MINING MACHINERY, TRANSPORT, AND MECHANICAL ENGINEERING

Research paper
https://doi.org/10.17073/2500-0632-2022-11-34
UDC 622.625.6

Effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims

E. M. Arefiev[1], K. A. Ryabko[2]
[1] Saint Petersburg State Institute of Technology, Saint Petersburg, Russian Federation
[2] Rostov State University of Railway Transport (Voronezh Branch), Voronezh, Russian Federation
elcross@mail.ru

Abstract
An increase in the rate of coal mining and a reduction of its prime cost can be ensured by comprehensive mechanization and automation of the system of mine auxiliary transport through the widespread introduction of overhead monorail tracks. The potential use of mine monorail tracks are conditioned by the following factors: low payload ratio of the train; reduction of the mine workings cross-section area due to transfer of auxiliary transport to the upper part of the workings; high operational safety; as well as the possibility of dismantling the track in the unused sections and subsequently installing it in new mine workings. The use of rubberized rollers in the drives of mine monorail locomotives enables the coefficient of adhesion of the wheel with the monorail to be increased. It also reduces dynamic loads and the noise level during operation. The purpose of this research is to assess the durability of polymeric rims of drive wheels for mine monorail locomotives, taking into account their operating conditions. Stress distribution over the contact area of the wheel rim with the monorail was determined, enabling the development of measures to increase the service life of drive wheels of mine monorail locomotives to be developed. It was established that the effect of the monorail track deformation has no significant impact on the durability of drive wheel rims of mine monorail locomotives. A mathematical model was obtained to determine the durability of drive wheel polymeric rims, taking into account the maximum dynamic forces arising during the contact of drive wheels with the monorail. The durability of wheel polymeric rims of mine monorail locomotives was assessed in accordance with the Bailey criterion with regard to the maximum values of dynamic contact loads arising during the monorail train movement. It was also established that an increase in the carriage mass from 20 to 47 kN leads to 32 % less durability of a monorail locomotive drive wheel rim (from 8700 to 5900 hours).

Keywords
mine monorail track, monorail locomotive, durability, service life, drive, polymeric rim, overhead monorail, undercarriage, dynamic loads

For citation
Arefiev E.M., Ryabko K.A. Effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims. *Mining Science and Technology* (*Russia*). 2023;8(1):59–67. https://doi.org/10.17073/2500-0632-2022-11-34

ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Влияние условий эксплуатации шахтных монорельсовых локомотивов на долговечность полимерных ободьев приводных колес

Е.М. Арефьев[1], К.А. Рябко[2]
[1] Санкт-Петербургский государственный технологический институт (технический университет), г. Санкт-Петербург, Российская Федерация
[2] Ростовский государственный университет путей сообщения (филиал в г. Воронеже), г. Воронеж, Российская Федерация
elcross@mail.ru

Аннотация
Увеличение темпов добычи угля и снижение ее себестоимости может быть обеспечено путем комплексной механизации и автоматизации системы шахтного вспомогательного транспорта за счет широкого внедрения подвесных монорельсовых дорог. Перспективность использования шахтных монорельсовых дорог обусловлена низким коэффициентом тары состава; снижением площади сечения выработок за счет вынесения вспомогательного транспорта в верхнюю часть выработок; высокой безопасностью

эксплуатации; возможностью демонтажа дороги на неиспользуемых участках и последующего монтажа в новых выработках. Использование обрезиненных роликов в приводе шахтных монорельсовых локомотивов позволяет повысить коэффициент сцепления колеса с монорельсом, снизить динамические нагрузки и уровень шума в процессе эксплуатации. Целью исследований является оценка долговечности полимерных ободьев приводных колес шахтных монорельсовых локомотивов с учетом условий их эксплуатации. Получено распределение напряжений по пятну контакта обода колеса с монорельсом, что позволит разработать мероприятия по повышению срока службы приводных колес шахтных монорельсовых локомотивов. Установлено, что влияние деформации монорельсового пути не оказывает существенного влияния на долговечность ободьев приводных колес шахтных монорельсовых локомотивов. Получена математическая модель для определения долговечности полимерных ободьев приводных колес с учетом максимальных динамических усилий, возникающих при контакте приводных колес с монорельсом. Проведена оценка долговечности полимерных ободьев колес шахтных монорельсовых локомотивов в соответствии с критерием Бейли с учетом максимальных значений динамических контактных нагрузок, возникающих при движении монорельсового состава. Установлено, что увеличение массы тележки с 20 до 47 кН приводит к снижению долговечности обода приводного колеса монорельсового локомотива на 32 % (с 8700 до 5900 ч).

Ключевые слова

шахтная монорельсовая дорога, монорельсовый локомотив, долговечность, срок службы, привод, полимерный обод, подвесной монорельс, ходовая тележка, динамические нагрузки

Для цитирования

Arefiev E.M., Ryabko K.A. Effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims. *Mining Science and Technology* (*Russia*). 2023;8(1):59–67. https://doi.org/10.17073/2500-0632-2022-11-34

Introduction

One way to increase coal production is to increase labor productivity. One important fact in this regard is the connectivity, comprehensive mechanization and automation of the mine auxiliary transport system by means of wide introduction of overhead monorail tracks becomes of great importance.

The potential of the use of monorail tracks in mines are conditioned by a number of essential advantages of this transport type: low payload ratio of the train; transfer of auxiliary transport to the upper part of the workings, enabling a substantial decrease in the section area and thus the capital expenditures for their construction; high safety of operation both at high and low speeds; simple automation; as well as possibility of dismantling the track in the unused sections and subsequently installing it in new mine workings.

The use of rubberized rollers in the drive of mine monorail locomotives enables the coefficient of adhesion with the monorail to be increased. It also enables a reduction in the dynamic loads and the noise level during operation. Therefore, the issue of the effect of mine monorail locomotives operating conditions on the durability of drive wheel polymeric rims is relevant.

Review of researches and publications

A number of papers of scientific-research and design organizations are dedicated to the design and upgrading of drives for monorail locomotives used in mines. The methods of calculating the main parameters and operating conditions for drive wheels of mine overhead monorail locomotives, as considered in scientific publications, do not fully reflect the effect of the interaction of the drive wheels with the monorail with regard to their durability. The synthesising of multipurpose methods on the effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims is a very complex scientific task. Analysis of computational and theoretical bases aimed at developing drives for overhead monorail locomotives shows the necessity of assessing the effect of their operating conditions on the durability of drive wheel polymeric rims.

Results of studies of the winch wheel rolling process aimed at increasing the draft force when driving on slopes are presented in [1]. The authors substantiate the possibility of increasing the tangential draft force by means of increasing the coefficient of adhesion between the wheels and the monorail by making winch wheels out of friction materials. This paper, however, does not address the issues of assessing the durability of drive wheel polymeric rims.

The study in [2] proposes a design of the mine locomotive drive which provides increased draft and braking properties due to the use of additional rubberized rollers kinematically connected with the drive wheels. The use of friction materials for roller lining allows the draft force and coefficient of adhesion to be increased up to 0.35...0.45 and the braking distance to be reduced. The above studies refer to the draft-braking properties of monorail locomotives, but do not cover the very relevant issue of studying the effect of increasing the coefficient of adhesion of additional rubberized rollers with a monorail on durability.

The results of studying the process of interaction between the drive carriage and the monorail using the original simulation model are presented in [3, 4]. The additional deformations of the monorail track due to inertial components arising in the process of the monorail train movement have been assessed, and the maximum dynamic loads arising in the "carriage-rail" system have been determined. The main provisions of the work under study do not reflect the effect of dynamic loads on the drive wheels.

Significant works are dedicated to the simulation of loads and justification of design parameters of tough elastic elements, justification of geometrical parameters of rubber-polymeric drive drums of a belt conveyor, prediction of complex failure of rubber materials, as well as the effect of increased speeds of monorail locomotives on the dynamic parameters of the locomotive–monorail system. Paper [5] provides a simulation of the loads arising in the rubber-cord elastic coupling. An epure of equivalent stresses of the elastic element was obtained. These results are valid for rubber-cord elements working in shear, while not taking into account the nature of loading of mine monorail locomotive drive wheels. Paper [6] describes the forces occurring in rubber linings of the belt conveyor drive drums. The stress-strain state of digital solid models was simulated. In paper [7] a comprehensive method of determining the parameters of rubber fracture is given. The proposed method allows a quantitative assessment of rubber strength depending on the applied mechanical impacts. However, it does not fully take into account the features of loading the rims of drive wheels of mine monorail locomotives. Papers [8, 9] present the results of numerical simulation of the locomotive impact on the overhead monorail track, aimed at improving the safety of mine monorail locomotives. However, the models obtained do not take into account the effect of dynamic loads on the truck of hauling carriages.

The main provisions of the studies under consideration do not fully determine the effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims, so they require additions and clarifications.

Operation of a wheel drive for overhead monorail locomotives in mines is characterized by several parameters: formation of draft force; creation of the necessary coefficient of adhesion of a wheel with a monorail; perception of alternative dynamic impacts from track roughness; as well as influence of braking forces and condition of interaction surfaces between a monorail and drive wheels. All these parameters have been well studied for ground-based motor road and railway vehicles, but they do not fully reflect the assessment of the influence of mine monorail locomotives operating conditions on the durability of drive wheel polymeric rims.

Purpose of research

During use, the drive wheels of a mine monorail locomotive, drive wheel polymeric rims experience periodic contact stresses due to the contact of the rim elements with the monorail. The relationship of rim durability to operating conditions determines the economically justified parameters. Thus, the assessment of durability of drive wheel polymeric rims of mine monorail locomotives is of scientific and practical interest.

Research methods

Studies aimed at determining the effect of operating conditions of mine monorail locomotives on the durability of drive wheel polymeric rims were carried out using the methods of differential and integral calculus, mathematical analysis and graphic interpretation.

The durability of polymeric and rubber rims of drive wheels for monorail tracks under dynamic contact loads can be determined in accordance with the Bailey criterion [10]:

$$N\int_0^{\Theta}\frac{dt}{L(\sigma,\,T)}=1, \qquad (1)$$

where N is the number of pulses to fracture; $L = L(\sigma, T)$ is the durability of rubber and polymeric products under the static loading mode; σ is the law of stress change; T is the absolute temperature of rim material (temperature of mine atmosphere); $\Theta = l_c/V$ is the pulse duration (time of contact of the rim fragment with a monorail); V is the average speed of train movement; here l_c is the length of the rim contact patch with the monorail (Fig. 1) determined by the Hertz formula [11]:

$$l_c=\sqrt{\frac{4F_d r_{red}}{\pi E_{red}}}, \qquad (2)$$

where F_d is the force of contact interaction between the monorail locomotive carriage wheel and the monorail; E_{red} is the reduced modulus of elasticity:

$$E_{red}=\frac{E_1E_2}{E_1+E_2},$$

where E_1, E_2 are the moduli of elasticity of the wheel rim and the monorail, respectively; r_{red} is the reduced radius of curvature,

$$\frac{1}{r_{red}}=\frac{1}{r_1}+\frac{1}{r_2},$$

where r_1, r_2 are the radii of curvature of the wheel rim and monorail.

When the carriage moves at constant speed V, the monorail deflects in the vertical plane by value z under the action of carriage mass m. This deflection is caused by the action of both static load and vertical forces of inertia (Fig. 2).

The mass of the carriage with the load is much greater than the mass of the monorail section, so the mass of the monorail can be neglected. The force with which the carriage acts on the monorail can be represented by the dependence:

$$F_d=mg-m\frac{d^2z}{dt^2}.$$

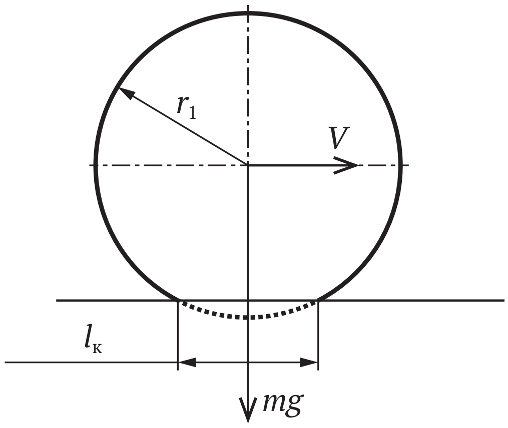

Fig. 1. Establishing the contact patch length of the wheel rim with the monorail

Given that coordinate $x = Vt$:

$$\frac{dz}{dt}=\frac{dz}{dx}\frac{dx}{dt}=V\frac{dz}{dx}.$$

Hence:

$$\frac{d^2z}{dt^2}=V^2\frac{d^2z}{dx^2}. \quad (3)$$

Given equation (3), the force with which the carriage acts on the monorail:

$$F_d=m\left(g-V^2\frac{d^2z}{dx^2}\right). \quad (4)$$

The monorail can be seen as a beam (see Fig. 2) acting on the curve; then, the deflection of the beam can be described by equation:

$$z(x)=\frac{F_d}{E_2J}\frac{x(L-x)^2}{3L},$$

where L is the distance between monorail hangers (section length); J is the moment of inertia of the monorail cross section.

Given equation (4) we obtain:

$$z(x)=m\left(g-V^2\frac{d^2z}{dx^2}\right)\frac{x^2(L-x)}{3LE_2J}. \quad (5)$$

The maximum dynamic load at the wheel contact with the monorail will occur in the middle of the span between the monorail hangers $L = x/2$, then, taking into account formula (5), we get:

$$F_{d_{\max}}=mg\left(1-V^2\frac{mL}{3EJ}\right). \quad (6)$$

The monorail for modern mine monorail tracks is made of a hot-rolled steel I-beam with a section height of 160 mm and the following parameters: $E_2 = 20.6\cdot10^7$ kN/m² and $J = 8.72\cdot10^{-6}$ m⁴.

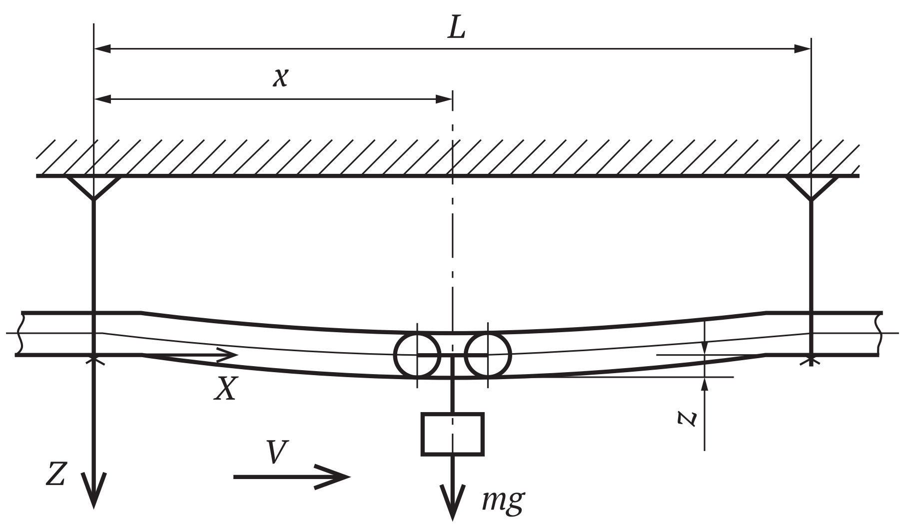

Fig. 2. Diagram of deformation of the overhead monorail track under the moving carriage

According to studies [3, 12], the maximum dynamic forces arising at the contact of a monorail with a drive wheel, depending on the carriage mass, change from 20 to 47 kN, and the maximum longitudinal bending varies from 7 to 15 mm (Table 1).

Table 1

Maximum dynamic forces arising from the contact of the monorail with the drive wheel and values of maximum longitudinal bending of the monorail depending on the carriage mass

Carriage mass m, t	Maximum dynamic forces, $F_{d_{max}}$, kN	Maximum longitudinal bending of monorail z_{max}, mm
2	20	6.3
2.5	25	7.5
4	42	13
4.5	47	15

Durability of rim material under static loading mode [13–15]:

$$L(\sigma)=\tau_0 \ln\left(\frac{\Delta p_\infty}{\Delta p_\infty-\Delta p_{cr}}\right)\exp\left(\frac{U_0-\gamma\sigma}{k'T}\right), \quad (7)$$

where τ_0 is the vibrational period of atoms in molecules; Δp_∞ is an increment of bond excessive stresses accumulation caused by thermal fluctuations; Δp_{cr} is the critical concentration of bond excessive stresses accumulation; U_0 is the energy of rim material chemical bond breaking activation; k' is the Boltzmann constant; and γ is the structure-sensitive parameter [16, 17].

As a rule, mine monorail locomotive haulage is used for the transportation of auxiliary cargo within one mine horizon where the temperature of the mine atmosphere is practically constant. Thus the influence of temperature change on the rim durability can be neglected.

The stress in the contact of two cylindrical surfaces can be determined by the Hertz formula. Taking into account the maximum dynamic forces arising from the contact between the monorail and the drive wheel, a stress occurs in the rubber or polymeric rim. The average value across the contact patch is as follows:

$$\sigma_{av}=\sqrt{\frac{E_{red}E_{d_{max}}}{\pi(1-\mu^2)r_{red}B}}, \quad (8)$$

where μ is the Poisson ratio of the rim material; B is the width of the wheel.

The change in stress pulses in time is well described by a parabola of the form:

$$\sigma(t)=A_1t^2, \quad (9)$$

where A_1 is the coefficient, which is determined by the shape of the stress pulse.

Coefficient A_1 can be determined by taking into account the average value of stress (8) and the duration of cycle Θ of the wheel rim fragment contact with the monorail:

$$A_1=\frac{3\sigma_{av}}{\Theta^3}.$$

Let us suppose that the monorail deflects along a circular arc. Then the radius of the arc when the carriage is in the middle of the span can be determined by the following dependence:

$$r_2=\frac{L^2}{8z_{max}}+\frac{z_{max}}{2}.$$

In this case, at the places where the monorail hangs on the fastening sections (see Fig. 2), the sections of the monorail can be considered horizontal, $r_2\to\infty$.

The results of calculations show that the number of cycles before failure when the carriage is at the places of monorail suspension ($r_2\to\infty$) and in the middle of the span

$$\left(r_2=\frac{L^2}{8z_{max}}+\frac{z_{max}}{2}\right)$$

differs by no more than 1 %. This conclusion was obtained on the basis of calculations performed according to equation (1), taking into account the durability of rubber and polymeric products under static loading mode L.

This allows us to conclude that the effect of monorail deflection can be disregarded when calculating the durability of drive wheel rims for mine monorail locomotives.

Taking into account equations (1), (7) and (9), we can determine rim durability T_r, h:

$$T_r=\frac{1{,}74\cdot10^{-3}}{V\int\limits_0^{\Theta}\frac{dt}{\tau_0\ln\left(\frac{\Delta p_\infty}{\Delta p_\infty-\Delta p_{cr}}\right)\exp\left(\frac{U_0-\gamma\sigma(t)}{k'T}\right)}}. \quad (10)$$

According to the results of simulating the working process of carriage interaction with the overhead monorail [3, 18, 19] the range of values of maximum dynamic forces arising from the contact of the monorail with the drive wheel was obtained: 20...47 kN per carriage. At the same time, there is a load of $F_{d_{max}}=10\cdot10^3...2.35\cdot10^3$ N per carriage wheel, respectively. For this range of contact forces, the rim can take from $1.1\cdot10^7$ to $6.7\cdot10^6$ interactions.

Using equation (10), we obtained a graphical dependence of wheel rim durability on the load

(Fig. 3), a hyperbolic dependence for the following conditions: $F_{d_{\max}}$ = 10...23 kN; T = 305.15 K; V = 3 m/s; r_1 = 0.08 m; B = 0.04 m.

Analysis of the dependences obtained shows that when the carriage mass increases from 20 to 47 kN, the durability of polymeric rims of mine monorail locomotives decreases by 32 % (from 8700 to 5900 h).

The formation of stress pulses is determined by the complex nature of interaction between the wheel rim and the monorail, as well as by the train speed and the current distance from the monorail suspension point to the fastening sections to the carriage [3, 20, 21]. This makes it difficult to obtain an analytical dependence describing the value of stress pulses. At the same time, the pulse shape is described quite well by a paraboloid of the following form:

$$\sigma(x', y') = A_2(x')^2 + B_2(y')^2,$$

where A_1, B_1 are coefficients determined by the stress pulse shape. Coefficient $B_1 = l_c$, taking into account the ratio of the length and width of the contact patch for the rim with the monorail, $A_2 = 1/2B_2$; x', y' are relative dimensions of the contact patch of the wheel rim with the monorail.

Based on the dependences calculated, the distribution of stresses over the contact patch of the wheel rim with the monorail was obtained. This has the shape of an elliptic paraboloid (Fig. 4). Graphic interpretation of stresses shows that the maximum stresses are concentrated at the top of the paraboloid.

Since the durability of the material is inversely proportional to stresses, the greatest wear will be on the rim surface along the line passing through the middle of its generators.

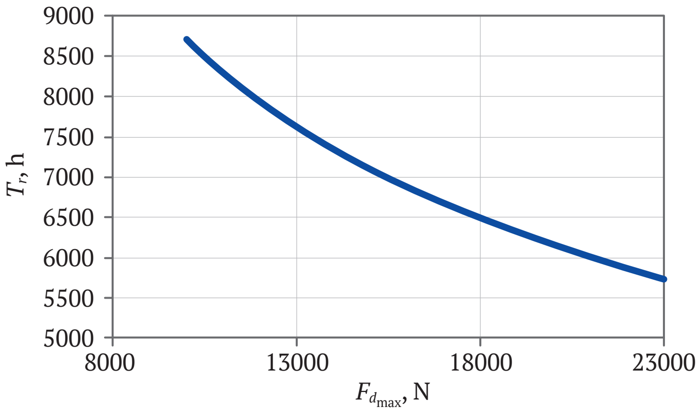

Fig. 3. Dependence of durability of monorail locomotive drive wheels on the force acting on one wheel

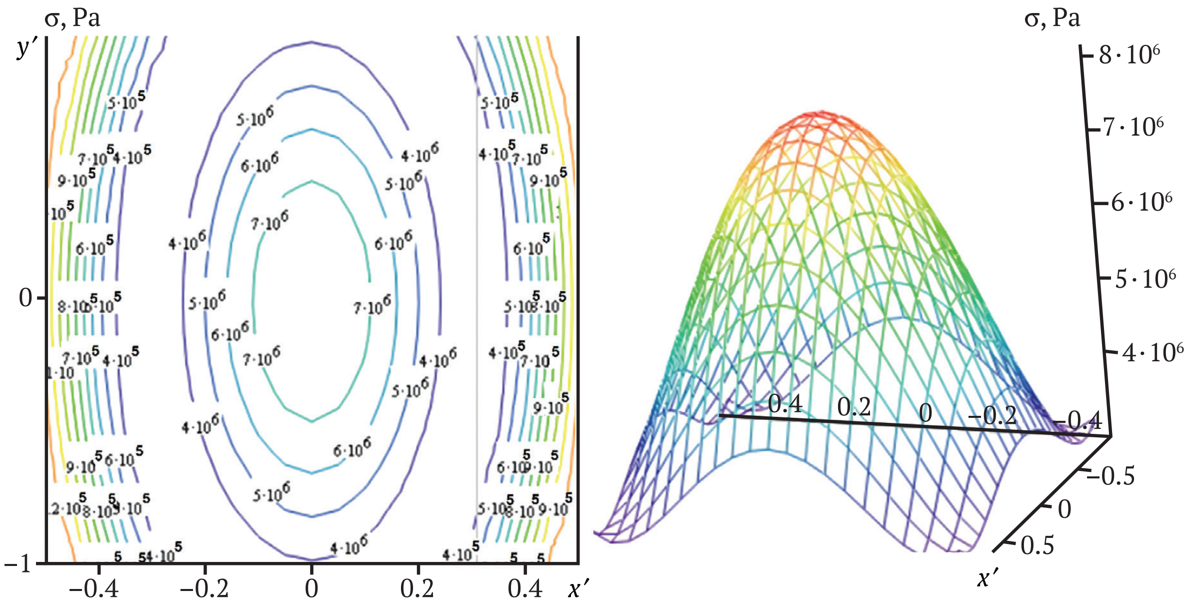

Fig. 4. Distribution of stresses along the contact patch of the wheel rim with the monorail: y', x' are relative dimensions of the contact patch

Practical use

Based on these dependencies, an algorithm was obtained to determine the parameters of drive wheels of monorail locomotives (wheel radius and rim material), in order to ensure the required durability T_{req} of their rims (Fig. 5).

The algorithm takes into account the parameters of the monorail track and the locomotive, enabling the maximum contact dynamic forces in the polymeric rim of drive wheels to be determined. Using the above methodology, it is possible to establish the parameters of the shape of the stress pulse change in time, as well as to calculate the durability of the rim, taking into account the parameters of the mine atmosphere and its material.

The results obtained can be used both in the process of developing technical assignments and designing the drive wheels of mine monorail locomotives, as well as in studies aimed at improving the design of drives for the rolling stock of the overhead monorail track. Also, the algorithm and calculation methods described above can be useful for engineers and technicians of mining enterprises interested in durability and increasing performance indicators of mine monorail locomotives running gears.

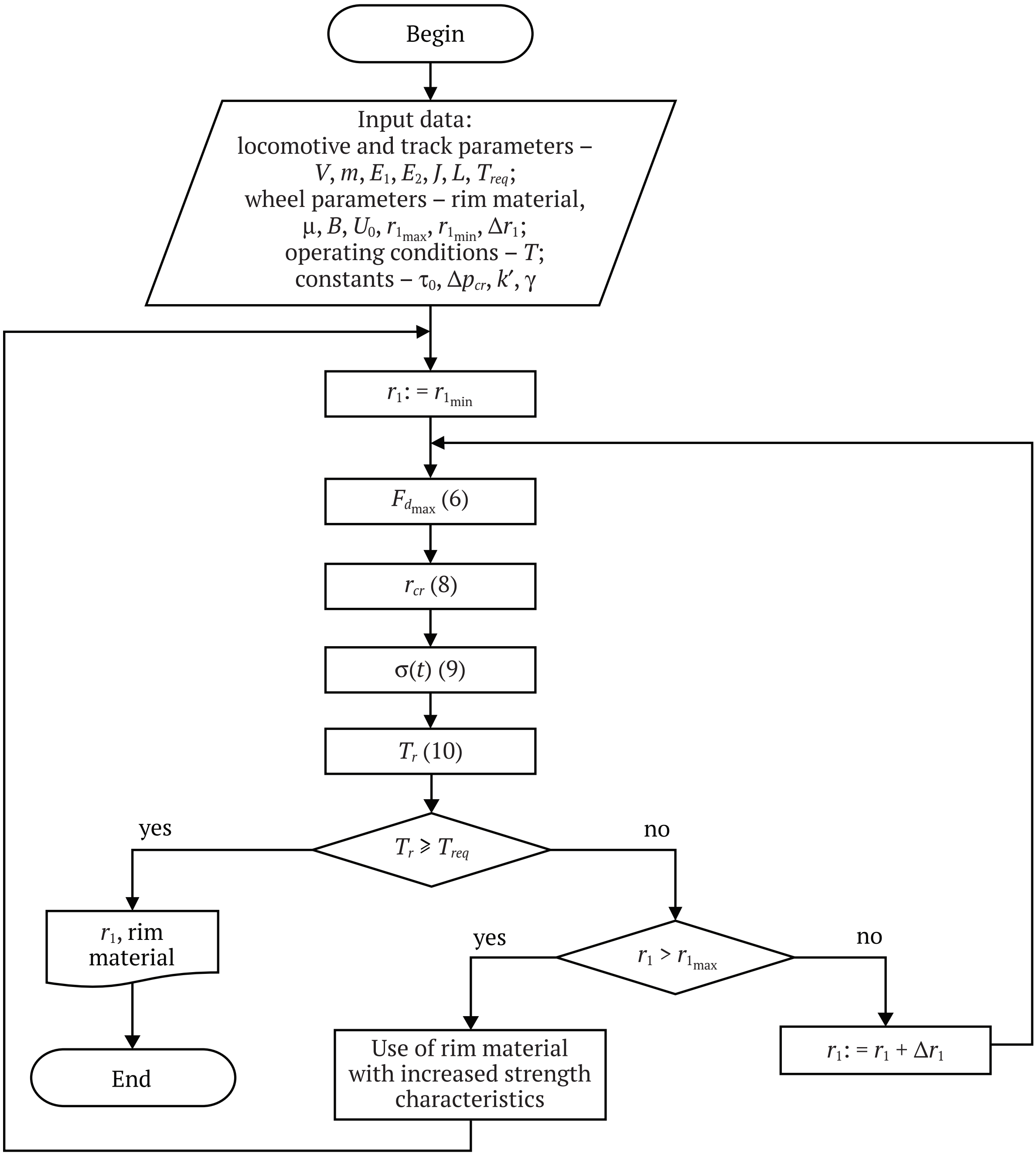

Fig. 5. Algorithm of determining the parameters of drive wheels of monorail locomotives to ensure required durability T_{req} of their rims

Conclusions and further research

A mathematical model was obtained to determine the durability of drive wheel polymeric rims, taking into account the maximum dynamic forces arising during the contact of drive wheels with the monorail. It was also established that the effect of the monorail track deformation has no significant impact on the durability of drive wheel rims of mine monorail locomotives.

An algorithm of determining the parameters of drive wheels of monorail locomotives to ensure the required durability T_{req} of their rims was determined.

The durability of wheel polymeric rims of mine monorail locomotives was calculated, taking into account the dynamic loads arising during the movement of the monorail train. Stress distribution over the contact area of the wheel rim with the monorail was obtained. This enables measures to increase the service life of drive wheels of mine monorail locomotives to be developed. An increase in the carriage mass from 20 to 47 kN leads to 32 % less durability of a monorail locomotive drive wheel rim (from 8700 to 5900 hours). Further research will be aimed at developing a comprehensive model to assess the durability of the drive wheel of mine monorail locomotives.

References

1. Kol'ga A.D., Agliullin A.S. Railway transport of mining enterprises: ways of efficiency improvement. *Gornoe Oborudovanie i Elektromehanika*. 2016;(5):23–28. (In Russ.)

2. Aleksandrov S.N., Bereginskiy V.I., Budishevskiy V.A., Melnikov S.A. Creation of mine locomotives for delivery of cargoes by the ways with the unconsistent and overrated profile. *Mining Informational and Analytical Bulletin*. 2009;(16):215–229. (In Russ.)

3. Gutarevych V.O. Dynamic loading of monorail bogies and suspended railway. *Bulletin of Higher Educational Institutions. North Caucasus Region. Technical Sciences*. 2015;(4):85–88. (In Russ.) https://doi.org/10.17213/0321-2653-2015-4-85-88

4. Gutarevych V.O., Kondrakhin V.P. Reduction of dynamic loads from suspended monorail tracks on mine working support. *Vestnik Donetsk National Technical University*. 2016;(6):7–11. (In Russ.)

5. Melezhik R.S., Vlasenko D.A. Load simulation and substantiation of design values of a pin flexible coupling with a flexible disk-type element. *Mining Science and Technology* (*Russia*). 2021;6(2):128–135. (In Russ.) https://doi.org/10.17073/2500-0632-2021-2-128-135

6. Ziborova E.Yu., Mnatsakanyan V.U. Justification of geometrical parameters of lining plates for a belt conveyor drive drum. *Mining Science and Technology* (*Russia*). 2022;7(2):170–179. https://doi.org/10.17073/2500-0632- 2022-2-170-179

7. Stoček R., Stěnička M., Zádrapa P. Future trends in predicting the complex fracture behaviour of rubber materials. *Continuum Mechanics and Thermodynamics*. 2021;33(2):291–305. https://doi.org/10.1007/s00161-020-00887-z

8. Szewerda K., Tokarczyk J., Wieczorek A. Impact of increased travel speed of a transportation set on the dynamic parameters of a mine suspended monorail. *Energies*. 2021;14(6):1528. https://doi.org/10.3390/en14061528

9. Herbus K., Szewerda K., Swider J. Virtual prototyping of the suspended monorail in the aspect of increasing the permissible travel speed in hard coal mines. *Eksploatacja i Niezawodność*. 2020;4:610–619. https://doi.org/10.17531/ein.2020.4.4

10. Kondrakhin V., Arefyev E., Khitsenko N. Assessment of inpact made by vibration cleaning on the conveyor-belt service life. *Bulletin of Kharkov National Automobile and Highway University*. 2012;(57):292–295. (In Russ.)

11. Aleksandrov V.M., Chebakov M.I. *Introduction to the mechanics of contact interactions*. Rostov-on-Don: TsVVR LLC; 2007. 114 p. (In Russ.)

12. Ryabko K.A., Gutarevich V.O. Substantiation of performance indicators of mine monorail locomotives. *Mining Science and Technology* (*Russia*). 2021;6(2):136–143. (In Russ.) https://doi.org/10.17073/2500-0632-2021-2-136-143

13. Vodolazskaya N.V., Shevchenko D.A. T*he problem of increasing the durability of machine parts operating in aggressive environments. Mechanical engineering of Ukraine through the eyes of scientists: progressive ideas – science – production*. Sumy: SumGU; 2010. Pp. 25–27. (In Russ.)

14. Litvinova I.A., Veselov I.V., Gamlitskiy Y.A. Improvement of rubber recipe for massive tires by addition of non-traditional fillers. *Proceedings of the Voronezh State University of Engineering Technologies*. 2019;81(4):196–204. (In Russ.) https://doi.org/10.20914/2310-1202-2019-4-196-204

15. Kablov V.F., Gamlitsky Yu.A., Tyshkevich V.N. *Mechanics of reinforced plastics and rubber-cord composites*. Volgograd: Volgograd State Technical University; 2014. 348 p. (In Russ.)

16. Kartsovnik V.I. Prediction of the creep of elastomers taking into account the forces of entropic elasticity of macromolecules (prediction of creep of elastomers). *Journal of Macromolecular Science, Part B*. 2018;57(6):447–464. https://doi.org/10.1080/00222348.2018.1470836

17. Luo R.K. Effective stress criterion for rubber multiaxial fatigue under both proportional and non-proportional loadings. *Engineering Failure Analysis*. 2021;121:105–172. https://doi.org/10.1016/j.engfailanal.2020.105172

18. Swider J., Szewerda K., Herbuś K., Jura J. Testing the impact of braking algorithm parameters on acceleration and braking distance for a suspended monorail with regard to acceptable travel speed in hard coal mines. *Energies*. 2021;14:7275. https://doi.org/10.3390/en14217275

19. Szewerda K., Krenicky T. Use of the MBS method in mining industry R&D projects. *Mining Machines*. 2022;40(2):110–120. https://doi.org/10.32056/KOMAG2022.2.6

20. Gutarevich V.O., Ryabko K.A., Ryabko E.V. Damping of lateral oscillations of the rolling stock of a mine suspended monorail road. In: *Collection of abstracts of reports of the VI international scientific and technical conference "Ways to improve technological processes and equipment of industrial production"*. Alchevsk: DSTU; 2021. Pp. 172–174. (In Russ.)

21. Szewerda K. Supporting development of suspended underground monorails using virtual prototyping techniques. In: *IOP Conference Series: Materials Science and Engineering. Innovative Mining Technologies (IMTech 2019 Scientific and Technical Conference)*. 25–27 March, 2019. Szczyrk, Poland. 2019;545:012018. https://doi.org/10.1088/1757-899X/545/1/012018

Information about the authors

Evgeny M. Arefiev – Cand. Sci. (Eng.), Associate Professor, Saint Petersburg State Institute of Technology, Saint Petersburg, Russian Federation; ORCID 0000-0001-5055-2370, Researcher ID B-2261-2016; e-mail elcross@mail.ru

Konstantin Al. Ryabko – Cand. Sci. (Eng.), Associate Professor, Rostov State University of Railway Transport (Voronezh Branch), Voronezh, Russian Federation; ORCID 0000-0003-4391-506X, Scopus ID 57203884218; e-mail railroader@yandex.ru

Received 20.11.2022
Revised 10.02.2023
Accepted 11.02.2023