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The Impact of Two-Layer Lubrication Parameters on the Service Life of Railway Rails

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Abstract. The prerequisites, basic hypotheses and sequence of creation of a mathematical model for estimation of service life of railway rails in conditions of two-layer lubrication are given in the article. The created mathematical model is presented in the final form. The model takes into account the geometry of the wheel-rail contact, the initial and constant surface roughness, actual loads on the rail, speed of the rolling stock, strength characteristics of steels and the antifriction additive, as well as the basic parameters of two-layer lubrication. The main parameters of lubrication include the concentration of solid antifriction additives in oil which is sufficient to fill irregularities of the contact surface; the boundary molecular oil film thickness. The results of calculations using the developed mathematical model are presented. The performed calculations reveal the positive effect of the parameters of a two-layer lubricant on the resource of rails. The anti-wear effect of the lubricant increases as the concentration of graphite in the oil increases and the weight of the carriage decreases. Based on the performed calculations, conclusions and recommendations were obtained regarding further experimental verification of the mathematical model, as well as the influence of the parameters of two-layer spray lubrication on wear and service life of transport rails.

1. Introduction

In previous works [1-3], physical representations were given regarding the positive effect of two-layer lubrication on the wear and service life of rails when spray lubricant is applied on their lateral working surface. It is determined that the main factors that affect the reduction of wear of rails in case of two-layer lubrication include an increase of the actual wheel-rail contact area by filling the microscopic surface irregularities with a layer of a solid antifriction additive (such as graphite, molybdenum disulfide, etc.); an increase of the thickness and bearing capacity of the second lubricating layer – the boundary molecular oil film which occurs on the friction surface and covers the first layer. Thus, the concentration of antifriction additive in oil, sufficient to fill the volume of surface irregularities, and the boundary molecular film thickness can be considered the main parameters of two-layer lubrication.

Despite the logic of the above physical representations, they do not cover the issues of theoretical and experimental substantiation of the influence of the specified parameters of two-layer lubrication on the service life of rails of railway transport. For example, there is no information on the effect of the concentration of the solid additive in the oil and the boundary layer thickness on the actual contact area. In addition, until now there is no mathematical model for determining the service life of rails in conditions of two-layer lubrication. These are the issues that this study deals with.

2. Analysis of recent studies and publications

In [1], the main directions of increasing the service life of technical systems by using nanotechnologies are presented. The special role is assigned to the methods of lubrication of friction surfaces, including in the wheel-rail contact; however, the ideas considered in the work are generalized and require further scientific and practical development for each technical system. Works [2-4] are the closest to the topic of this study. For example, in [2], the mechanism of the effect of the molecular oil film thickness on the development of major defects of rails is revealed, but this mechanism is the result of single-layer lubrication. On the other hand, although [3, 4] presents data on the physical basis of the effect of two-layer lubrication on wear of rails; such data do not provide an opportunity of analytical prediction of the service life depending on the basic parameters of lubrication. Given that the main design parameters that affect the wear of rails include the contour and actual contact areas, then the existing methods of analytical estimation of such areas should be understood and applied to develop a mathematical model of the service life. Works [5-7] can be used for this purpose. However, works [5, 6] deal with the determination of the design parameters of hydraulic machines and do not take into account the actual loads and surface roughness in the wheel-rail contact of the railway transport. In order to develop a mathematical model of service life of the rail, it is more expedient to use approaches and analytical dependencies of [7-11], since it provides a theoretical basis for predicting the wear of tribological systems under different conditions of lubrication.

3. Statement of the objective and tasks of the study

The purpose of the work is estimating the influence of the parameters of two-layer lubrication on the service life of rails in curved track sections on the basis of the analysis of the calculated data obtained using the developed mathematical model. To achieve this goal, the following tasks are solved in the work:

– developing a mathematical model for estimation of the service life of rails in curved track sections in conditions of two-layer lubrication;

– calculating the wear and service life of rails using the developed mathematical model at variable loading from a wheel and different concentration of graphite in oil.

4. Development of mathematical model

To develop the mathematical model, we choose a deterministic approach, which consists in simple mathematical determination of the service life as the ratio of the limit linear wear of the rail to the amount of wear of the rail over the contour contact area per loading cycle [6], i.e. wear from the wheel pair. In this case, service life of the rail (in millions gross tons), depending on the number of wheel pairs and the weight of the car, will be determined by dependence (1).

The main hypothesis in the development of a mathematical model is the following assumption about the predominant types of wear of the rail under the action of load from the wheel. In the studies, we assume that at the running-in stage, the predominant type of wear is wear from plastic contact of rough surfaces. We assume that such wear occurs when a wheel with the maximum weight of the car once passes the rail and is equal to the difference between the initial radius of irregularity R_a and the height of irregularity R_p after deformation (Figure 1).

After running-in, the lateral working surface of the rail is subjected to monotonic continuous wear, in which the linear wear of the rail increases as the number of load cycles increments. In the mathematical model, the wear of a single irregularity per cycle is ΔR_p, while the wear of a rail per cycle is defined as the sum of wears ΔR_p in all irregularities within the contour area of the wheel-rail contact (Figure 1). The prevailing type of such continuous wear is mechanical wear with elastic contact.

According to the second hypothesis, the effect of two-layer lubrication on the wear rate of the rail is increasing the actual contact area by the value of $S_{oil} + S_{gr}$ (Figure 1), where S_{oil} depends on the boundary molecular film thickness of the second layer of lubrication, and S_{gr} depends on the concentration of graphite powder in oil.

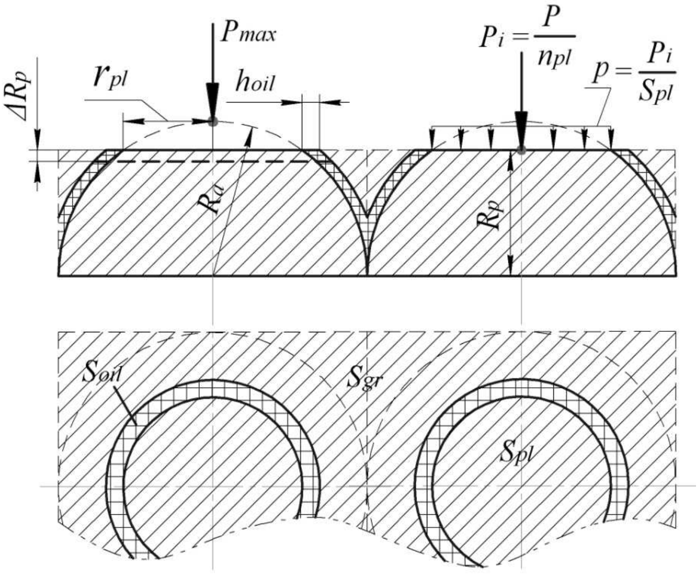


Figure 1. Design drawing of the contact of the wheel with the rough surface of the rail: n_{pl} – number of irregularities on the surface of the wheel-rail contact, pcs.; R_a– initial radius of the irregularity, m; P_{max}– maximum lateral load of the wheel on the rail, N; P_i – load on the irregularity, N; R_p – height of the irregularity after plastic deformation, m; ΔR_p – linear wear of the inequality per load cycle, m; r_{pl} – radius of the contact area for the irregularity, m; S_{oil} – projection of the area occupied by the boundary film on the irregularity, m^2; S_{gr} – projection of the area occupied by the graphite layer, m^2.

Based on the above hypotheses and the adopted design drawing, the mathematical model of the service life of rails in conditions of two-layer lubrication will have the following form:

$$T(m_{vag}, c_{gr}) = \frac{I_{LIM}}{I_{ic}(m_{vag}, c_{gr}) \cdot n_{par}} \cdot m_{vag} \ , \tag{1}$$

where T – life of the rail, MGT; m_{vag} – weight of the car, t; c_{gr} – concentration of graphite in oil, %; I_{LIM} – maximum permissible weight wear, kg; I_{ic} – wear per one load cycle, kg; n_{par} – number of wheel pairs in the car;

$$I_{LIM} = S_{kon} \cdot h_{LIM} \cdot \rho_{st} \ , \tag{2}$$

where S_{kon} –contour area of the lateral contact of the wheel with the rail, m^2; h_{LIM} – limit value of lateral wear of the rail, m; ρ_{st} – density of rail steel, kg/m^3;

$$I_{ic}(m_{vag}, c_{gr}) = \Delta V_{seg}(m_{vag}, c_{gr}) \cdot n_{pl} \cdot \rho_{st} \ , \tag{3}$$

where ΔV_{seg} – volume of worn-out material on the irregularity, m^3;

$$\Delta V_{seg}(m_{vag}, c_{gr}) = \pi \cdot \int\limits_{Rp(m_{vag}) - \Delta Rp(m_{vag})}^{Rp(m_{vag})} \left(Ra^2 - x^2\right) dx \ , \tag{4}$$

where Rp – height of the irregularity after plastic deformation from P_{max}, m; Ra – radius of the initial irregularity, m; ΔRp – single wear of the irregularity for the respective number of cycles, m;

$$Rp(m_{vag}) = \sqrt{Ra^2 - \frac{P_{\max}(m_{\max})}{\pi \cdot \sigma_{st}}} \ , \tag{5}$$

where m_{max} – maximum weight of the car, t; P_{max} – maximum lateral load of the wheel on the rail, N; σ_{st} – yield strength of the rail steel, MPa;

$$\Delta Rp(m_{vag}, c_{gr}) = \frac{P_i(m_{vag}, c_{gr}) \cdot Rp(m_{vag})}{E \cdot S_{pl}(m_{vag}) \cdot n_{IC}\left(m_{vag}, c_{gr}\right)} \ , \tag{6}$$

where P_i – load on the irregularity, N; E – modulus of elasticity of rail steel, MPa; n_{IC} – number of cycles until the irregularity wears by the value ΔRp;

$$P_i(m_{vag}, c_{gr}) = \frac{m_{vag} \cdot 10^3 \cdot g}{n_{par} \cdot 2 \cdot n_{pl}} \cdot 0.6 - \sigma_{gr} \cdot S_{gr} \ , \tag{7}$$

where σ_{gr} – strength limit of graphite, MPa; g – free fall acceleration, m/sec^2;

$$S_{pl}(m_{vag}) = \pi(Ra^2 - Rp(m_{vag})^2) + \pi\left((Ra + h_{oil})^2 - Ra^2\right) \ , \tag{8}$$

where h_{oil} – thickness of the lubricating film, m;

$$S_{gr}(m_{vag}, c_{gr}) = \sqrt{S_{graf}(m_{vag})^2 - \left(S_{graf}(m_{vag}) - S_{graf}(m_{vag}) \cdot \frac{c_{gr}}{c_{LIM}(m_{vag})}\right)^2} \ , \tag{9}$$

where c_{LIM} – limit value of concentration of graphite powder in oil, %;

$$n_{IC}\left(m_{vag}, c_{gr}\right) = \left(\frac{\sigma_{st}}{P_i(m_{vag}, c_{gr}) / S_{pl}(m_{vag})}\right)^6 \ , \tag{10}$$

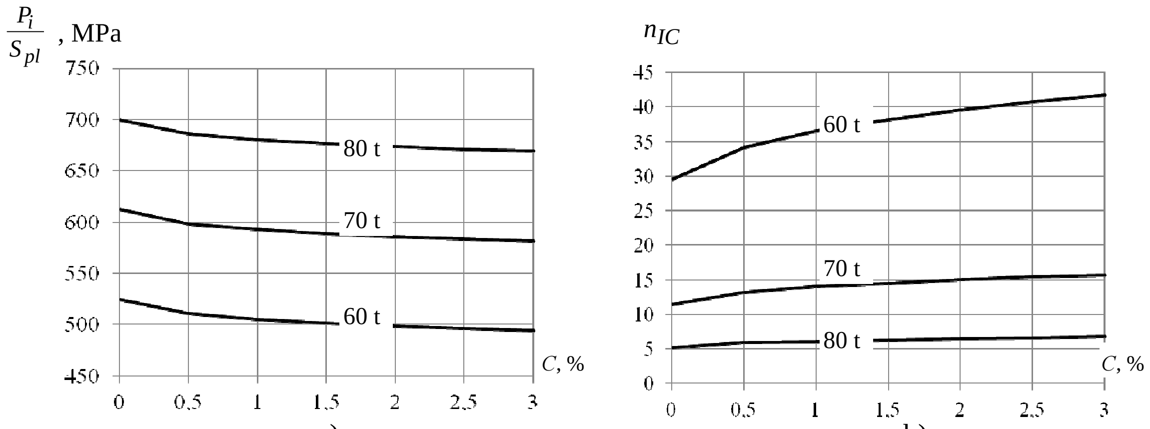
$$S_{graf}(m_{vag}) = 4 \cdot Ra^2 - \pi\left(Ra^2 - R_P(m_{vag})^2\right) , \tag{11}$$

$$c_{LIM}(m_{vag}) = \frac{4 \cdot Ra^2 \cdot R_P(m_{vag}) - \pi\left(\int_0^{R_P(m_{vag})} (Ra - x)^2 dx\right)}{16 \cdot Ra^2 \cdot R_P(m_{vag})} \cdot 100 \ . \tag{12}$$

The model takes into account the geometry of the wheel-rail contact, the initial and constant surface roughness, actual loads on the rail, speed of the rolling stock, strength characteristics of steels and the antifriction additive, as well as the basic parameters of two-layer lubrication. The main parameters of lubrication include the concentration of solid antifriction additives in oil which is sufficient to fill irregularities of the contact surface; the boundary molecular oil film thickness.

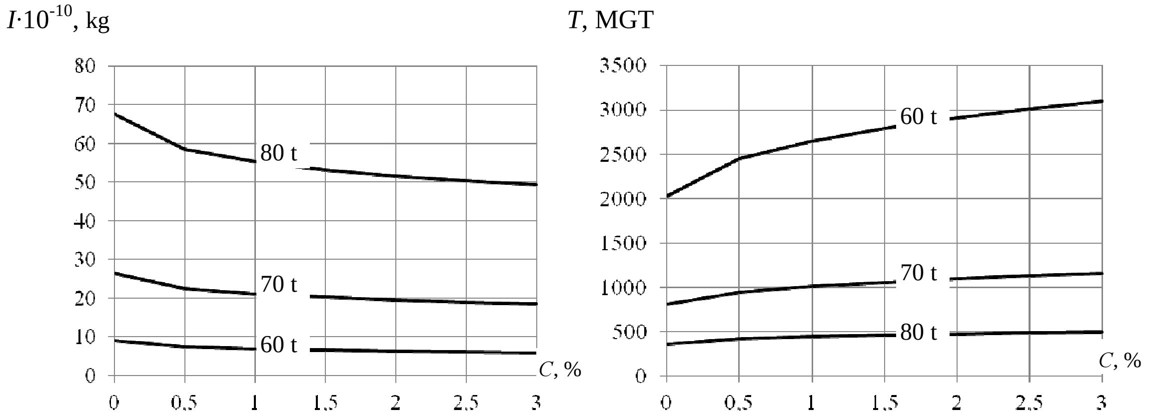
5. The results of the calculation and their discussion

Let us calculate the basic parameters of the developed mathematical model. For this purpose, some of the following values are taken: S_{kon} = 120 mm^2; h_{LIM} = 0.013 m; ρ_{st} = 7800 kg/m^3; n_{par} = 4. The results are shown as diagrams in Figures 2 and 3.



a) b)

Figure 2. The results of calculations for the developed model: a) dependence of specific pressure, b) dependence of number of loading cycles of the irregularity to failure of volume limited by height ΔR_p, on concentration of graphite in oil and the weight of the car.



a) b)

Figure 3. The results of calculations for the developed model: a) dependence of wear rate of the rail, b) dependence of service life of the rail on concentration of graphite in oil and the weight of the car.

According to the diagram (Figure 2, a)), when two-layer lubrication is used, the specific pressure on the rail surface decreases depending on the concentration of graphite in oil by 4 to 9%, which leads to a respective increase in the number of loading cycles (Figure 2, b)) . Such phenomena slow down the wear rate. When graphite is added to the oil at a concentration of 3%, the wear rate decreases by 28 to 33%, if the weight of the car is 60 to 80 t (Figure 3, a)). It is established that by changing the graphite concentration up to 3% the service life of the rail can be increased from 400 MGT to 500 MGT for cars weighing 80 t and from 2000 MGT to 3100 MGT for cars weighing 60 t (Figure 3, b).

6. Conclusions

1. It was determined analytically that the use of two-layer lubrication of rails on the main railways results in the reduction of pressure in the wheel-rail contact and an increase in the number of loading cycles to failure of volumes of the rail surface layer under conditions of elastic deformation. As a

consequence, the service life of the rail increases if the railway car weight is 800 MGT to 1150 MGT, which confirms the high efficiency of two-layer lubrication.

2. Further studies should focus on verification of the calculated data by experimental methods. Such methods include physical simulation of the wheel-rail contact in the curved section of the track and the full-scale testing of rails of the main railway tracks.

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