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RESEARCH

Static Coefficient of Rolling Friction at High Contact Temperatures and Various Contact Pressure

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A B S T R A C T

The paper theoretically and experimentally analyzes the influence of increased temperature and load contact in the value of the coefficient of rolling friction. Theoretical analyzes show that at temperatures of the order of 200 ^{0}C, exist thermal potential necessary to narrow contact zone leads to a redistribution of the contact pressure and an increase in torque performance. Based on the measurement results, established the regression coefficient of friction depending on the temperature, normal load and geometry parameters of contact elements (radius of curvature of the contact elements). Material of examination contact pairs is steel ASTM A-295 hardness 64-66 HRC. The measurement results indicate a very significant impact on the temperature coefficient of friction, normal load and contact geometry (the radius of curvature of the contact elements). According to the authors future research should focus on optimizing the choice of materials that under the given conditions of mechanical and thermal load of contact to ensure a minimum value of the coefficient of rolling friction.

1. INTRODUCTION

The force of friction occurs at the contact of two bodies. Friction can be divided into static friction and dynamic friction [1]. The force of friction in the stationary phase increases with the tangential displacement to the amount needed to keep body movement occurred in contact. Micro movement, which can be called the intial movement, occurs in the contact zone and the preceding the phase of movement. This micro movement could reach a relatively large value when one of the contact surface has a small tangential stiffness compared with the second contact surface, such as rubber and metal contact. The main parameters of static friction of are the maximum force of static friction, which is realized at the time the macro movement, and the corresponding value of the micro-movement.

The static coefficient of friction depends on many parameters, first of all of a normal load, temperature, processing quality and material of the contact surfaces [2-6]. Many authors have investigated the influence of contact surface roughness parameters on the value of the coefficient of static friction. It has been concluded that the static coefficient of friction increases with increasing surface roughness parameters [4,5]. Parameters of surface roughness skewness, and kurtosis, have a greater impact on the static coefficient of friction in relation to the other parameters [7,8].

Understanding the static coefficient of friction is impossible without an analysis of the mechanisms under which it is formed, which was the target of numerous studies. McFarlane and Tabor [9] examined the static friction in contact steel balls and block indium. They came to the conclusion that the material begins to flow until the contact surface is not large enough to withstand the load. Even at very low values of tangential force, leads to tangential flow of material in the contact layer. The real contact surface is increases until the moment when the tangential force becomes greater than the force of friction but then starts macro slip.

There are several mechanisms that may occur due to an increase in the force of static friction with increasing dwell time [10]. The authors present the conditions under which the size of the static friction is greater than the friction of movement, from the aspect of impact of temperature on the roughness nature of the movement (creep motion). Generally, at temperatures above zero, the coefficient of static friction is greater than the coefficient of kinetic friction caused by different processes activated by heat, eg a chain interdiffusion or forming capillary bridges (fueled by heat).

Chang et al [11] analyzed the force of adhesion and contact load at the rough metal surfaces and used to determine the static coefficient of friction. It is shown that the coefficient of friction depends on the material properties and the topography of the contact surface, as well as that depends on the external load versus general law defined friction.

Numerous experimental examination of static friction referred to the moment of transition from sleep mode to a state of movement, whereby the actual contact conditions almost always occurs "stick-slip" effect. Authors D.-H. Hwang et al. [12] came to the conclusion that the greatest value of the coefficient of static friction related to contacts of a pair of steel / alumina, and that the smaller the value achieved with the homogeneous material (steel / steel), and that such a result is primarily the result of "stick-slip" effect.

Etsion and Amit [13] experimentally investigated the effect of normal load on the static coefficient of friction, in very smooth metal surfaces. Normal load has been in the range of 10^{-3} N to 0,3 N. This load was applied to samples of small diameter made of three different aluminum alloys which are in contact with nickel-plated surface. The tests were conducted under conditions of controlled humidity and air purity. Dramatically increasing the static coefficient of friction is observed when a normal load is reduced to the lowest level. This behavior is attributed to adhesive forces which play an important role and are prominent at low normal loads and smooth surface.

The effect of temperature on the friction characteristics of the material is a very common topic of many papers [14-18]. One of the most important conclusions these papers is that the static coefficient of friction increases with increasing temperature, which is partly a result of increased plasticity of most contact materials at elevated temperatures.

The behavior of static and dynamic coefficient of friction during the warm indentation and injection molding explained Worgull, Hetu, Kabanemi and Heck in a scientific paper [18]. Based on the experimental analysis of temperature influence during the indentation, static friction coefficient varies at temperatures between 110 °C and 170 °C and has a value of 0.86 to 2.13. It has been found that the static coefficient of friction increases significantly with increasing temperature.

Experimental investigation of the static coefficient of friction measurements were performed in the equipment of different design and geometry of the contact pairs [1,5,15,19-22]. Whereby the reference [20-22] is related to the measurement instrumentation for the measurement of the coefficient of static friction rolling.

Frictional characteristics of the rollers bearings are dependent on the material of the contact pair, design, tolerances, surface topography contact and lubricants. In order to determine the value of the coefficient of static friction small bearings Budinski [20] proposed a modification of the test of slope plane defined by the standard ASTM G. 164. Eftimie et al. [24] analyze the behavior of the transition between static and dynamic friction coefficient in a cylindrical joint, in order to reach high reliability when loads are acting. The friction between cylindrical contact faces is analyzed both in dry and lubricated conditions up to the moment that the assembly starts moving while tilting the entire assembly. It means that it is analyzed a complex static friction developed along a chain and its sprocket.

The rolling movement of the micro balls (stainless steel with a diameter of 285 μm) by V groove presented by Ta-Wei Lin et al. [21]. The measured values of the coefficient of static frictionwho has moved within the limits of 0.01 in cases without additional load, and 0.07 in the value of the load of 40 g. The dynamic coefficient of friction in terms of without additional loads amounted to 0,007 to 0,045 at a load of 40 g. Based on the literature review can be noted that a very small number of papers deals with the problem of determining the static coefficient of friction.

The authors of this paper, with an emphasis on literature review failed to reach the experimental data related to the static coefficient of rolling friction at high contact temperatures and various contact pressure. The authors, in order to realize the experiment developed a measurement instrumentation that allows a very precise determination of the static coefficient of rolling friction at at high contact temperatures and various contact pressure.

2. THEORETICAL BACKGROUND

Based on the literature review can be concluded that at temperatures greater than zero, the coefficient of static friction greater than the coefficient of kinetic friction caused by different processes activated by heat. The static coefficient of friction increases with increasing temperature, which is the result of an increase in the plasticity of most contact materials at elevated temperatures.

According to the border states of balls rolling on a flat surface (Fig. 1a and 1b) and cited literary source [22] static coefficient of rolling friction can be determined from the equation 1, which follows from the equation of balance body rolling down an slope plane (Fig. 2b).

$$f = \frac{e}{R} = tg\alpha \tag{1}$$

Where is:

f – static coefficient of rolling friction;
e – coordinate that determines the position of the resultant reaction N;
R – the radius of the body;
α – angle of plane.

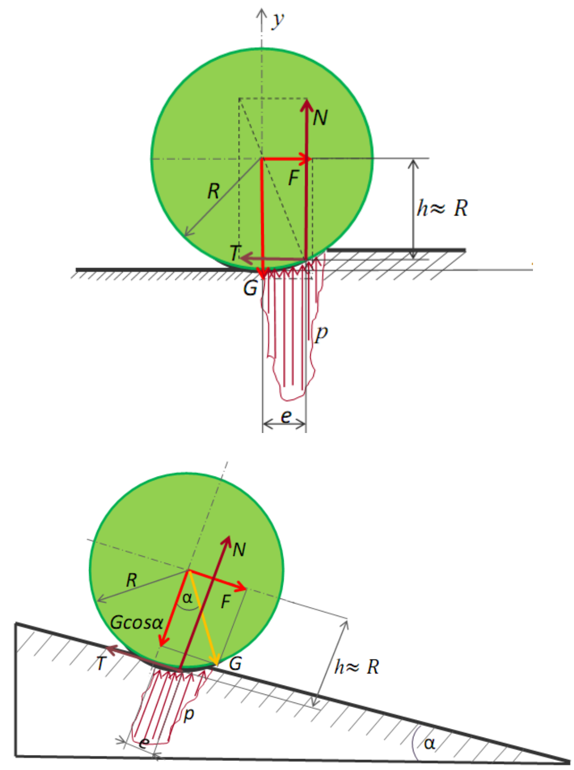
a)
b)


Fig. 1. The equilibrium of the body in movement of rolling.

In order to clarify the theoretical phenomenon of temperature on the static coefficient of friction rolling starts from the assump:

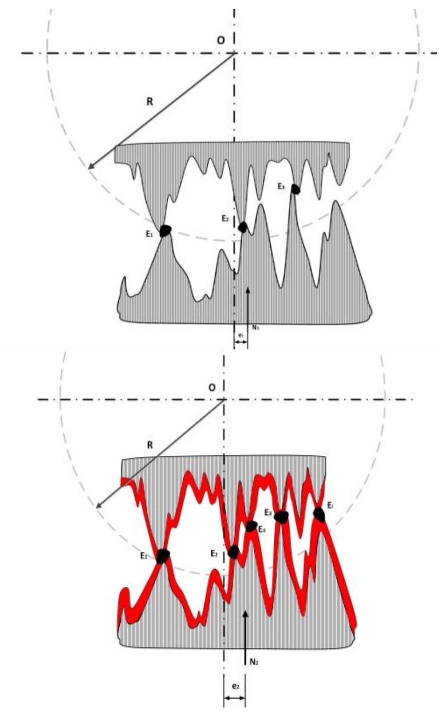
a) In the case contacting the balls on a flat surface, without the presence of temperature, contact is achieved on the tops of roughness, whereby a large number roughness contact pair (balls and flat surfaces), there is no real physical contact. Respectivelly, there is some empty space (Fig. 2a.). For example, the contact is carried out in the vicinity of points E1, E2 and E3.
b) During heating contact pair comes to the spread of both body and filling the empty space between the roughness (Figure 2b.),

whereby leads to the formation new contacts and increase the real contact area, where the balls contact with the flat surface achieves around points A4, ..., Ai.

c) In the limiting case of body equilibrium in rolling motion (Figure 3a and Figure 3b.) comes to the redistribution of the resulting reaction forces N which is in relation to the axis of the sphere moved by the value e_1. Based on the foregoing (stated a and b) it is logical to assume that the value of "e" will be higher during the heating contact pair, ie. e2> e1. Respectively, moment of rolling resistance would be higher, ie, the moment would have an increasing trend in increasing temperature.

$$M_K = N \cdot e \tag{2}$$

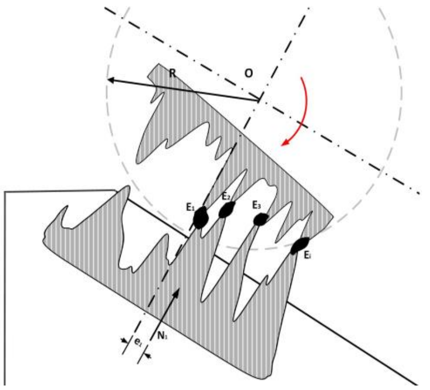
a)



b)

Fig. 2. The real contact area of sphere and flat surface before heating (Fig. 2a.), and after heating (Fig. 2b.).

a)



b)

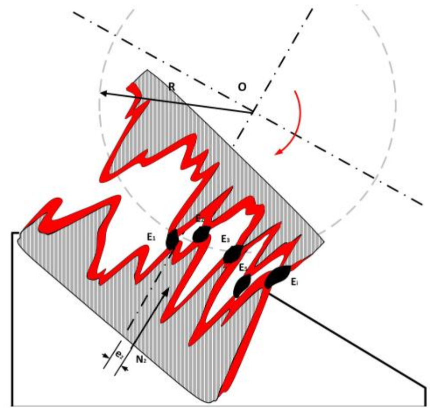


Fig. 3. Position of resultant force N without heating of the contact pair (Fig. 3a.), and with heating the contact pair (Fig. 3b.).

In accordance with the above mentioned authors suppose that between the static coefficient of rolling friction and the size of thermal dilatation of the contact pair there is a certain correlation. Considering the stochastic nature of real contact area and nonlinear temperature field, it is very difficult to quantify the theoretical effect of temperature on the friction coefficient. However, according to previous considerations the authors suppose that between the static coefficient of rolling friction and the size of thermal dilatation of the contact pair there is a certain correlation. In this regard, it can be shown that at temperatures on the order of 200^0C, thermal dilatation sphere exceed the value of the maximum height of roughness even rougher machined sphere.

Very easily can be shown that the change of the radius of the sphere which is caused by the amount of heatingi:

$$\Delta R = R_0 \cdot (\sqrt[3]{(1+\beta \cdot \Delta t)} - 1) \tag{3}$$

where is:

ΔR - changes in the radius of sphere caused by heating; R_0 – the radius of the sphere before heating; β – the coefficient of thermal expansion of the material sphere; Δt – the temperature difference between sphere before and after heating.

Using the equation 3 obtained results $\beta = 1{,}2 \cdot 10^{-5}$ (the temperature coefficient of expansion of steel), $R = 5$ mm i $\Delta t = 200^0 C$ radial expansion of the sphere is $4 \mu m$. This value exceeds the value of the maximum height of roughness fine ground or polished surfaces. Thus, the increase in temperature of 200 ^{0}C sphere created the necessary conditions for thermal expansion roughness in the contact zone of the sphere with a flat surface. This reality explains the assumptions previously exposed to a model that talks about increasing the modulus rolling (2), and an increase in size "*e*". This explanation is more realistic if one takes into account that at hight temperatures heat up both contact elements (contact pair) in which there is obviously a thermal potential necessary to narrow contact zone contact occurs over the tops of roughness as shown in Figures 2b. and 3b.

3. EXPERIMENTAL INVESTIGATION

Experimental investigations were carried out on tribometer that works on the principle of the inclined plane (Fig. 4). Contact pair together with a system for heating (electrical resistance heater) and a probe for measuring temperature at point near the contact zone samples are rotated from the horizontal to the desired angle. Measuring the angle of rotation of plane is performed on a mechanical principle with the accuracy of reading the angle of one minute. The measurement system is separated from the high temperature zone.

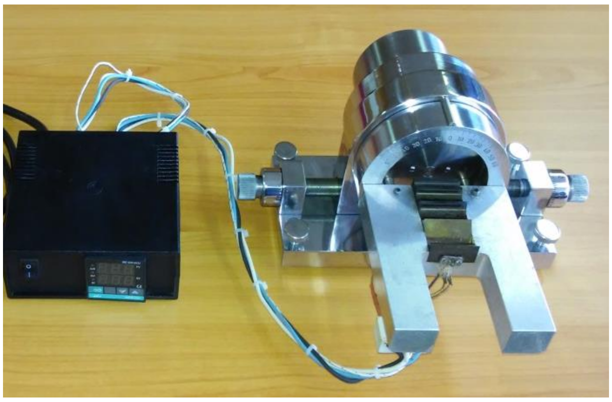


Fig. 4. Photographic representations of tribometer.

Experiments were carried out with contact pairs of relatively small beads (different diameters) and block different radii of curvature. The diameters of the tested balls are in the range of 2-15 mm, material tested of the balls and the steel block ASTMS A-295 hardness 64-66HRC. Roughness of the balls is Ra≤0,0025 microns. Block was made with contact surfaces of different radii of curvature (R 2 = -10 mm). The roughness of the processed surface of the channel block was in the range of $R_a = 0,7 - 0,85 \mu m$. Experiments were performed in a discreet increase of temperature: T=20 ^{0}C – 200 ^{0}C. A total of 324 independent experiments performed. Example the distribution of temperature fields in the contact elements is shown in Fig. 5 .

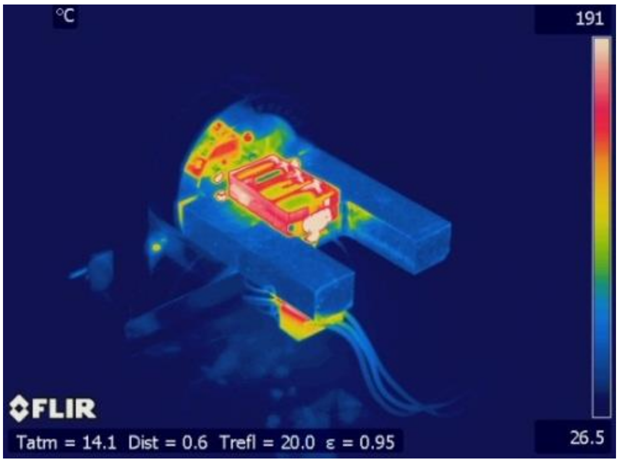


Fig. 5. Thermovision snapshot distribution of temperature fields.

3D diagram of the measured values of the coefficient of friction in dependence on temperature and normal relations between the load and the radius of curvature of the contact geometry, ie. indicator is shown in Fig. 6.

$$\frac{F_n \cdot R}{d/2} \tag{4}$$

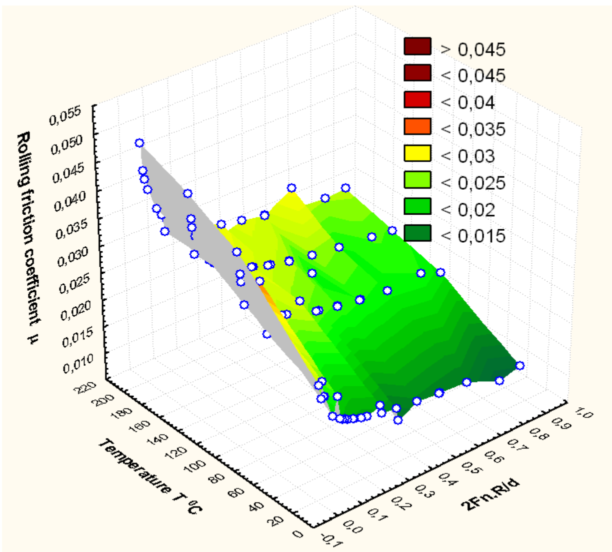


Fig. 6. 3D preview experimentally obtained depending coefficient of friction on the temperature and contact geometry.

4. DISCUSION

Within the theoretical considerations given in this paper the authors explain the assumptions on which it was expected that at high temperatures to reach a significant increase in the coefficient of static friction rolling. A theoretical model based on redistribution of the resultant contact pressure due to the increase in temperature. Based on the calculated value of about thermal expansion is shown that the thermal dilatation value exceeds the maximum height of roughness ground or polished contact pairs. The authors, based on the analyzed literature, find that it does not provide a general explanation of the reasons a significant increase in the coefficient of friction with increasing temperature. In this connection, the theoretical model outlined in this paper represents a contribution to the theoretical clarification of this phenomenon. Experimental tests were performed with changing values of temperature and contact pressure. From the diagrams shown in Fig. 6 can be, in general, noted that the coefficient of friction increases when the temperature increase and the increase ratio (4), or in increasing the normal load, and / or the radius of the curve on the block and the decreasing diameter of the balls. Whereby it can be concluded that the investigated conditions, the temperature has a greater impact than the ratio of the normal load and the radius of curvature of the block toward the radius balls. The relation (4) is obviously an indication of the specific pressure because it involves factors that directly affect the value of the theoretical Hertz contact pressure. In this regard it can be concluded that the results in a line with literature data related to the global impact of temperature and contact pressure on the value of the coefficient of friction. Experimental investigation , as noted above, were carried out with three replications of each of the independent experiments. This fact greatly increases the level of reliability of measurement instrumentation and measurement results and is in accordance with literature data [22].

5. CONCLUSION

Based on the literature review can be concluded that the examination of the impact of temperature and contact pressure on the value of static coefficient of rolling friction has not been the topic of more extensive research. In the field of static coefficient of rolling friction at elevated temperatures have not been any studies in terms of global perception of the complex impact of the normal loads, the size of the contact surface and the temperature coefficient of rolling friction. Within the theoretical considerations given in the paper, the authors show that at temperatures of the order of 200 ^{0}C there is a large potential of heat necessary for the proper contact zone there is a very significant redistribution of the contact pressure and an increase in torque performance. The measurement results indicate a very significant effect of temperature and Hertz contact pressure on the value of the coefficient of friction. Based on these results it can be concluded that the coefficient of rolling friction increases by more than 50 % of the change in temperature of the order of 200 ^{0}C. With regard to this fact, the authors of this study believe that future research should be directed toward material testing contact pairs, in which, as a function of the analyzed sizes (F_n, T, d, R) obtained the minimum coefficient of rolling friction. Optimization in this sense can have a significant tribological effects and industrial applications in the field of optimizing the selection of materials in processes characterized by rolling friction at high contact temperatures.

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