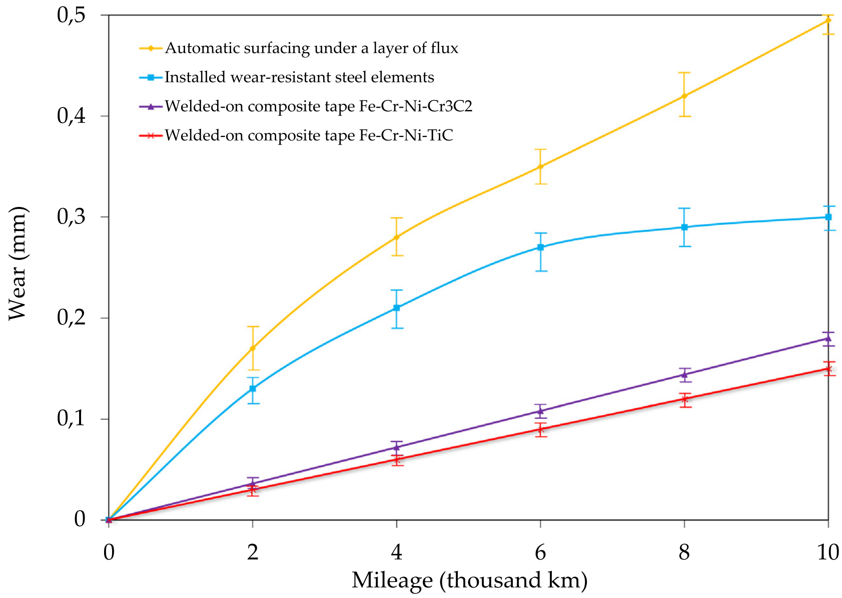


Fig. 10. Experimental results of the wear of the working side surface of the central bowl of the rail truck bolster during bench tests of loaded freight cars, depending on the mileage.

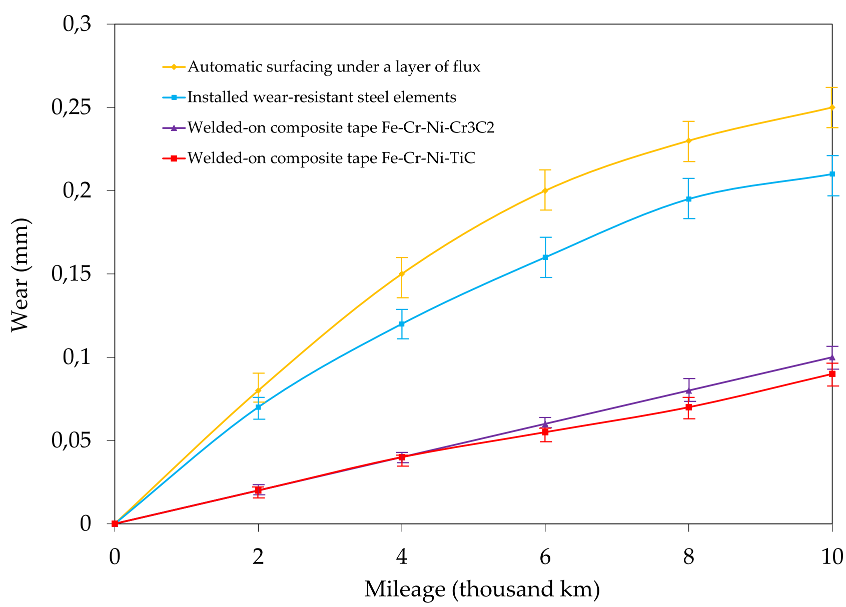


Fig. 11. Experimental results of the wear of the working side surface of the central bowl of the rail truck bolster during bench tests of empty freight cars, depending on the mileage.

Also in the work, the results of the total amount of wear of the working side surfaces of the center plate assembly (Figs. 12, 13) for various repair options depending on the mileage were obtained. The nature and amount of wear were similar to the above-described wear results of the working side surface of the central bowl of the rail truck bolster. The total value of wear of the working side surface of the center plate assembly, depending on the mileage, is 2.4–4.3 times less of contact welding of composite tapes of the compositions Fe-Cr-Ni-Cr_3C_2 and Fe-Cr-Ni-TiC compared to the wear value when surfacing is applied under a flux layer and 2.0–3.7 times less compared to the method of installing wear-resistant elements. The total amount of wear of the working side

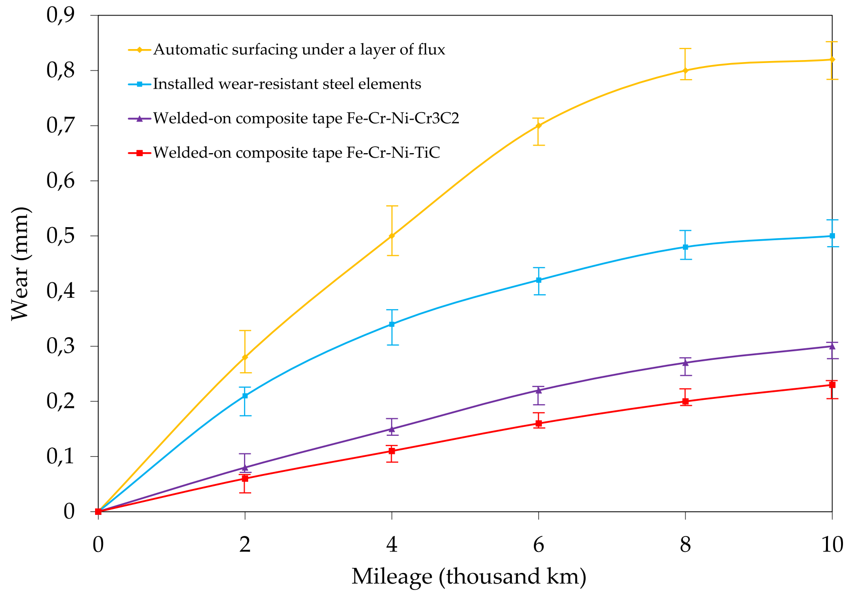


Fig. 12. Experimental results of the value of the total wear of the working side surfaces of the center plate assembly, depending on the mileage of the loaded freight car.

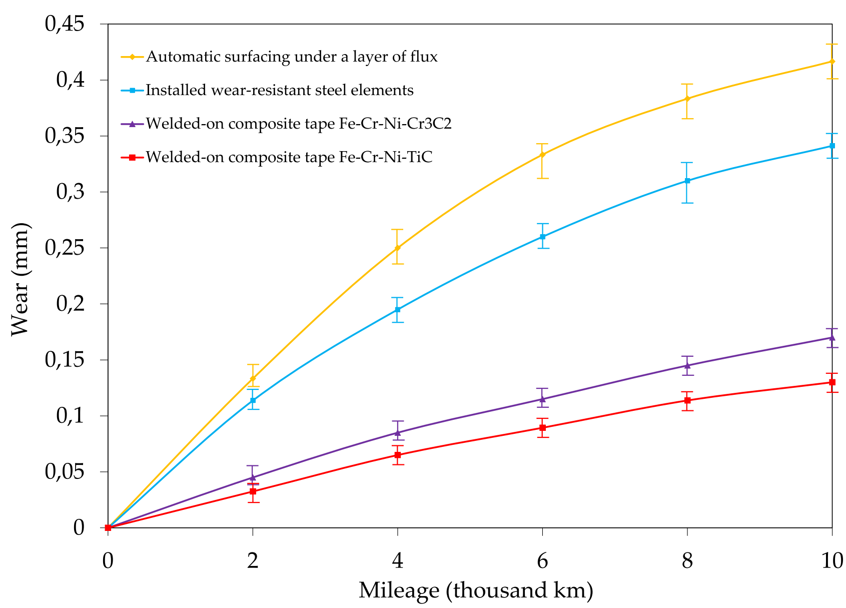


Fig. 13. Experimental results of the value of the total wear of the working side surfaces of the center plate assembly, depending on the mileage of an empty freight car.

surface of the center plate assembly for an empty freight car is 1.41–2.15 times less compared to the variant of a loaded freight car.

5. Conclusions

An increase in the intensity and speed of train movement leads to an uneven distribution of wear on the working surface of the central bowl of the rail truck bolster, which leads to an increase in operational loads on the freight car. To solve the problem of reducing the wear of the working surface of the central bowl of the rail truck bolster, as well as to ensure a uniform distribution of wear, it is proposed to weld the composite tape using contact welding. The projected composite tape has tribomechanical properties with variable characteristics.

As a result of the theoretical studies carried out, a mathematical model of the distribution of the filler concentration in the projected composite tape was obtained for the first time. With the help of this mathematical model, the main indicators of the tribomechanical properties of the composite material and the counterbody can be taken into account. In this case, the distribution of concentration leads to uniform wear of the working surface of the central bowl of the rail truck bolster during operation.

Experimental results of bench tests of the center plate of a freight car indicate the feasibility of using composite tapes (Fe-Cr-Ni-Cr_3C_2, Fe-Cr-Ni-TiC) for contact welding on the working surface of the central bowl of the rail truck bolster. Thus, there was a decrease in the value and a uniform distribution of wear on the working surface of the central bowl of the rail truck bolster in comparison with traditional repair methods. The reduction in wear of the working surface of the central bowl of the rail truck bolster with the designed composite tapes ranged from 1.6 to 5.6 times.

The total amount of wear of the working side surface of the center plate assembly when applied:

– submerged arc surfacing technologies: 0.82 mm per 10,000 km for loaded freight cars and 0.44 mm per 10,000 km for empty freight cars;
– wear-resistant elements: 0.48 mm per 10,000 km for loaded freight cars and 0.33 mm per 10,000 km for empty freight cars;
– composite tape Fe-Cr-Ni-Cr_3C_2 with contact welding: 0.28 mm per 10,000 km for loaded freight cars and 0.14 mm per 10,000 km for empty freight cars;
– composite tape Fe-Cr-Ni-TiC with contact welding: 0.22 mm per 10,000 km for loaded freight cars and 0.12 mm per 10,000 km for empty freight cars.

Confirmation of the adequacy of theoretical studies of the wear of the working side surface of the central bowl of the rail truck bolster, which was based on a comparison with experimental results, made it possible to establish an error value that does not exceed 6.25%.

By the amount of wear of the working side surface of the central bowl of the rail truck bolster, the value of the service life of the center plate assembly can be predicted. Thus, for repairs using a Fe-Cr-Ni-Cr_3C_2 composite tape with contact welding, the service life can be 320,000 km. For a Fe-Cr-Ni-TiC composite tape with contact welding, the service life can be 420,000 km.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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