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NEW APPROACH TO THE TESTING OF DYNAMICALLY STRESSED CONTACT SURFACES

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Abstract: *The presented paper deals with a new theoretical approach to the loading analysis of contact surfaces during rolling. The experimental part of the research is based on the laboratory testing, with use of two new-type designed devices. These testing equipments enable us to study dynamical phenomena of loading with a possible rise of wave processes and with general slips in contact region of rolling couple for a chosen materials specimens.*
Key words*: contact surfaces, rolling kinematical pair, dynamical loading, slip (adhesion) characteristic, contact temperatures*

1. INTRODUCTION

The persistent problems of damage to contact surfaces when being dynamically strained may only be resolved gradually, using up-to-date metallographic methods, i.e. experimental analysis of samples taken from the contact-stressed areas. However, this generally known fact has its difficulties. In this paper we want to point out especially those facts, which result from possible problems related to the knowledge of loading modes.

In principle there are two basic approaches. One is the analysis of samples taken from the contact area of a real component, which has been subjected to a work load. This method is generally used in cases of evaluation of the state, which obviously shows the existing erosion of the contact surface.

However, preventing the occurrence of contact layer erosion requires such laboratory processes, which can be based on knowledge of the nature of loading the material samples and its history and, especially, on the information characterizing the dynamics of loading. This is crucial (and still widely ignored) in roll-away type contact pairs.

Special attention is paid to the wheel and rail contact pair, which especially with an wheel of adhesion driven, is a typical example of dynamic load. In spite of this, most of the analyses of forces are unfortunately based on the classical Hertz theory.

For example, the work [1] points out the fact that the contact spot is the area where the force effect is of an impact nature. From the view of the material it is necessary to consider the influence of the speed of deformation, which can affect all material constants, including the basic parameters of the fracture mechanics.

An additional phenomenon, which must be paid special attention, is the origination of contact temperatures, which, especially as a result of tangential forces, may reach values at which structural influence of the material may occur in local areas [2].

2. PHENOMENON OF OCCURRENCE OF POSSIBLE WAVE EFFECTS IN THE CONTACT AREA

The real material volumes in the contact area constitute a continuum in which, under specific conditions of loading, the energy is transferred by means of wave effects. The impact nature of the load can be described by amplitude density with a band spectrum, which in reality can overlap the line spectrum of natural frequencies, which is typical of the continuous environment of contact areas. Before the analytical speculation, based on [3], it is necessary to point out that the assumption of a homogenous continuum in the given case is not absolutely correct due to the existence of a considerably influenced thin superficial layer. Its dimension is very small in comparison with the dimensions of the contacting bodies. Therefore the indicated speculation can be considered a useful guide towards the values of the occurring dynamic stresses. The compression wave propagates in the direction of the normal line of the contact **(x)** at dilation speed $\mathbf{c_1}$. Its magnitude depends on modules E and G, Poisson number η, Lamé constant λ_1 and density ρ. The relations are:

$$c_1 = \sqrt{\frac{\lambda_1 + 2G}{\rho}} \quad ; \quad \lambda_1 = \frac{E \cdot \eta}{(1+\eta)(1-2\eta)} \qquad (1)$$

For E = 2.1 x 10^{11} Pa, G = 0.8 x 10^{11} Pa, ρ = 0.795 Ns^2m^{-4}, η = 0.3, the value of the dilation speed is $\mathbf{c_1 = 5.97 \times 10^3\ ms^{-1}}$**.** The corresponding dynamic stress in the direction of the normal line x is established by the following equation:

$$\sigma_x = E\frac{1-\eta}{(1+\eta)(1-2\eta)}\frac{v_0}{c_1} = 0{,}47 \cdot 10^8\, v_0 \text{ [Pa]} \qquad (2)$$

It is obvious that the dynamic stress value depends on the impact speed $\mathbf{v_0}$. This we will establish on the basis of the following speculation: from the static point of view, the length **L** of the instant contact spot is non-zero. As a result of rolling away at translational speed **v,** segment length **L** continuously emerges and disappears in time t = L v^{-1}. This time is a very small value even at relatively low translational speeds **v**.

Therefore, when defining the speed $\mathbf{v_0}$ we can start with limit value L $\to$ 0, which also results in $\mathbf{v_0 \hat{=} v}$. For example, for v = 100 km/h we get the stress value of σ_x = 1305 MPa. We realize that this stress value corresponds to an extremely short instant of time. The considered medium (steel) can register these short instants. However, in classical theories about the limit states of material this fact is not accepted. For completeness, let us also state that the components of stress in the plane perpendicular to normal line **x** are defined by the relation

$$\sigma_y = \sigma_z = \lambda_1 \frac{v_1}{c_1} \qquad (3)$$

In connection with the speculation about the propagation of deformation waves, it is necessary to point out the phenomenon of Rayleigh waves. This wave motion process is specific in the fact that the plane of oscillation is perpendicular to the tangential plane. The amplitudes in the direction of the normal line decrease exponentially. Therefore the described wave motion manifests itself predominantly as the skin effect. For details see [3], which contains the following empirical formula for the speed of propagation of these waves:

$$c_r = c_2\left(0{,}153\eta^{0{,}89} + 0{,}877\right) \qquad (4)$$

Here speed $\mathbf{c_2}$ is the speed of the transverse wave motion and equals $\mathbf{c_2 = 3{,}200\ ms^{-1}}$. For the Poisson number η = 0.3 we obtain $\mathbf{c_r = 4{,}470\ ms^{-1}}$. The phenomenon of propagation of the described superficial wave motion actually exists. Still, it has not yet been answered which part of energy is transferred by means of this kind of wave motion. From the analogy of high-frequency transfers of electricity by normal conductors we know that this **skin-effect** transfers a considerable part of the transported electricity. This necessarily brings the question whether it is not the same in case of the dynamic load of contact surfaces.

Owing to the fact that thin superficial layers of the rolled-away wheel show substantial changes in material constants, there are conditions for additional waves, described by Love [4]. These are shear waves. The occurrence of these waves is conditioned by the existence of a thin elastic layer, which adheres to an elastic medium with distinctly different material constants.

3. ON THE OCCURRENCE AND IMPORTANCE OF THE THERMAL EFFECT IN THE CONTACT

Adhesion drive is typical in the occurrence of tangential force **T**, the instant magnitude of which is given by the instant value of the normal line wheel force and the status of the contacting surfaces in the contact. The rail vehicle theory uses the **slip characteristic**, which, in principle, expresses the tangential deformation property of the surfaces, accompanied with increasing tangential slips **s**. The processes taking place in the contact area necessarily have a **thermodynamic nature and are diffusion processes**. In case of small tangential deformations and slips the generated contact temperature will be very low, so the material volumes are in a state near the thermodynamic equilibrium. The system behaves as isolated, minimally influenced by any external effects. If the linearity of the dependence of slip **s** on tangential force **T** in this area were positively proved [7], the possibility of the change of steepness of the slip characteristics can be ruled out. If we accept the established phenomenon of the instant relation between tangential force **T** and normal line force **R**, i.e. if we introduce the term **coefficient of adhesion** μ, the slip characteristic is the function of $\mu = f(s)$. For the mean value of the generated contact temperature $\mathbf{T_K}$ we suggest the following relation:

$$T_k = 1{,}11 \frac{\mu R}{\sqrt[b]{a \lambda \rho \cdot c_p}} \Phi \tag{5}$$

where μ is the coefficient of adhesion, **R** is the wheel force [N], **a**, **b** are the lengths of half-axes of the contact surface [m], $\lambda = 55.0$ is the thermal conductivity of steel [$Js^{-1}m^{-1}K^{-1}$], $\rho = 0.79 \times 10^4$ is the density of steel [Ns^2m^{-4}], $\mathbf{c_p} = 460$ is the specific thermal capacity of steel [$J\,kg^{-1}K^{-1}$], $\Phi = \sqrt{v_1} - \sqrt{v_2}$ is the speed function [$(ms^{-1})^{0,5}$]. Then the slip is expressed by the equation

$$v_2 = v_1 - s\, v_2 \tag{6}$$

where $\mathbf{v_1}$ is the circumferential speed of the wheel and $\mathbf{v_2}$ is its advancing speed. The speed function can then be expressed in the following form:

$$\Phi = \sqrt{v_1} - \sqrt{v_1 - s v_1} = \left(1 - \sqrt{1-s}\right)\sqrt{v_1} \tag{7}$$

As we are interested in the progress of contact temperatures $\mathbf{T_K}$ in the entire range of the slip **s**, let's introduce the respective analytical function in the relation for contact temperature $\mathbf{T_K}$. Its expression is based on the fact mentioned earlier, that the adhesion processes have a strong diffusion nature. In processes of a similar type it has been proved that we can describe them successfully from the probability position, e.g. on the basis of the Gauss distribution. By introduction of the **error function** [5, 6], expressing the dependence of the coefficient of adhesion μ on slip **s,** we get the following relation:

$$\mu(s) = \frac{1}{2}\operatorname{erf}\left(\frac{s}{\sigma\sqrt{2}}\right) = \frac{1}{\sqrt{\pi}} \int_0^{\frac{s}{\sigma\sqrt{2}}} \exp\left[-\left(\frac{s^2}{2\sigma^2}\right)\right] ds \tag{8}$$

The symbol σ is the standard deviation of normal distribution (the mean value of the distribution function is zero). The stated function limits to the value $\mu = 0.5$. According to the research done by the adhesion drive theoreticians [7, 8], the adhesion characteristics have a real peak and with the increasing slip **s** the adhesion process converts to the process of shear friction. Therefore we further propose the corrected function **μ(s) = kor.erf (s),** as a subtraction of two functions, while setting the condition that for $s \to \infty$ the coefficient of adhesion converts into the coefficient of pure shear friction **f**. The corrected function is:

$$\mu = \mu_1(s) - \mu_2(s) = \frac{1}{2}\operatorname{erf}\left(\frac{s}{\sigma_1\sqrt{2}}\right) - a_1\left[\operatorname{erf}\left(\frac{s - v_2}{\sigma_2\sqrt{2}}\right) + 1\right] \tag{9}$$

So as to fulfil the condition stated above, the value of the correction coefficient is given by the equation

$$a = 0.25 - 0.5\, f \tag{10}$$

Statistical parameters σ_1, σ_2, ν determine the shape of the slip characteristics. Their values will be established by experimentation on the upcoming laboratory testing device.

For obtaining essential orientation, ***Fig. 1*** contains the calculated progress of the slip characteristic for alternative values of parameter ν_1 and the coefficient of shear friction f = 0,1.

From the progress shown in ***Fig. 2*** it can be seen that the steepness of the characteristics, defined by the tangent in point [0, 0], is influenced by parameter ν_2. The actual value of steepness, which, in our view, may be only one, can only be determined by experimentation.

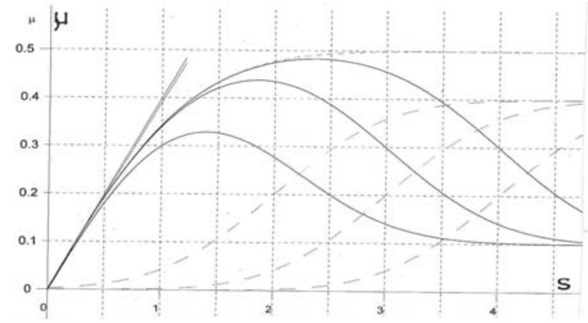

Fig. 1

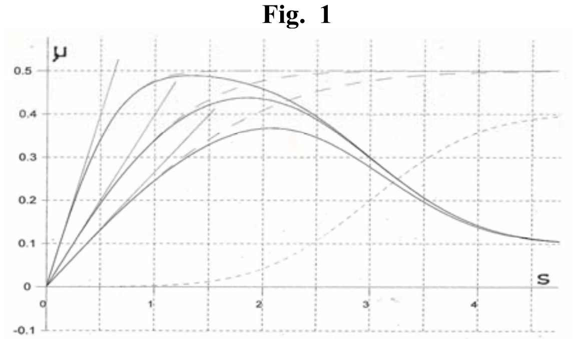

Fig. 2

So as to set the criterion of linearity we start with the relation for derivation of the corrected function in point [0, 0]. This has the following form:

$$\frac{d\mu}{ds} = \frac{1}{\sigma_1\sqrt{2\pi}} - \frac{2a_1}{\sigma_2\sqrt{2\pi}}\exp\left(-\frac{v_2^2}{2\sigma_2^2}\right) = \frac{1}{\sqrt{2\pi}}\left[\frac{1}{\sigma_1} - \frac{2a_1}{\sigma_2}\exp\left(-\frac{v_2^2}{2\sigma_2^2}\right)\right] \tag{11}$$

For the definition of the criterion of linearity the condition was used that the deviation of function **μ(s)** from the tangent in point [0, 0] is less than or equal to the deviation, which corresponds to the change of slip by 0.1%:

$$\frac{d\mu(0)}{ds}\cdot s = \mu(s + 0{,}1) \tag{12}$$

After substituting the corrected function μ(s) = kor.erf (s) we will arrive at the sought dependence of temperature $\mathbf{T_K}$ on slip **s**:

$$T_K = \frac{1{,}11R}{b}\sqrt{\frac{v_1}{a\lambda\rho\,\mathrm{c_p}}}\left(1 - \sqrt{1-s}\right)\cdot \mathrm{kor\ erf}(s) \tag{13}$$

Fig. 3 contains the example of calculated temperatures $\mathbf{T_K}$ for speeds v_1 = **10**; **30**; **50** $\mathrm{ms^{-1}}$. The wheel force is R = $\mathbf{10^5}$ N, the radius of the wheel is **625** mm, the radius of the profile of the wheel tread is **340** mm, the radius of the rail head is **300** mm. The corresponding dimensions of the contact spot according to Hertz are a = **14.32** mm; b = **5.77** mm.

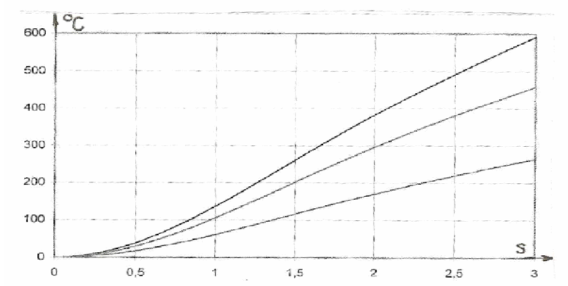

Fig. 3

4. LABORATORY DEVICE FOR DYNAMIC LOADING OF MATERIAL SAMPLES

A new type of testing device for the dynamic loading of test samples from the railway wheel/rail was developed in the laboratories of the Jan Perner Transport Faculty of the University of Pardubice. In principle it is the study of the contact area of the material, stressed by the time-variable radial force **R = R(t)** and incurred tangential force $\mathbf{T_{(t)}}$ as a result of the slip process. The principle of the device can be seen in the diagrams in ***Fig. 4, 5***.

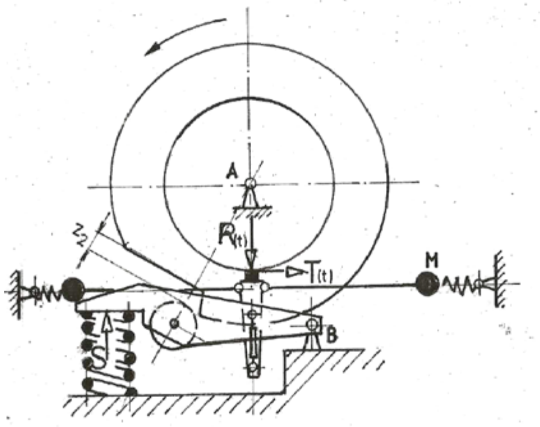

Fig. 4

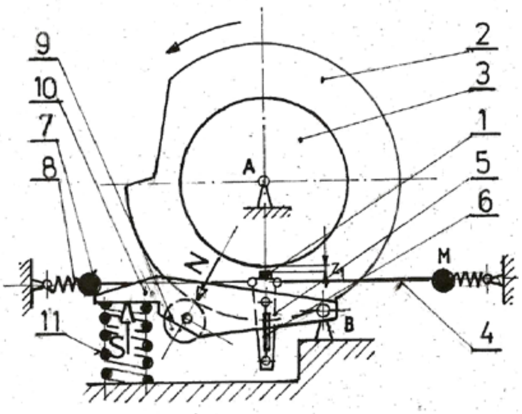

Fig. 5

Tested sample **1** is placed on the vertical rest **5**, which is linked to the pressure lever **10** by two vertically arranged tensometric dynamographs **6**. In the horizontal direction the rest **5** is bound by horizontal drawbars **6**, connected to the springs **8** with masses **7**. The pressure lever **10**, revolving around axis **B**, is controlled by the wound spring **11**. The roll-away pulley **9** is located on the lever **10**. The position according to ***Fig. 4a*** refers to the situation when the spring with the set strength **S** induces reaction **N** between the pulley **9** and disc **2** with cut-out. Clearance $\mathbf{z_1}$ is set between the tested sample **1** and the working disc **3**. During the controlled rotation of discs **2** and **3** at the circumferential speed, corresponding to the selected slip **s,** the pulley **9** fits into the disc **2**, whose cut-out is adjusted so that clearance $\mathbf{z_2}$ appears. At this moment the dynamic reaction $\mathbf{R_{(t)}}$ occurs between the sample **1** and the surface of the disc **3**. At the existence of the set slip **s** the dynamic tangential force $\mathbf{T_{(t)}}$ is incurred. Its magnitude and progress are determined by the modal setting by the horizontal link of the rest **2**, which is realized by tuning using the masses **7**. Two modes of loading are distinguished by the simultaneous evaluation of the time progress of the dynamic forces $\mathbf{R_{(t)}}$ and $\mathbf{T_{(t)}}$. If the line spectrum of the force **T(t)** is separated from the band spectrum of the force $\mathbf{R_{(t)}}$, the loading mode is near the possible occurrence of transient performance of self-excited oscillations of the relaxation type. If both spectra overlap mutually, the process of dynamic load of the sample **1** is accompanied by wave processes.

The described test device thus provides the possibility of study of the influence of self-excited oscillations on the service life of the sample, and in the latter case the experimental study of the possible effects of wave processes is expected. The concept of the device enables simulating the real load of the contact spot with adjustable real slips. At the same time, as the sample is located on the stationary rest **5**, it provides the possibility of measuring the incurred contact temperatures.

5. LABORATORY DEVICE FOR THE STUDY OF ADHESION CHARACTERISTICS´

For the experimental study of the progresses of tangential forces at the set or variable slip **s** another type of laboratory device was developed, which is expected to verify or supplement the existing opinions, which are based on the established coefficient of adhesion μ, i.e. on the ratio between the radial loading force and the incurred tangential force. The principle of its activity is described by means of the diagram in ***Fig. 5***. The tested samples of material **2**, **3** are disc-shaped and of the same diameter.

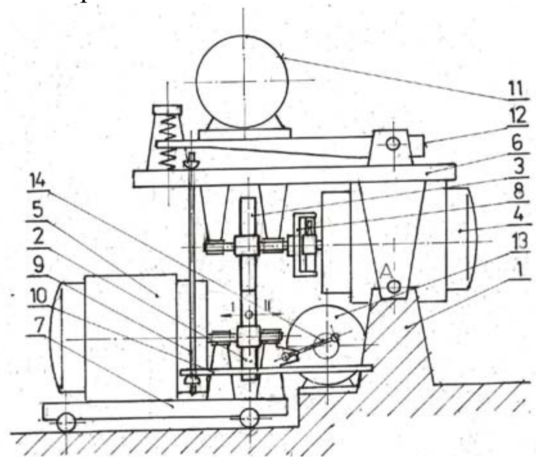

Fig. 6

Both discs are driven directly by the vector-controlled synchronous servomotors **4**, **5**. The upper system **3**, **4** is located on the rest **6**, which is pivoted in relation to the machine frame **1** around the indicated axis **A**. The servomotor **5** is located on the horizontally-sliding rest **7**. The shaft of the upper disc **3** is fitted with the torsionally-flexible dynamograph **8**. The radial loading of both discs can be adjusted by means of the vertical drawbars **9**, which are linked to the girder dynamographs **10** in the bottom part. The dynamic component of this loading is incurred by the pair of rotational vibrators **11**, whose motors are equipped with programmable control. The bearing of the vibrators on the spring-loaded rest **12** enables their self-synchronization. The horizontal oscillation of the rest **7** (indicated by arrows I, II), which bears the servomotor **5**, is controlled by the program-controlled motor **13** by means of the crank mechanism **14**.

The device is proposed for two test modes. In the **first mode** the speeds of both motors are set so that the selected tangential slip is incurred; it is also possible to set transverse oscillation of the rest **7**. The flexible dynamograph **8** sends a signal about the value of the adhesively transferred torque including its changes in time. In this way it is possible to test the working modes within the entire range of the set tangential slips with the contribution of the transverse slips. The modes are tested either as stable, or as transient. The **second mode** of tests has a similar nature, except that one of the servomotors is controlled as a generator. In this case the slip is incurred by adhesive processes in the contact of both discs.

At these tests especially the dynamic manifests of the system around the maximum of the incurred tangential force are monitored, where unstable states are presumed on the basis of the classical adhesion theory.

6. CONCLUSION

This paper gives basic information about two new types of testing devices for the study of the influence of the dynamic load of contact surfaces in the contact area of a rolling kinematical pair. The essential substantiation of building these facilities is presented in the introduction. Chapter 2 deals with the possible occurrence of wave effects in the contact of the adhesion drive of a rail vehicle and points out the necessity of experimental research, focused on the limit states of the material. Chapter 3 presents speculation about thermal effects in the contact along the slip characteristics, which is described within the entire range on the basis of the probability theory.

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НОВ ПОДХОД ПРИ ИЗПИТАНИЯТА НА ДИНАМИЧНО НАТОВАРЕНИ КОНТАКТНИ ПОВЪРХНОСТИ

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РЕПУБЛИКА ЧЕХИЯ

Резюме: *Представеният доклад разглежда нов теоретичен подход към анализа на натоварване на контактни повърхности по време на търкаляне. Експерименталната част на изследването се базира на лабораторни изпитания с използването на две устройства от нов тип. Тези съоръжения за изпитания дават възможност да изследваме динамичните явления при натоварване с възможно появяване на вълнови процеси и с общи приплъзвания в контактната зона на търкалящата се двойка за определени образци на материали.*

Ключови думи*: контактни повърхности, въртяща се кинематична двойка, динамично натоварване, характеристика на плъзгане, температура на контакта.*