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ADHESION CONTROL IN THE SYSTEM OF "WHEEL-RAIL"

Summary. The paper reviewed the proposed promising method for jet-abrasive treatment of contact surfaces of wheel and rail. The mathematical model of metal removal and the depth of penetration of abrasive particles, which are used in the method for determining surface roughness profile formed by jet-abrasive processing. Concluded that the choice of parameters and treatment regimes for optimal profile of the surface roughness.

УПРАВЛЕНИЕ СЦЕПЛЕНИЕМ В СИСТЕМЕ «КОЛЕСО-РЕЛЬС»

Аннотация. В работе проведен анализ методов очистки фрикционных поверхностей колеса и рельса. Предложен перспективный способ струйно-абразивной обработки контактирующих поверхностей колеса и рельса. Предложены математические модели съема металла и глубины внедрения абразивной частицы, которые используются в методике для определения образованного профиля шероховатости поверхности при струйно-абразивной обработке. Сделан вывод о выборе параметров и режимов обработки для получения оптимального профиля шероховатости поверхности.

INTRODUCTION

The role of the railway transportations in the transport system of Ukraine is very high. For the majority of large Ukrainian enterprises, railway transport is the main and the only provider of transportation services. Railway transport services all the key industries of Ukraine: metallurgical, machine-building, building, fuel-energy industry, etc. For long-term and large-scale development of the transport industry of Ukraine, rail transport should have a maximum throughput of transport networks and the maximum transport capacity of locomotives, provide for the needs of the society in the transport services with minimal impact on the environment. The increase of speed and volume of transportation of locomotives entails the development of measures for improvement of adhesion of the locomotives, which depends on the processes occurring in the "wheel-rail" contact.

1. DIRECTIONS OF WORKS ON INCREASE AND STABILIZATION OF ADHESION BETWEEN WHEELS AND THE RAILS

Experience of usage of railways and special researches [1, 2] show that the adhesion coefficients of the locomotives may vary from 0.06 to 0.45 and differ significantly from the calculated ones.

Analysing the causes that lead to significant fluctuations of values of the adhesion of wheels with the rails, it was found that a change of the friction properties of the surfaces of friction of wheels and rails, which depends on a number of different external factors, has considerable influence on the value of the coefficients of adhesion. Therefore, the goal of the exploitation is the impact on the friction properties of the surfaces of friction of wheels and rails by preventing the formation of superficial layers of dirt or the implementation of measures for their removal. According to this approach are the following measures: ***prevention measures***, which are able to prevent the emergence of layers of pollution (control of fallen leaves, drops of water, etc.); ***cleaning*** allows to influence on the molecular component of the adhesion coefficients by cleaning the surfaces on the wheel and rail, in order to increase their adhesion (for example, mechanical cleaning, chemical cleaning, cleaning with the sources of high energy, slowdowns, water jet, etc.); ***activation of friction*** allows influence on the mechanical component of friction coefficient by applying different friction modifiers, feeding of the sand or alternative materials, etc. Consider in details the main existing methods for cleaning and activation of contact surfaces of wheel and rail.

1.1. Mechanical methods of cleaning

Mechanical cleaning of the rails [1 - 3] provides mechanical removal of the pollution from the working surface of the rail heads using located in front of the moving vehicular and installed at an angle to the longitudinal axis of the rail scrapers, rotating metal brush or knife for cleaning the bottom surfaces of the rail head. A device that allows with the help of the rubber roller to remove excess moisture located on the rails is also used.

Operational test of the devices for mechanical cleaning of the rails on the domestic and foreign railways have detected low quality of cleaning. The disadvantages of mechanical cleaning include the possibility of its use in a limited range of speed of movement (not more than 15-20 km/h) [1, 2]; cleaning devices accumulate the surface contamination, and become unable implement to complete the process of cleaning; mechanical cleaning is very time-consuming and not always effective, as the adsorbed pellicle are almost impossible to mechanically remove.

There is a method and the device for improvement of adhesion properties of the locomotive, characterized by the fact, that at the moment of the beginning of slipping of wheel with the rail the flow of air in the area of their contact with the speed and temperature that eliminates skidding is carried out [1]. The temperature of the fed air is +375°÷430°C. The technical result is the reduction of wear of wheels and rails, reduction of exploitation expenses (sand) and increase of the adhesive interaction in the contact zone of the wheel with the rail with the cleaning and drying of the contact zone, which leads to increased adhesion properties and the end of slipping. The disadvantage of this method is the need to use a large amount of energy spent for heating the supply air, which leads to more energy expenditure.

The adhesion of wheels with the rails was observed during washing the rails with hot water and the subsequent fanning with dry air. The greatest effect was observed at the speed of the locomotive of up to 10 km/h and when the sand [1]. Washing of the rails with jet of water does not completely remove oil pollution from their surfaces, but promotes intensive corrosion of rails and, ultimately, leads to reduction of adhesion of wheels and the rails. Cleaning of the surface of rails with flame was used, and it is believed that solvents of the oils in combination with water and steam can be more effective.

1.2. Chemical methods of cleaning

Nowadays we know chemical methods of cleaning [1, 2] that use the solutions of different ether, acetone, benzene, some acids, chemicals composed of quartz, based on rapid chemical interaction of chemicals sent to the rails and organic content of pollutants in the form of absorbed pellicles of grease and fatty acids with the formation of the products of the reaction, slightly preventing the molecular and mechanical adhesion of wheels and rails, as well as volatile gaseous substances. However, the application of this method is connected with well-known difficulties arising in connection with the duration of the process of chemical treatment. For effective chemical treatment of the surface of rails is not only required for a long time, but repeating it after the passage of every two or three trains. This treatment improves the general condition of the rails, but does not exclude cases of slipping of locomotives due to the possibility of the formation of local pollution of rails shortly after the cleaning. On the roads of the USA experiments on cleaning rails using manufactured chemical RC successfully conducted, having in its composition particles of quartz, as well as in the experimental ring of central research institute of the Ministry of Railways experiments were conducted to increase the coefficient of adhesion with acetone when slowing down.

Also is offered device and method for increase of adhesion between wheel and the rail [1],that is, that the liquid before applying to the rails process of the ultrasonic radiation and bring it to the status of cavitation, and in this state serves on the surface of the rails. Processing of liquid carry out ultrasonic vibrations with frequency from 18 to 20 Khz at the sound pressure $1 \cdot 10^5 – 1 \cdot 10^6$ N/m^2 within 0.1-10 min. Liquid which is applied to the surface of the rail, can be an aqueous solution of nitrite-nitrate with calcium detalin or an aqueous solution of nitrite-nitrate calcium chloride with detalin. When applied to the surface of the rail liquid, brought to the state of cavitation, organic substances, covering in the form of pellicle on surface of the rail, are removed from the rail surface under the influence of arising of hydraulic shock and at the same time strengthens the surface of riding of the rail. As a result of the use of this method adhesion coefficient increases by approximately 40%.

Increased coefficient of adhesion of wheels with the rails [1] by drawing on the friction surface the substance, connecting together with the evaporation of particles of dirt between themselves and with the surface of friction. Particularly, aqueous solution of polyamide resin in mass concentration of 30-40% can be caused on the friction surface, and the solution of alkali. At drawing on a surface of friction solution of polyamide resin it penetrates in the capillary space between the particles of surface contamination, making surface layer hydrophobic. Then the friction surface of the rail and wheel treated with an alkaline solution, for example, 2% solution of caustic potash, which causes rapid hardening of the surface layer of dirt and after drying improves its mechanical properties (the shear strength and viscosity), improves friction characteristics of tracks of the friction of rails. The proposed method allows to realize higher values of the coefficient of adhesion (0,35 - 0,4) and get more stability in traction of locomotive wheels with the rails.

1.3. Thermomechanical cleaning with slowdown

Slowdown of the driving wheels of locomotives is a necessary though undesirable from the standpoint of wear tires and brake pads, but a fairly common technique used for locomotive crews. Usually it is used in winter as a preventative measure to clean the tires before the prolonged boom, but also it was used in antislipping systems. Slowdown is intended to remove the excess torque from boxing wheelset, with the brake pads acting on the wheelset in the course of 20 seconds or more to clean up the surface of rolling tires with some of their heating, which slightly increases the adhesion coefficient. The disadvantages of this method of cleaning should be assigned that antislipping slowdown requires the use of locomotives on the highly sensitive detection systems, slipping, increases the duration of the brake compressor. We also cannot prevent the use of worn brake pads, as this increases the time needed for pressing pads to bandage, and boxing axis may acquire such velocity that a slight slowdown to restore the grip is not possible.

1.4. Cleaning with high-energy sources

Way to electrospark responsible for cleaning high temperature exposure on the surface, allowing a high degree of purification from all contaminants, including pellicle of absorbed gases, which are one of the reasons for lowering the coefficient of adhesion. Experimental studies of the effectiveness of electrospark cleaning showed an increase coefficient of adhesion as a result of spark treatment from 0,1-0,2 up to 0,6-0,7 and more. Metallographic research of the working surfaces of the samples showed that the electric effect leads to the formation treated surface of a thin layer of martensite with transition zone of mixed structure. The presence of solid martensitic protrusions and the formation of juvenile clean surfaces are obviously the main reasons for increasing of the adhesion coefficient. But connection of martensitic inclusions with the base metal band or rail, wich is not strong, leads to chipping of them as the result of friction, what leds to 50% increase wear of contacting bodies [1].List of major shortcomings include low processing capacity of the track, whose velocity during the tests did not exceed 3 km / h. In the practical applications of this method of cleaning for the locomotives should bear in mind the need for multiple electrodes, providing a stable and uniform work which when powered by a single power source provides well-known difficulties. You should consider the impact speed of the locomotive, since the use of cleaning with electric-pulse duration of the working current at low speed may increase, creating the preconditions for the emergence of significant structural changes of the processed surfaces, the presence of a small air gap between the electrode and the rail, not exceeding 10 mm, does not allow to operate the installation at high speeds, running the plant is a source of radio and acoustic noise that can disrupt the normal functioning of the relay communication [1].

One of the promising ways to increase the coefficient of adhesion is plasma cleaning of the track before the passage of trains .For this purpose, the locomotive is equipped with two low-temperature plasma generator (plasmatron), powered by the electric current source. In practice, there are plenty of various schemes of plasma generators, but electrode and electric arc plasma burners are most suitable for transport conditions. Conducted laboratory studies of plasma generators have established the fundamental possibility of using plasma for the removal of anti-friction coating the working surface of the rail, which could affect adhesion of the locomotive. This method also has several disadvantages: plasmatron should have a wide range of power control, high efficiency, remote control and working resources corresponding to turnaround the locomotive, as well as work on nedefitsitnom gas to be extremely reliable in the manufacture, simple in operation and maintenance, different vibration and firmly oppose to other factors of mechanical action.

Also significant work to increase the coefficient of friction by cleaning the surface of the rail-cooled argon-hydrogen plasma burner is carried out [1]. Effectiveness of the burner correspond to an increase adhesion coefficient of about 0,1–0,2. However, the data are insufficient for definitive conclusions about the effectiveness of the device. Constructive device was not appropriate for direct application on the locomotive, and the process of clearing the rail is still poorly understood.

The essence of the proposed method of processing with microwave and UV - radiation [1] lies in the fact that the contact surface of wheel and rail flux of electromagnetic energy adjustable ultra-high frequency (UHF) from $3{\cdot}10^5$ to $3{\cdot}10^{10}$ Hz is served, and the contact surface of rails further affects the flow of controlled ultraviolet radiation (UV) frequency range from $3{\cdot}10^{13}$ $3{\cdot}10^{14}$ Hz. Thus, the contact surfaces are treated simultaneously as a microwave, and UV - radiation. This joint processing layers of surface dirt flow of electromagnetic energy adjustable frequency range from $3{\cdot}10^5$ to $3{\cdot}10^{10}$ Hz allows to stimulate the electrons of surface of contamination to the energy level of 5 eV, resulting in their transfer through the "forbidden" zone to unoccupied levels of the conduction band, which leads to an increase in dielectric losses in the material surface contamination and, consequently, to the destruction of their structures and the removal of moisture from the contact area. Removing the liquid phase from the layer of surface contamination leads to a quick increase in the coefficient of adhesion of the locomotive wheels with the rails from 0.2 (before treatment) to 0,6-0,7 (after treatment with the contact surfaces of the proposed method).

Laser cleaning of a rail includes the receipt of a pulsed beam of high intensity and direction of the laser beam on the surface of the rail, so as to destroy at least a portion of contaminants from the surface of the rail. With the help of local and non-contact laser irradiation various surfaces can be cleaned of the coatings deposited on them or uneven dirt. On the basis of examinations conducted by a large amount of high-power pulsed lasers Fraunhoferov Institute of Laser Technology (ILT) in conjunction with the British company Laserthor have developed a diode-pumped lasers and working on the basis of fiber optics technology [1]. To clear the running surface of rails the method of freeze-cleaning is preferred. In this case, the formed pellicle of contamination is locally heated to a temperature exceeding the threshold of evaporation without exposing at the same basic material thermal stresses. Thanks to this pellicle can be deleted almost without compromising the basic material. The surface rail does not have time to warm up due to too small a total input energy. Since the evaporation of the pellicle is extremely locally produced steam and particles of the pellicle material can be successfully captured and is removed without entering the atmosphere. Therefore, in this case we are talking about an environment friendly process. When cleaning the surface of the rails required relatively high processing speed is approximately equal to 60 km/h, or 1000 m/min. At the same time focusing device should be compact and satisfy the requirements of necessary mechanical strength due to its placement near the rail head, and to ensure optimal treatment should be the simultaneous action of several lasers with pulse power of 100 kW.

There were efforts for ways to improve the friction characteristics of the friction pair "wheel-rail" through exposure to the contact of electric current and magnetic field [1]. It was found that with increasing current density from 68 to 176 A/mm^2 coefficient of friction of disc on the plane to "dry" contact to the experimental data increases from 0.325 to 0.512. With increasing magnetic field from 0.6 to 7.40 kA / m coefficient of friction increases from 0.176 to 0.220. The growth of coefficient of friction was observed on current until the pick-up or later during the pre-displacement. The average value of the coefficient of friction without external physical fields under the same test conditions was equal to 0.16. When exposed to electromagnetic fields it can occur as a hardening of the friction of bonds and their softening. An increase in the density of the electromagnetic field can lead to local melting of the material pair friction (wheel and rail) and electroerosion phenomena that requires no additional hardware to control the density of the feed of the electromagnetic field.

There are methods of cleaning the rails based on feeding current to the inductive coils located along the arc of tires of wheels [1, 2]. At the time of pick-up from the place to increase the traction of the locomotive the DC voltage is served to the induction coils, which are in the contact zone between the ties with the rails. This creates a magnetic force of attraction, and thereby adhesion weight of the locomotive rises. After the end of the pick-up mode from place from supply voltage to the coil is stopped. As a result, an increase in adhesion coefficient by about 20% is achieved, but the proposed system was complicated, and additional consumption of copper tripped into question the possibility of its widespread adoption.

1.5. Submission of hard abrasive particles

Currently, the stabilization of the main values of adhesion coefficient by the most widely used is by filing a silica sand on the rails. However, the feeding of sand in a contact zone continues to be ineffective in humid, wet and icy rails, even with increased consumption. The methods and devices increasing of the traction by applying one layer of sand in the wheels in contact from rail are known. This effect is achieved by pre-electrification of abrasive granular material. A number of technical solutions for the construction of a sand system are based on the electrification of the particles and for increasing of the adhesion of wheel with rail [1].

The main advantages of the proposed method is:

- effective use of bulk material;
- increase of adhesion coefficient by 20-30% due to the location of sand in a single layer with certain distance between the particles on the track of rolling of wheel and rail;
- eco-efficiency, which is achieved by reduction in the volume of crushed sand particles;
- reduction of wear intensity of the “wheel-rail” system;
- reduction of resistance of movement of the train.

Company Tess (Japan) manufactures innovative system Cerajet System [1],designed to prevent slipping motored wheelsets of locomotives and railcars. The system provides uniform flow and distribution on the running surface of rail of solid ceramic particles, which flows with the same efficiency at 1 / 3 less than the quartz sand. It does not create problems with insulation failure of cables passing from the outside track structure, as well as pollution turnouts with excessive amount of sand. Cerajet system has already been spread on the lines of railways and urban rail transport networks in several countries.

1.6. The use of friction modifiers

The modifiers that create a very high level of friction and are used to increase traction of locomotives for traction and braking efficiency are called activators of friction. In the papers [1, 2] attempts to create all-season traction activator, providing all-weather, stable adhesion coefficient of the locomotive wheels with rails not less than 0,3 and effectively clean the surface of the traction of wheels of the locomotive from surface contamination. The optimum composition of the filler all-season adhesion activator, which provides a coefficient of adhesion 0,32±0,02 is being found, conducted a comparative lab tests of wear quartz sand and briquette of activator of adhesion, showing that the use of adhesion activator reduces the value of abrasive wear by more than 2 times and reduce the amount of sand by 50 times.

2. SUBSTANTIATION OF PERSPECTIVE METHOD OF ADHESION CONTROL IN THE SYSTEM OF "WHEEL-RAIL"

Each of the above methods of purification or activation of contact surfaces of wheel and rail has disadvantages. The main ones are:

- increase the wear or change the structure of the surface being cleaned;
- the impossibility of effective operation of the device over the entire range of operating speeds of the locomotive;
- costs of installing equipment necessary for the implementation of cleaning and maintaining it in working condition;
- the impact on the environment and track facilities;
- the complexity of installation on the locomotive, its maintenance and unlongevity of work.

The authors offer a promising new way to clean [1], which is jet-abrasive cleaning of contact surfaces of wheel or rail using free abrasive. Its advantages is not only in the possibility of removal of surface contamination, a significant increase in adhesion by formation of an effective surface roughness, due to increased contact area of wheel and rail, but in the simplicity of application design and operation.

Variable adhesion conditions require a differentiated selection of tilting the nozzle to the surface of interaction between wheel and rail and the distance to the workpiece, depending on the level and structure of pollution of the rails.

The proposed method of cleaning depending on the structure of the real structure of the surface layer of rails, provided the change of four cleaning regimes, each of which corresponds to a definite angle of attack of abrasive surface of the rail. In the *I* mode of cleaning *with a slicing jet* (α=10°–15°) will only clean the surface of rail by jet-abrasive cleaning from surface contaminants adsorbed on the oxide layer (air, water vapor, oil, dust), which is selected in the range:

$$1 \cong \frac{(h_{pol}^{min} + h_{pol}^{max})}{h_{pol}^{max}} \cong 2, \quad (1)$$

where: h^{min}_{pol} – minimum thickness of the removed layer of surface contamination; h^{max}_{pol} – maximum thickness of the removed layer of surface contamination.

Angle of attack of abrasive material to the surface of the rail at the *I* mode of cleaning the corners correspond to attack *II* cleaning mode, but the rate for the *I* mode of cleaning jet of abrasive material at the nozzle exit is relatively less than the speed of *II* cleaning mode and is within 20-50 m/sec.

The intensity of the withdrawal of contaminants depending on the angle of attack α and the jet velocity *V* of the abrasive at the nozzle exit is determined by the formula [1]:

$$Q = d_ч \cdot \left(\frac{5 \cdot \pi \cdot \rho_ч \cdot (1-\mu_p^2) \cdot V^2 \cdot sin^2 \alpha}{4 \cdot E} \right)^{2/5}, \tag{2}$$

where: α – angle of attack of abrasive material to the surface of the rail; μ_p – Poisson's coefficient; E – elastic modulus; $d_ч$ – diameter of particles of abrasive material; V – velocity of the abrasive at the nozzle exit; $\rho_ч$ – density of particles of abrasive material.

For rails, which are in operation for a short period of time and have even and smooth surface without microscopic geometry cavities and microcracks exhibited *II* second cleaning mode *with a slicing jet* (α=10°–15°) – cleaning without changing the surface microgeometry rails. Distinctive features of the *II* mode of cleaning from the *I* mode is the fact that in this mode, the cleaning jet velocity V of abrasive material at the nozzle exit is in the range of 50-100 m/s and there is a removal of surface contaminants absorbed on oxide layer (air, vapor water, oil, dust) and/or a layer of oxide pellicles - FeO, which is chosen in the range:

$$1 \le \left(\frac{h_{pol}^{min} + h_{of}^{min} + h_{pol}^{max} + h_{of}^{max}}{h_{pol}^{max} + h_{of}^{max}} \right) \le 2, \tag{3}$$

where: $h^{min}{}_{of}$ – minimum thickness of the removed layer of oxide pellicles; $h^{max}{}_{of}$ – maximum thickness of the removed layer of oxide pellicles.

Under emergency braking regime *III* cleaning mode *with oblique jet* (α=30°–45°), providing intensive exfoliation and removal of a layer of surface contamination and/or a layer of oxide pellicles and their impact on the metal layer to remove any burrs and scale, rounding of sharp edges, the formation of an optimal surface microgeometry of the rail and simultaneous delivery of abrasive material to the contact of wheels with the rail in a single layer (for high adhesion qualities standard deviation of the profile of the interacting surfaces of wheel and rail $R_a = 0,7 \div 0,9$ mkm [1]) in the range:

$$1 \le \left(\frac{h_{pol}^{min} + h_{of}^{min} + h_{mat}^{min} + h_{pol}^{max} + h_{of}^{max} + h_{mat}^{max}}{h_{pol}^{max} + h_{of}^{max} + h_{mat}^{max}} \right) \le 2, \tag{4}$$

where: $h^{min}{}_{mat}$ – minimum thickness of removed layer from the surface of the material (rail); $h^{max}{}_{mat}$ – maximum thickness of removed layer from the surface of the material (rail).

The number of abrasive particles that came into contact with processable surface is determined by the formula [1]:

$$n = 12Rh \cdot \frac{\chi \cdot Y(\beta)}{\beta^2 \cdot (x^{-2} + 3\sigma^2)} (1 - \varepsilon_3) k_p, \tag{5}$$

where: R – typical size of the particles of abrasive material; h – penetration depth of particles of abrasive material; χ – particle occupied by the abrasive material per unit volume of flow; β – shape coefficient of particles of abrasive material; $Y(\beta)$ – function that depends on β; x – average size of particles of abrasive material of this grain; σ – standard deviation of particles of abrasive material, $\sigma = 0,17 \cdot x$; ε_3 – coefficient, which considers coupling of particles in the flow; k_p – coefficient, which considers the number of particles of of abrasive material machining.

The resulting surface microroughness is determined by the formula [1]:

$$R_a = 0{,}026 \cdot \sqrt{\frac{h_{max} \cdot a \cdot b \cdot l}{R^2}}, \qquad (6)$$

where: a and b – major and minor axis of the ellipse of the contact with the of abrasive material processable surface of rail; h_{max} – maximum depth of penetration of abrasive material; l – unit of length of the normal section of processed surface of rail; R – radius of the particles of abrasive material.

From (6) the parameter of the surface microroughness R_a completely and uniquely is determined by the maximum penetration depth of abrasive material h_{max}. Due to the impact parameter h_{max} you can actually indefinitely reduce or increase the parameter of the surface microroughness R_a to the necessary size *0,7-0,9* mkm.

If it's necessary to increase the adhesion on highly contaminated rails (under emergency braking) the *IV* mode of cleaning *with the hitting jet* (α=90°) – provides cleaning and reinforcement of the running surface of rails. Under the influence of a direct blow of abrasive material removal of surface contamination is observed, the destruction of the layer of oxide pellicles and the work-hardening the surface of rail. Maximum depth of the abrasive particles in the *IV* mode of cleaning with hitting jet:

$$h_{max} = 2 \cdot k_m^{0,5} \cdot V \cdot R \cdot \sin\alpha \sqrt{\frac{\rho_ч}{3 \cdot k_R \cdot c \cdot \sigma_S}}, \qquad (7)$$

where: k_m – coefficient considering the influence of neighboring particles; k_R – coefficient considering the influence of grit particles of abrasive material on the actual contact area; c – coefficient that estimates the carrying capacity of the contact surface; σ_S – boundary of material yield strength of the rail.

CONCLUSIONS

Based on studies in the field cleaning and activation of the wheel surface, or rail from dirt worked out a method of cleaning, which is jet-abrasive cleaning of contact surfaces of wheel or rail using free abrasive, to improve their quality of adhesion, due to intensive removal of surface pollution and create an optimum for a pair of friction "wheel-rail" microrelief managed, depending on operating conditions, the parameters of microgeometry of surfaces, which leads to an increase in actual contact area and, consequently, to improve the adhesion of locomotive wheel and the rail.

Bibliography

1. Казаринов В.М., Вуколов Л.А.: *Коэффициенты сцепления колесных пар с рельсами при торможении.* Исследование автотормозной техники на железных дорогах СССР, Науч. тр. ВНИИЖТ. Транспорт, Москва, 1961, вып. 212, с. 5-28.
2. Лисицын А.Л., Потапов А.С.: *Выбор расчётного значения коэффициента сцепления локомотивов.* Электрическая и тепловозная тяга, 1976, №4, с. 42-44.
3. Нувиньон М., Бернар М.: *Новое в коэффициенте сцепления электровозов.* Бюллетень технико-экономической информации МПС, 1961, №7.

4. Каменев Н.Н.: *Эффективное использование песка для тяги поездов*. Тр. ЦНИИ МПС. Транспорт, Москва, 1968, вып, 336.
5. Спицын М.А.: *Физическая природа сцепления колес с рельсами и способы повышения величины коэффициента сцепления.* Исследование автотормозной техники на железных дорогах СССР, Науч. тр. ВНИИЖТ. Транспорт, Москва, 1961, вып, 212, с. 39-44.
6. Исаев И.П., Лужнов Ю.М.: *Проблемы сцепления колес локомотива с рельсами*. Машиностроение, Москва, 1985.
7. Исаев И.П.: *Случайные факторы и коэффициенты сцепления*. Транспорт, Москва, 1970.
8. Ламанов А.В., Щурин К.В., Слутин А.Ф.: *Способ повышения сцепных свойств рельсового транспортного средства и устройство для его осуществления.* Патент *2252166 C1* Российская Федерация, опубл. 20.05.2005, бюл. № 4.
9. Лужнов Ю.М.: *Сцепление колёс с рельсами (природа и закономерности)*. Интекст, Москва, 2003.
10. Кащеев Н.Т., Спицын М.А.: *Заклинивание колесных пар и меры его предупреждения*. Транспорт, Москва, 1964.
11. *Rail Surface and Locomotive Wheel Slipping*. Monthly Bul. of IRCA, vol. XXXVIII, № 2, 1961.
12. Ляпушкин Н., Бендиткис Р.С., Ванаг Я.А. и др.: *Устройство для увеличения сцепления колеса с рельсом.* А.с. № 712297 СССР, опубл. 30.01.80, бюл. № 4.
13. Лужнов Ю.М., Шевандин М.А., Федоров А.Е. и др.: *Способ повышения сцепления колес железнодорожного транспортного средства с рельсами.* А.с. № 712156 СССР, опубл. 05.05.80, бюл. № 17.
14. Золотых А.И.: *Физические основы электроискровой обработки металлов*. ГИТТЛ, Москва, 1953.
15. Лазаренко Б.Р., Лазаренко Н.И.: *Электроискровая обработка металлов*. Госэнергоиздаг, Москва, 1950.
16. Доббс Д.: *Плазменная горелка применима при низких скоростях движения*. Железнодорожный журнал, 1969, № 7.
17. Лужнов Ю.М., Попов В.А., Пыпаев В.А.: *Способ повышения сцепления колес железнодорожного транспортного средства с рельсами.* А.с. № 943053 СССР, опубл. 15.07.82, бюл. № 26.
18. *Скоростная очистка рельсов лазерным излучением*. Железные дороги мира, 2005, № 2, http://www.css-rzd.ru/ZDM/2005-02/05002-1.htm.
19. Воробьев Д.В.: *Улучшение фрикционных характеристик пары трения колесо-рельс за счет воздействия на контакт электрического тока и магнитного поля*: дис. … к. т. н., Брянск, 2005.
20. Сливинский Е.В., Зайцев А.А., Сираев Р.О.: *Локомотив*. Пат. 2314949 C1 Российская Федерация, опубл. 20.01.2008, бюл, № 4.
21. Пойлов Л.К., Сапрыкин Л.И.: *Оценка надёжности электромагнитных увеличителей сцепления.* Тр. ЛИИЖТа, вып. 370, 1974.
22. Кравченко Е.А.: *Обоснование резервов повышения тяговых качеств локомотива и их реализация управлением скольжения в системе колеса с рельсом*: дис. … к. т. н., Луганск, 2010.
23. *InnoTrans 2008 – крупнейшая выставка железнодорожной техники. Часть II.* Железные дороги мира, 2008, № 11, с. 12-13.
24. Кикичев Ш.В.: *Повышение эффективности активизаторов сцепления путем улучшения их адгезионных характеристик*: автореф. дис. … к. т. н. Ростов-на-Дону, 2009.
25. Окулова Е.С.: *Модельная оптимизация и прогнозирование трибохарактеристик системы «путь – подвижной состав» (на примере магистрального электровоза ВЛ-80)*: автореф. дис. … к. т. н., Ростов-на-Дону, 2006.

26. Голубенко О.Л., Горбунов М.І., Кашура О.Л. и др.: *Спосіб підвищення зчеплення в зоні контакту колеса з рейкою.* Деклараційний патент на корисну модель № 48516, опубл. 25.03.2010, бюл, № 6.
27. Стефанович Т.О.: *Технологічне забезпечення якості поверхонь деталей машин обробленням струменем незв'язаних твердих тіл*: автореф. дис. к.т.н.: 05.02.08 / Т.О. Стефанович. Національний університет "Львівська політехніка", Львів, 2007.
28. Голубенко О.Л.: *Зчеплення колеса з рейкою*: Моногр. – Фірма «ВІПОЛ», Киев, 1993.
29. Тамаркин В.А., Азарова А.И.: *Теоретические основы оптимизации процессов обработки деталей свободными абразивами*. Вестник машиностроения, 2002, № 6, с. 50-54.
30. Тихонов А.А., Плотникова М.М.: *Формирование профиля шероховатости при гидроабразивной обработке.* VI Всероссийская научно-практическая конференция «Инновационные технологии в обучении и производстве», Камышин 15–16 декабря 2009.

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