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COMPUTER SIMULATION OF THE LINING WEAR PROCESS IN FRICTION BRAKES

Summary. In this paper the simulative model of the friction lining wear process in a winding gear, post type brake is presented. In the modelling procedure, the wear characteristics of the friction materials and the brake variables typical for winding brakes, for example, the elastic property of the brake elements were taken into consideration. The modelling friction lining wear process was used to predict associated changes in the pressure distribution, and other mechanical characteristics of the brake system. The computer modelling proved that the lining wear process is complex and essentially influences the mechanical characteristics of the brakes. In the wear process a preliminary period may be distinguished in which the changes in pressure distribution between shoes and drum result from the volumetric lining wear. After this preliminary period the mechanical characteristics of the brakes become stable at a certain level. The length of the preliminary period is determined by the elastic properties of the brake elements. The results from computer simulation may be used in the disign procedure of the brake system. The presented model may be modified depending on the specific requirements. After modification, any wear characterics of the friction materials can be taken into consideration so that the mechanical brake system of any structure may be analysed.

1. INTRODUCTION

The classical approach to a mathematical modelling of the pressure distribution between the shoes and the drum in a post type brake is based on certain assumptions, namely that the brake elements are perfectly rigid and that the wear of the linings is directly proportional to the pressure in the area of contact analysed. In practic none of the above conditions are satisfied. The pressure distribution is different from the theoretically predicted pattern due to the brake shoes and drum strain.

The wear characteristics of the friction materials are not usually taken into consideration and only very simplified models are applied. For example, the directly proportional dependence between wear and pressure. Wear of friction linings changes some brake variables, such as the geometry of the brake shoes, the geometry of contact between the brake elements and the friction characteristic of the brake. It is very important to know the algorithm for computing the friction characteristic of brake and its changes during service. The modelling of the brake characteristic can be restricted to the modelling of the friction lining wear process since the thickness of linings is the only parameter which changes value during service.

In this paper simulative model of the friction lining wear process in a winding gear, post type brake is presented. Wear process simulation was carried out by applying a mathematical model of the brake shoe - drum system. Assumptions were made that the value of the coefficient of friction between the lining and the drum was constant, and that working cycle of the brake was defined. Theoretical results were verified by industrial data.

2. SIMULATIVE MODEL OF THE FRICTION LINING WEAR PROCESS

Braking processes in winding gears can be divided into emergency braking and operational braking. These differ in frequency of occurence and in frictional parameters, such as the contact pressure and the sliding velocity between the brake shoes and path.

The total braking energy, used for stopping a hoisting system, can be presented as a function of the kinetic energy of the system.

$$E_b = \lambda(E_k) \tag{1}$$

where:

Eb is the braking energy,

λ is coefficient [1],

E_k is the kinetic energy of a hoisting system.

Wear of lining results from the sliding friction between the brake elements during both emergency and operational brakings. If the volumetric wear of the linings during a single operational braking is I_{vo} and during an emergency braking is I_{ve} then wear process is characterized by the coefficient $\varkappa$

$$\varkappa = \frac{\sum_{i=1}^{n_o} I_{voi}}{\sum_{j=1}^{n_e} I_{vej}} \tag{2}$$

where:

n_o and n_e are the numbers of operational and emergency brakings in a defined service period.

The volumetric wear is the function of the effective intensity of wear [2, 3], therefore the friction force work can be presented as follows:

$$I_v = \int_A e_g \frac{1}{\gamma} q \, dA \tag{3}$$

where:

e_g is the effective wear intensity,
γ is the density of the lining material,
q is the elementary friction force work (per unit area),
A is the friction surface area of the lining.

The wear properties of friction materials are described by the effective wear intensity, which expresses the ratio of the gravimetric wear (ΔW) of the lining material to the work of the friction forces during braking [2, 3].

$$e_g = \frac{\Delta W}{\sum E_b} \tag{4}$$

where:

$dA = b.R.d\theta$,
b is the width of lining (Fig. 1),
R is the radius.

In order to find out the relation between various variables and the effective wear intensity the regression equation (5) was used

$$e_g = k_o \left(\frac{HK}{U}\right)^{\alpha_1} k_w^{\alpha_2} p^{\alpha_3} \tag{5}$$

where:

HK	is the hardness of the brake lining materials
U	is the impact strength of the brake lining materials
k_w	is the coefficient of reciprocal covering
p	is pressure
k_o	is constant
$\alpha_{1,2,3}$	are constants.

For the specified type of friction material and the determinate brake parameters the equation (5) can be simplified to the form (6)

$$e_g = kp^{\alpha} \tag{6}$$

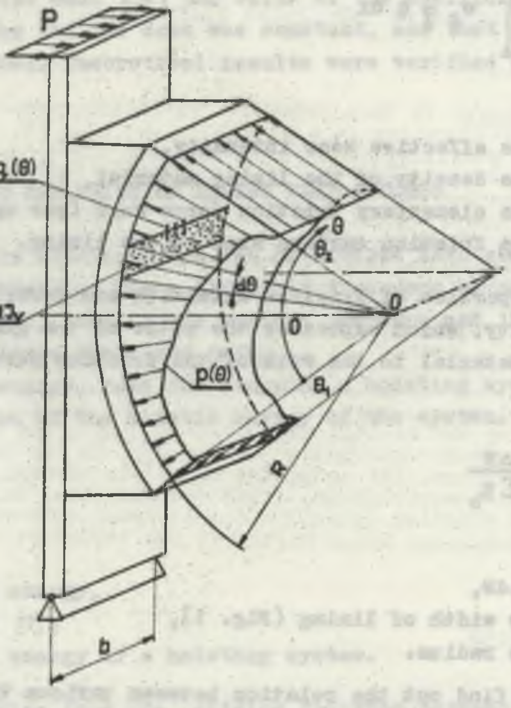

Fig. 1. Main parameters describing the post type brake of winding machine
Rys. 1. Główne parametry opisujące hamulec szczękowy maszyny wyciągowej

The elementary friction force work for the given angular coordinate (Fig. 1) depends on the pressure between the brake shoes and the drum, and the coefficient of friction. The elementary friction force work for one braking process can be calculated as follows.

$$q(\theta) = \mu p(\theta) s_b \tag{7}$$

where:

μ is the coefficient of friction,
$p(\Theta)$ is pressure,
s_b is braking distance.

If during certain service life there are n_o operational brakings and n_e emergency brakings then after substituting (1), (3), (6) and (7) equation (2) can be presented as follows.

$$\varkappa = \frac{\lambda_o}{\lambda_e}\left(\frac{v_o}{v_e}\right)^2 \frac{\displaystyle\sum_{i=1}^{n_o} \frac{\int_{\Theta_1}^{\Theta_2} \left[p_o(\Theta)\right]^{\alpha+1} d\Theta}{\int_{\Theta_1}^{\Theta_2} p_o(\Theta) d\Theta}}{\displaystyle\sum_{j=1}^{n_e} \frac{\int_{\Theta_1}^{\Theta_2} \left[p_e(\Theta)\right]^{\alpha+1} d\Theta}{\int_{\Theta_1}^{\Theta_2} p_e(\Theta) d\Theta}} \tag{8}$$

where:

v_o is the initial sliding velocity during operational braking,
v_e is the initial sliding velocity during emergency braking,
λ is the coefficient according to equation (1).

3. PRINCIPLES OF THE WEAR PROCESS SIMULATION

Modelling of the lining wear process is based on an analysis of sequent, discrete states, which the tribological system friction lining - path reaches gradually during service. State "k" is characterized by the following parameters (Fig. 2):

- the pressure distribution $p^k(\Theta)$ as calculated in [1]
- the thickness of the lining $u^k(\Theta)$
- the radial clearance $\Delta^k(\Theta)$ between the brake shoe and the drum.

The assumption has been made that the above parameters are constant along the width of the lining.

The transition from the state k to $k+1$ is discrete by calculating one step of the linear lining wear $\delta_w^k(\Theta)$ in one computing cycle. It was

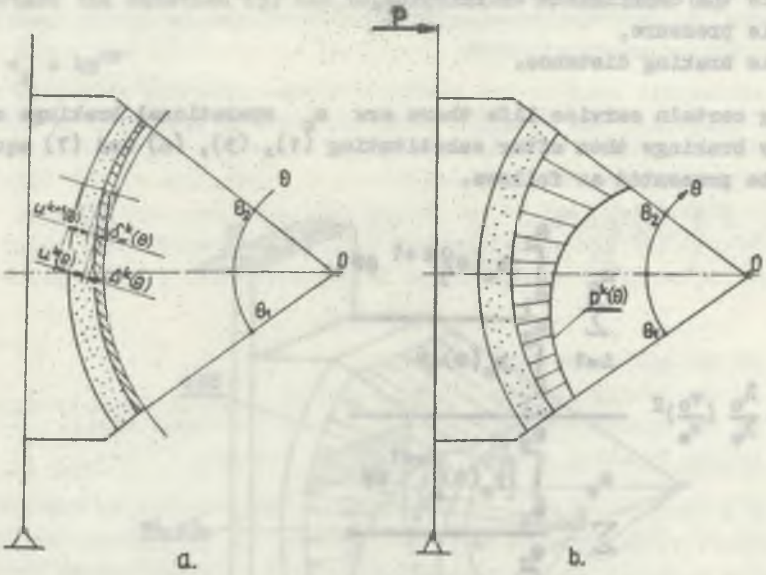

Fig. 2. The tribological system: friction lining - path at the discrete state "k"

a) unloaded shoe, b) loaded shoe

Rys. 2. System tribologiczny: okładzina cierna - bieżnia w stanie dyskretnym "k"

a) nieobciążona szczęka, b) obciążona szczęka

assumed that the value of the linear lining wear at co-ordinate Θ is a function of the pressure at that given point, therefore

$$\delta_w^k(\Theta) = k_2\left[p^k(\Theta)\right]^{\alpha} \tag{9}$$

The transition from state k to k+1 consist of the following changes:

- the thickness of the lining

$$u^{k+1}(\Theta) = u^k(\Theta) - \delta_w^k(\Theta) \tag{10}$$

- the radial clearance between the brake shoe and the rim

$$\Delta^{k+1}(\Theta) = \Delta^k(\Theta) + \delta_w^k(\Theta) \tag{11}$$

The transition from state k to k+1 is accompanied by the volumetric decrement of the lining which is equal to the lining wear in one step of the program

$$\delta I^k = bR \int_{\theta_1}^{\theta_2} \delta_w^k(\theta)\, d\theta \tag{12}$$

or after substitution (9)

$$\delta I^k = k_2 bR \int_{\theta_1}^{\theta_2} \left[p^k(\theta)\right]^{\alpha} d\theta \tag{13}$$

The simulation process consists of two kinds of computing cycles:

- type O, which is characterized by the pressure distribution appearing during operational brakings, and which simulates the lining wear during this braking process,
- type E, which is characterized by the pressure distribution appearing during emergency brakings and which simulates the lining wear this braking process.

If a defined stage of simulation consists of k computing cycles, then the ratio between the volumetric wear computed according to the computing cycles type O and type E, is as follows:

$$\frac{\sum\limits_{i=1}^{o} \delta I_o^i}{\sum\limits_{j=1}^{e} \delta I_e^j} = \varkappa^* \tag{14}$$

where:

$o + e = k$,
o is the number of cycles type O,
e is the number of cycles type E

The simulative model of the wear process is based on the principle that the ratio $\varkappa^*$ is equal, at every stage of simulation, to the coefficient $\varkappa$ calculated according to equation 8.

Therefore,

$$\varkappa^{*} = \varkappa \tag{15}$$

From the above principle the need arises for the selection of one type of computing cycle at each stage of calculation. Coefficient $\varkappa$ depends on the pressure distribution and should be repeatedly corrected during the simulation procedure.

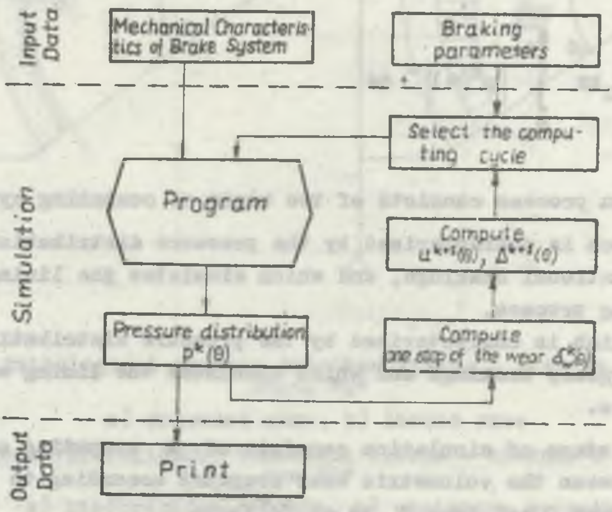

Fig. 3. Block diagram of the simulation process
Rys. 3. Układ blokowy procesu symulacji

The precision of the simulation process depends on the value of the constant k_2.
Satisfactory results from, the simulation can be obtained for such values of the constant k_2 where the ratio between one step of the linear lining wear $\delta_w^k(\Theta)$ and the radial strain is less than 0,3.

Fig. 3 shows a block diagram of the simulation procedure. For correspondence to the real braking process in winding machines there was necessity to simulate change in rotational direction. The orientated coefficient of friction was introduced as follows.

$$(\vec{\mu})^{k} = \mu(-1)^{k+1} \tag{16}$$

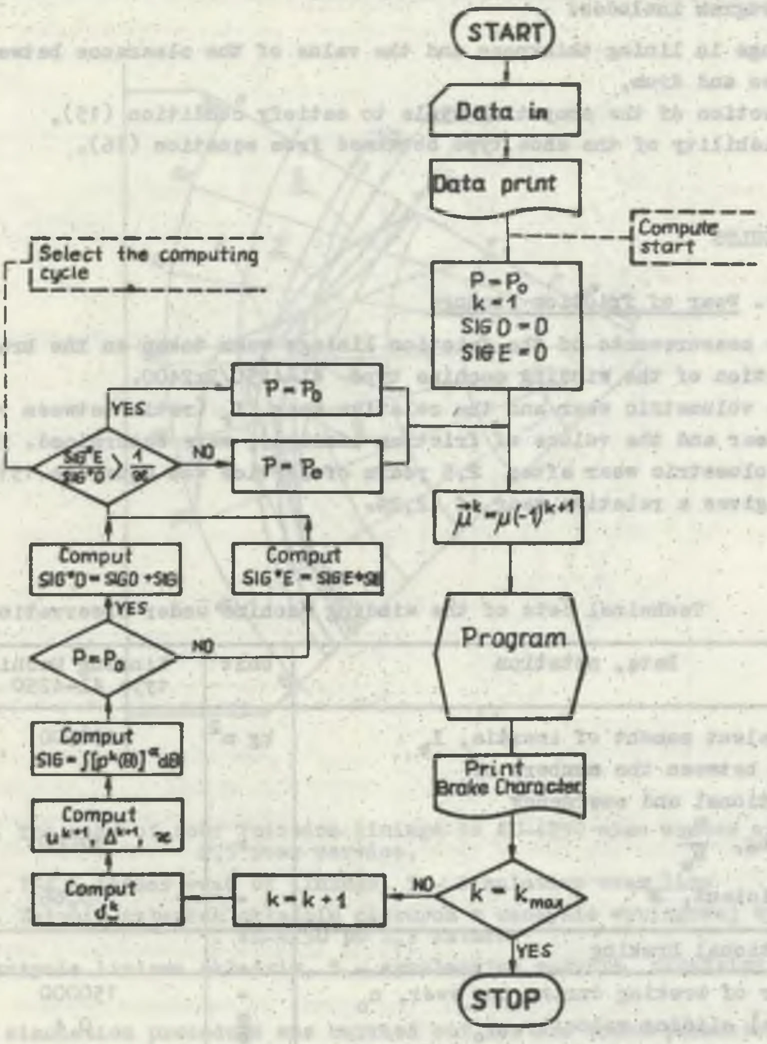

Fig. 4. Flow diagram of the computer simulation program of the friction lining wear process

Rys. 4. Graf programu symulacji komputerowej zużycia okładzin ciernych

where

$(\vec{\mu})^k$ is the value of the orientated coefficient of friction in k cycles of computing.

A flow diagram of the computer simulation program is shown in Fig. 4.

The program includes:

- change in lining thickness and the value of the clearance between shoes and drum,
- selection of the computing cycle to satisfy condition (15),
- variability of the shoe type obtained from equation (16).

4. RESULTS

4.1. Wear of friction linings

The measurements of the friction linings wear taken on the brake installation of the winding machine type 4L-4250/2x2400.

The volumetric wear and the relative wear I_r (ratio between volumetric wear and the volume of friction linings), were determined. The average volumetric wear after 2,5 years of service was aqual to 1318 cm^3, which gives a relative wear of 12,2%.

Table 1

Technical data of the winding machine under observations

Data, notation	Unit	Winding Machine type 4L-4250
Equivalent moment of inertia, I_e	kg m^2	670500
Ratio between the numbers of operational and emergency braking, $\frac{n_o}{n_e}$	-	12000
Coefficient, $\varkappa$	-	3,66
Operational braking		
Number of braking during one year, n_o	-	150000
Initial sliding velocity, v_o	$\frac{m}{s}$	0,4
Max. loading of shoe, P_o	kN	35,4
Duration of braking, d_o	s	0,2
Coefficient, λ_o	-	0,31
Emergency braking		
Initial sliding velocity, v_e	$\frac{m}{s}$	16
Max. loading of shoe, P_e	kN	145,8
Duration of braking, d_e	s	4,0
Coefficient, λ_e	-	0,65

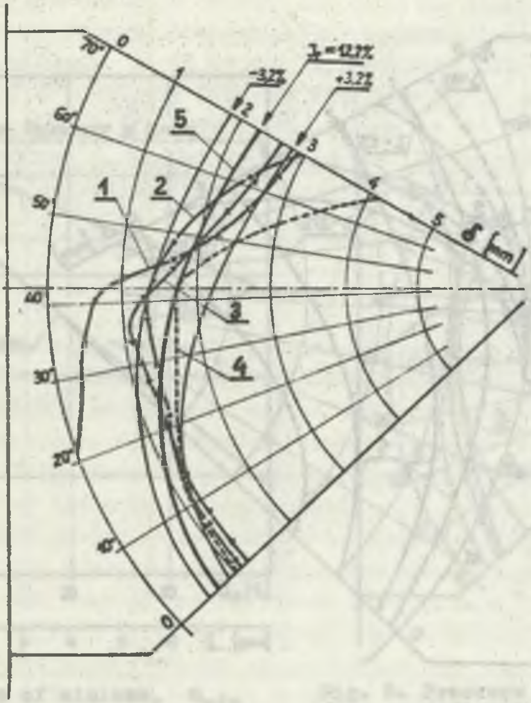

Fig. 5. The wear of four friction linings in 4L-4250 mine winder after 2,5 year service,
1÷4 - linear wear of linings, 5 - simulative wear line

Rys. 5. Zużycie czterech okładzin ciernych w maszynie wyciągowej typu 4L-4250 po 2,5 latach
1÷4 - zużycie liniowe okładzin, 5 - symulacyjne zużycie okładziny

The simulation procedure was carried out for the brake parameters shown in Table 1 with the assumptions that the coefficient of friction $\mu = 0,4$, and that the new lining abuts the brake path along its whole length ($\Delta = 0$).

Results from the measurements and the simulation are shown jointly in Fig. 5. Diagrams show the linear wear of the linings (curves 1÷4) and the simulative wear line (curve 5) corresponding to the relative wear 12,2%. The results indicate that in spite of some differences between the four linings there is some conformity between the wear measurements and the simulative results.

The simulative investigation enables a detailed examination of the wear process. The friction linings wear process, the linear wear for

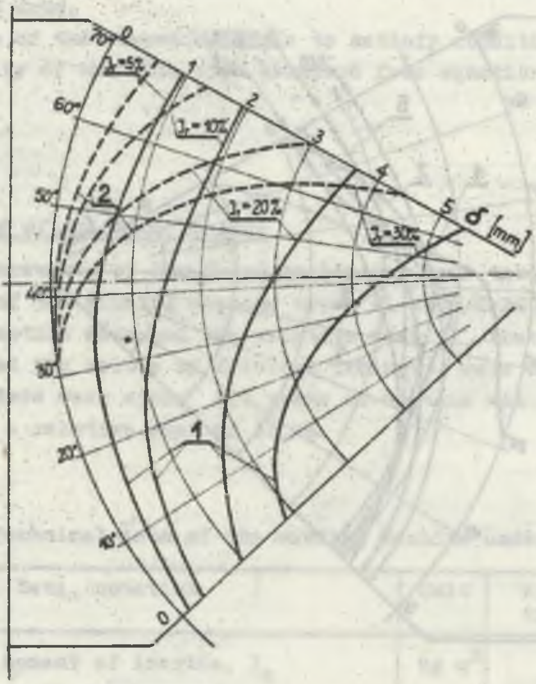

Fig. 6. The linear wear for various values of relative wear I_r and wear components resulting from a operational braking and an emergency brake action

1 - total wear, 2 - wear components resulting from an emergency braking

Rys. 6. Zużycie liniowe dla różnych wartości zużycia względnego I_r i składowe zużycia wynikające z działania hamulca manewrowego i bezpieczeństwa

1 - zużycie ogólne, 2 - zużycie pochodzące od działania hamulca bezpieczeństwa

various values of relative wear, and the wear components resulting from an operational and an emergency brake action are presented in Fig. 6. Only the upper part of shoes were working during emergency braking irrespective of the wear stage.

Accurate prediction of friction linings service life is important. The durability of friction linings is controlled by the minimum permissible thickness of the linings. Based on the simulative experiments, changes in the thickness of the linings and the durability of the linings can be determined (Fig. 7). The values of the effective wear intensity and of the mechanical energy dissipated during braking are taken into consideration for the calculation of linings service life.

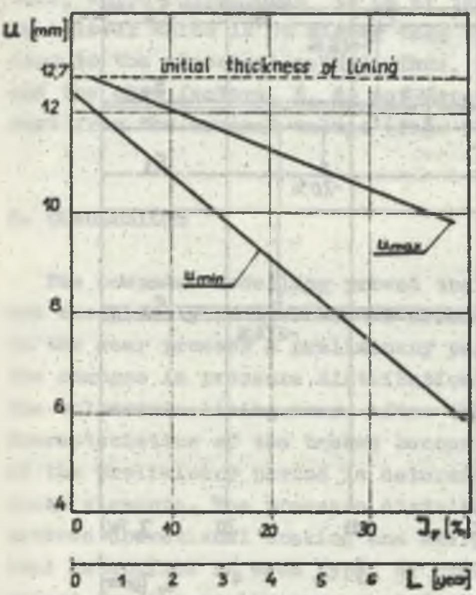

Fig. 7. Changes of minimum, u_{min} and maximum, u_{max} lining thickness as function of service life, L

Rys. 7. Zmiany grubości okładziny minimalnej t_{min} i maksymalnej t_{max} w funkcji czasu pracy L

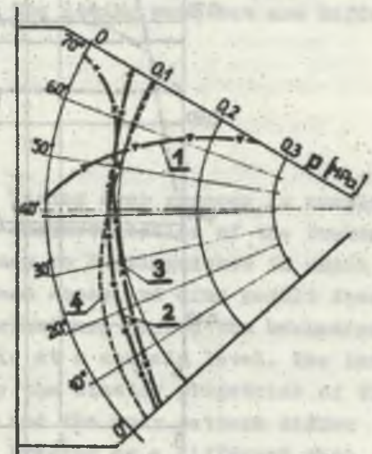

Fig. 8. Pressure distribution during operational braking between brake shoe and drum as a function of relative wear of lining

1 - I_r = 0%, 2 - I_r = 3%, 3 - $I_r >$ $\geq$ 6%, 4 - sinusoidal distrubution

Rys. 8. Rozkład nacisków podczas hamowania manewrowego między okładziną a bieżnią jako funkcji względnego zużycia okładzin

1 - I_r = 0%, 2 - I_r = 3%, 3 - $I_r >$ $\geq$ 6%, 4 - rozkład sinusoidalny

4.2. Changes in the brake characteristics

During service the friction lining progresive wear process is indicated by;

changes in the pressure distribution between the brake shoes and the drum and the change in the brake factor (Fig. 8 and 9), which is presented as a function of the relative wear of the lining and of the working life of the brake system. The pressure distribution changes with the relative wear (Fig. 8). At the beginning of the service the pressure is concentrated only on the upper part of the lining and then progressively approches a nominal distrubution. The values of the brake factors also

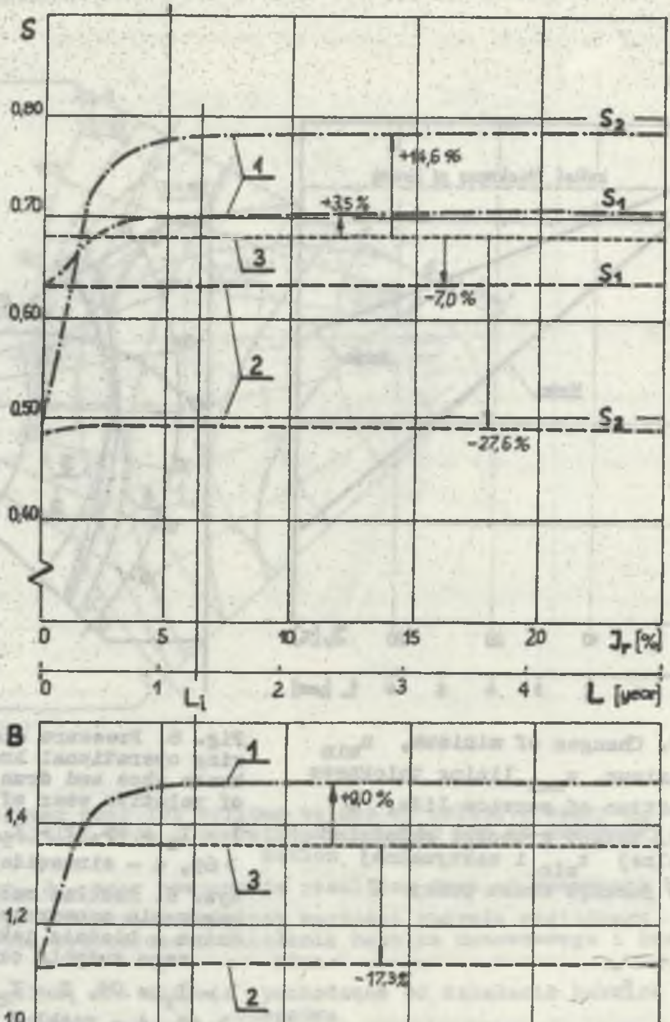

Fig. 9. The shoe factor S and the brake factor B as a function of the relative wear of lining, I_r and service life, L

1 - operational braking, 2 - emergency braking, 3 - nominal values, L_i - initial service life, S_1 - leading shoe factor, S_2 - trailing shoe faktor

Rys. 9. Stała szczęki S i stała hamulca B jako funkcja zużycia względnego okładzin I_r i czasu pracy L;

1 - hamowanie manewrowe, 2 - hamowanie bezpieczeństwa, 3- wartości nominalne, L_i - czas pracy początkowy, S_1 - stała szczęki bieżnej, S_2 - stała szczęki przeciwbieżnej

change correspondingly (Fig. 9). At the beginning of the lining service the brake factor and the shoe factors for both the leading and the trailing shoes increase slowly. However, after approximately one year of service, which corresponds to 6% of the relative wear, their values settle on a level which is 9% higher than the nominal one, as calculated according to the classical method. Thus, the values of the brake factor, B, and the shoe factors, S, do not depend on the lining wear but are different from the nominal values (Fig. 9).

5. CONCLUSIONS

The computer modelling proved that the lining wear process is complex and essentially influences the mechanical characteristics of the brakes. In the wear process a preliminary period may be distinguished in which the changes in pressure distribution between shoes and drum result from the volumetric lining wear. After this preliminary period the mechanical characteristics of the brakes become stable at a certain level. The length of the preliminary period is determined by the elastic propetries of the brake elements. The pressure distribution and the wear pattern differ between operational braking and emergency braking as a different shoe load is applied in each type of braking. The operational braking, except for the preliminary period characterizes the pressure and wear distribution approching the nominal pattern. During emergency braking, irrespective of wear ratio, the pressure is concentrated on upper part of the shoes with high gradient of pressure along the linings.

The modelling procedure of the lining wear process in winding machine brakes takes into consideration the wear properties of friction materials. The effective wear intensity, as determined in other tribological investigations [2, 3], appears to be the most suitable indicator of the wear properties of the materials.

The modelling procedure enables the predition of friction lining wear and the associated changes, such as the pressure distribution, the brake factor and other mechanical characteristics of the brake. The results may be used in the design procedure of the brake system. The presented model may be modified depending on the specific requirements. After modification, any wear characteristics of the friction materials can be taken into consideration so that the mechanical brake system of any structure may be analysed.

NOTATION

b - width of shoe
e_g - effective wear intensity
k_w - coefficient of reciprocal covering
n - number of braking
p - pressure
q - elementary friction force work
s_b - braking distance
u - thickness of lining
v - initial velocity
A - area friction surface
B - brake faktor
E_b - braking energy
E_k - kinetic energy
HK - hardness
I_v - volumetric wear
L - service life
R - radius
S - shoe factor
U - impact strength
ΔW - gravimetric wear
α - coefficient (6)
γ - density
δ_w - linear lining wear
μ - coefficient of friction
$\varkappa$ - coefficient (2)
μ - coefficient (1)

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SYMULACJA KOMPUTEROWA PROCESU ZUŻYCIA OKŁADZIN W HAMULCACH CIERNYCH

Streszczenie

W artykule prezentowany jest model symulacyjny przebiegu procesu zużycia okładziny ciernej hamulca szczękowego maszyny wyciągowej. W modelowaniu uwzględnione zostały własności zużyciowe materiału okładziny oraz charakterystyczne dla maszyny wyciągowej parametry pracy hamulca. Odwzorowanie zużycia okładziny odbywa się przy uwzględnieniu cech sprężystych elementów mechanizmu hamującego i geometrii przylegania szczęki do bębna.

Zaproponowany model symulacyjny umożliwia prognozowanie przebiegu procesu zużycia okładziny ciernej oraz eksploatacyjnych zmian parametrów charakterystyki mechanicznej hamulca. Modelowanie komputerowe potwierdziło, że zużycie okładzin ciernych jest procesem złożonym, zasadniczo wpływającym na mechaniczną charakterystykę hamulca.

W procesie zużycia można wyróżnić okres wstępny, w którym rozkład nacisków między szczękami a bieżnią jest wynikiem objętościowego zużycia okładziny. Po tym okresie mechaniczne charakterystyki hamulców stabilizują się na określonym poziomie. Długość tego okresu jest zdeterminowana przez sprężyste własności elementów hamulca. Wyniki symulacji komputerowej mogą być zastosowane w procesie konstruowania układów hamulcowych. Model matematyczny hamulca może być modyfikowany zależnie od potrzeb. Po modyfikacji dowolna charakterystyka zużyciowa okładzin może być rozpatrywana, jak również układy hamulcowe o dowolnej konstrukcji.

КОМПЮТЕРНОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА ИЗНОСА ОБЛИЦОВКИ ВО ФРИКЦИОННЫХ ТОРМОЗАХ

Содержание

В статье представлена симуляционная модель прохода процесса износа фрикционной облицовки тормозной колодки подъёмной установки. В моделировании взяты во внимание свойства износа материала облицовки характерные для подъёмной машины и параметры работы тормоза. Изображение износа облицовки происходит при учёте свойств упругости элементов тормозного механизма и геометрии прилегания колодки к барабану. Предложенная симуляционная модель позволяет прогнозировать протекание процесса износа фрикционной облицовки и тоже эксплуатационных перемен параметров механической характкристики тормоза.

Компютерное моделирование подтвержило что износ колодок это сложный процесс значительно влияющий на механическую характеристику тормоза. В процессе износа можно отличить вступительный период в котором распределение давлений между колодками а дорожкой является результатом объёмного износа облицовки. После этого периода механические характеристики тормозов стабилиризуются на определённом уровне. Длина этого периода зависит от свойств упругости элементов тормоза. Результаты компютерной симуляции можно применять в процессе конструирования тормозных устройств. Математическую модель тормоза можно довольно изменять.