

The Impact of One Heat Treated Contact Element on the Coefficient of Static Friction

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ABSTRACT

The subject of the paper includes theoretical considerations, the conducting of experimental tests, and the analysis of exposed test results related to determination of the coefficient of static friction of previously heat-treated contact pairs. One contact element is previously, before the procedure of determining the coefficient of static friction, heated at temperatures in the range of ambient temperature to 280°C and then cooled down to ambient temperature. The results of experimental tests of five different materials show that depending on the heat treatment of one contact element, there is a significant decrease in the coefficient of static friction. The authors of the paper consider that the reasons for the decreasing coefficient of static friction are related to oxide formation and changes in the surface layer of the contact element which is previously heat-treated.

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1. INTRODUCTION

Numerous theories are based on hypotheses and different observations, which occur from experimental data and explain the influence of different contact surfaces on the value of the coefficient of friction. In researches [1,2] the authors show that increasing the temperature of the body in contact has a significant impact on increasing the coefficient static of friction. Static friction is realized at the moment of macro tangential displacement of a moving body in relation to a motionless body [3,4]. The coefficient of static friction depends on a number of parameters, primarily the contact surface, normal load, atmosphere and temperature, surface absorption, surface finish and material of contact surfaces [5-9].

Experimental tests [10-15] are based on the observation of changes in the coefficient of static friction due to changes in temperature of the contact surfaces. In these studies, it is found that the influence of increased temperature leads to tribochemical changes on the surfaces of contact pairs. The changes are shown in the form of the appearance of oxides, borides, carbides and nitrides, which causes the change in the coefficient of static friction. It is observed that keeping the contact pairs at higher temperatures increases the oxide layer, which results in the increasing of the coefficient of static friction. When the surface contact between the contact pairs becomes completely based on the contact of iron oxide, it leads to stabilization of the coefficient of static friction due to appropriate chemical and thermal reactions [10]. According

to [16] it is experimentally confirmed that the coefficient of static friction of tool steel has a lower value at temperatures around 800 °C. Experimental results indicate that the coefficient of static friction between the contact pair of nitrided tool steel and boroned steel is lower at higher temperatures compared to tool steel without surface nitriding. Reducing the coefficient of friction with increasing temperature can possibly be connected to the formation of a concentrated oxide layer, which is caused by oxidation at higher temperatures [16]. Vanadium (V) significantly reduces the coefficient of friction at higher temperatures due to the ability of forming lubricating oxides, V₂O₅ [16,17]. Experimental tests [18] show that the TiN coating has a higher coefficient of friction during the entire temperature range from 25 °C to 700 °C, compared to the VN coating. Researches show that the reason for the decreasing coefficient of static friction of VN coatings is the previously formed oxide layer which consists mainly of V₂O₅ oxide. The mentioned oxide has a low shear strength and very low melting point, which leads to lower coefficients of static friction at higher temperatures because of its crystallographic structure [19].

Based on analysis of literature references, it can be concluded that the heat treatment of contact pairs has a very important and complex influence on the value of the coefficient of static friction. Obviously, the different materials of the contact pairs give smaller or larger values of the coefficient of static friction, depending on the values of preheating temperatures.

2. THEORETICAL CONSIDERATIONS

The principle of measuring the coefficient of static friction over an inclined plane (Fig. 1) is based on gravity. The coefficient of static friction, as it is known, is the ratio of the friction force and the force normal to the contact surface, where the condition of equilibrium on an inclined plane is given with expression $F_{\mu} > mg \sin \alpha$. In the boundary condition of sliding friction, we have:

$$\mu = \frac{F_{\mu}}{N} = \frac{mg \sin \alpha}{mg \cos \alpha} = \operatorname{tg} \alpha. \quad (1)$$

where μ – is the value of the coefficient of static friction, F_{μ} - the friction force, m – the body mass,

g – the acceleration due to gravity, α – the angle of the inclined plane.

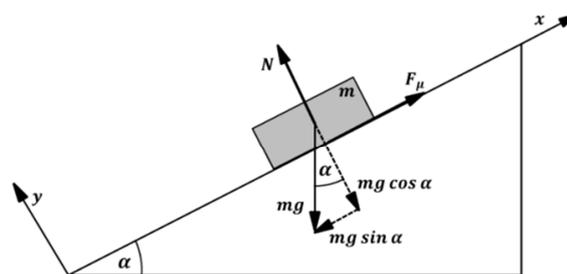


Fig. 1. Equilibrium of body on an inclined plane.

Measurement error in the coefficient of static friction is a consequence of the measurement error of angle α in relation to the ideal horizontal plane at the moment when the body that is located on an inclined plane starts the motion from the motionless state. According to research [1,2] measurement error is:

$$\varepsilon = \frac{\operatorname{tg}(\alpha + \Delta\alpha) - \operatorname{tg} \alpha}{\operatorname{tg} \alpha} \cdot 100 [\%]. \quad (2)$$

where ε – is the relative measurement error, $\Delta\alpha$ – the measurement error of angle α .

Analysis of expression 2 shows that the measurement error depends on accuracy of the inclined plane angle and the measured value of the coefficient of static friction. As we can measure this angle with accuracy of $\Delta\alpha = 1'$ and due to knowledge that the coefficient of static friction is $\mu = \operatorname{tg} \alpha$, for $\mu = 0.1 \div 0.35$ the relative measurement error is between 0.03% and 0.1% (see Fig. 2).

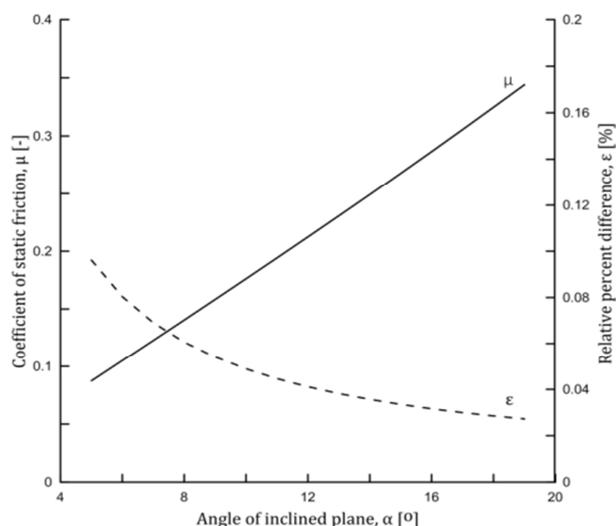


Fig. 2. Graphic representation of the relative measurement error of the coefficient of static friction obtained on an inclined plane.

The authors of this paper started from the idea of determining the value of the coefficient of static friction of one previously heat treated contact element using measurement instrumentation, which is described in more detail in the researches [20]. One contact element is previously heated to temperatures at discrete values up to 280 °C and then cooled to an established ambient temperature. It is assumed that such measured value of the coefficient of static friction includes the effects of heat treatment, i.e. the effects of the oxide layer formed on a contact element.

3. EXPERIMENTAL RESEARCH

The aim of these experimental tests, in comparison with performed research in this area so far, is to affirm the trends of changing the coefficient of static friction in the function of technological heritage related to the preheating treatment of contact pairs with various metal materials. Measurement of the coefficient of static friction is performed on a tribometer that works on the principle of an inclined plane [1,2]. Schematic representation of the tribometer and contact pairs is shown in Fig. 3.

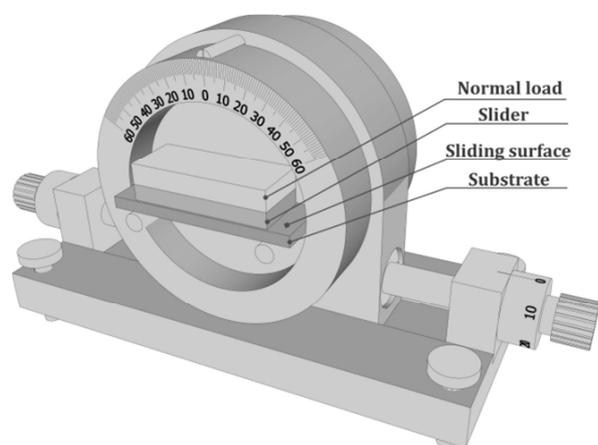


Fig. 3. Schematic representation of tribometer and contact pairs.

The value of normal force which loads the slider, which is located on the substrate, is defined by the load of 2N. The slider is made of steel EN C45. The materials of the second contact element are:

- EN X160 CrVMo12 1,
- EN S 235 JRG2,
- CuSn12,
- Grey iron 26, and
- Aluminium Al.

The chemical composition and hardness of these materials are shown in Table 1. The measured value of surface roughness of elements in contact ranges in the interval $R_a = 0.8 \div 1.0 [\mu m]$. The experiment is performed under conditions of before heat treatment of the slider and after its heat treatment. The heat treatment of the slider is performed in a special chamber. After the chamber temperature reaches the desired value, the contact element is kept there for 30 minutes, and then it is cooled to ambient temperature. The described experimental procedure is carried out for heating temperatures $T_1 = 100^\circ C$, $T_2 = 200^\circ C$ and $T_3 = 280^\circ C$. For all mentioned conditions the coefficient of static friction is measured. Every measurement is repeated 12 times, and the mean values of the coefficient of static friction μ_{av} are determined, these are shown in Table 2. In order to more clearly determine the changes the coefficient of static friction the parameter k_μ is introduced, which represents the relative ratio:

$$k_\mu = \frac{(\mu_{av})_{T=20^\circ C}}{(\mu_{av})_{T_i}} \cdot 100, [\%]. \quad (3)$$

where $(\mu_{av})_{T=20^\circ C}$ - is the mean value of coefficient of static friction if the slider is not heat treated and $(\mu_{av})_{T_i}$ - the mean value of the coefficient of static friction if the slider is heat treated, on temperatures $T_1=100^\circ C$, $T_2=200^\circ C$ and $T_3=280^\circ C$. The calculated values of the parameters k_μ are shown in Table 2. The change of mean values of the coefficient of static friction μ_{av} , and the change of parameters k_μ are shown in Figs. 4 and 5.

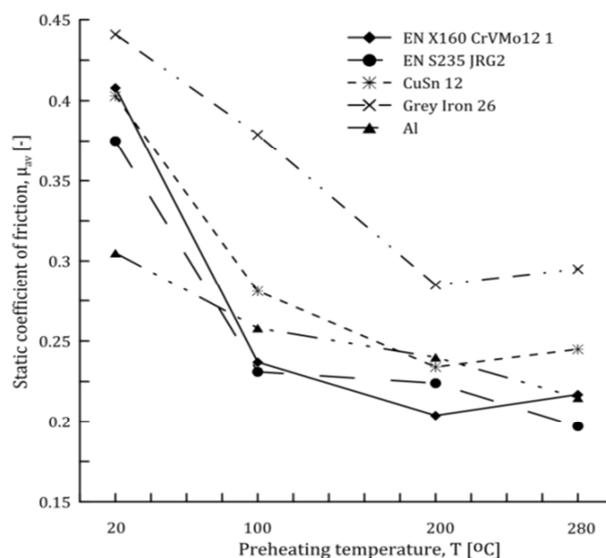


Fig. 4. Dependence of the coefficient of static friction from temperatures of the previous heat treatment.

Table 1. Chemical compositions and hardness of tested materials.

Material	HV	Elements [wt.%]											
		C	Mn	Si	Cr	Mo	Ni	P	S	Al	V	Cu	Sn
EN C45	130	0.42-0.5	0.5-0.8	<0.4	<0.4	<0.1	<0.4	<0.045	<0.045	-	-	-	-
EN X160 CrVMo 12 1	190	1.52	0.36	0.25	11,8	0.81	0.14	-	-	-	1.1	-	-
EN S 235 JRG2	130	<0.2	<1.4	<0.55	<0.3	<0.08	<0.3	<0.045	<0.045	>0.02	-	-	-
CuSn 12	122	-	<0.2	<0.01	-	-	<2	<0.6	<0.05	<0.01	-	<88.5	11-13
Grey iron 26	260	3.18	-	2.17	0.7	-	0.37	0.6	-	-	-	-	-
Al	138	-	-	-	-	-	-	-	-	99.5	-	-	-

Table 2. Calculated mean value of the coefficient of static friction μ_{av} and parameter k_{μ} depending on test temperatures and contact materials.

Material	Pretreatment temperature of slider [°C]							
	20		100		200		280	
	μ_{av} [-]	k_{μ} [%]	μ_{av} [-]	k_{μ} [%]	μ_{av} [-]	k_{μ} [%]	μ_{av} [-]	k_{μ} [%]
EN X160 CrVMo12 1	0.408	100	0.237	58.1	0.204	50	0.217	53.2
EN S 235 JRG2	0.375	100	0.231	61.6	0.224	59.7	0.197	52.5
CuSn12	0.403	100	0.281	69.7	0.234	58.1	0.245	60.8
Grey iron 26	0.441	100	0.379	85.9	0.285	64.6	0.295	66.9
Al	0.305	100	0.258	84.3	0.24	78.4	0.215	70.3

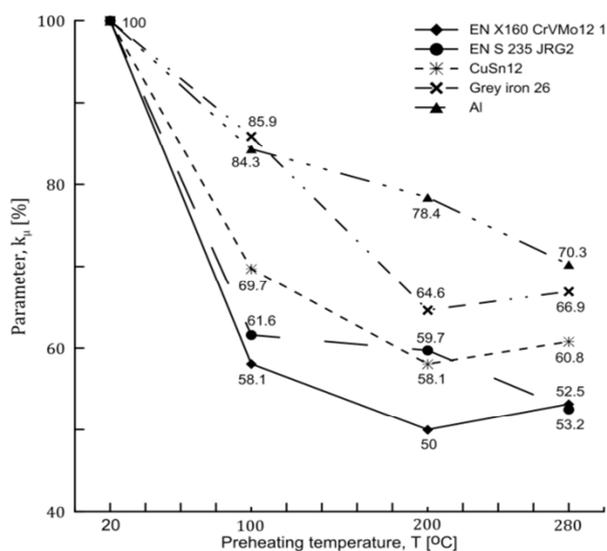


Fig. 5. Diagram of the value of the coefficient of static friction expressed by parameter k_{μ} .

4. DISCUSSION

The results of experimental studies indicate the significant effect of previous heat treatment of one contact element to the value of the coefficient of static friction. The diagram shown in Figure 4 presents the trend of the coefficient of static friction in the function of the preheating temperature of one contact element.

In order to better observe the value of the coefficient of static friction, a diagram

representation of the parameter k_{μ} is introduced on Fig. 5. The mentioned diagram shows changes in the value of the coefficient of static friction expressed in percentage. The mean values of the coefficient of static friction at ambient temperature (μ_{av})_{T=20°C} are taken as the maximum value of parameter (k_{μ})_{T=20°C} = 100 % in the diagram (Fig. 5). It can be concluded that in all five considered contact pairs the coefficient of static friction is significantly reduced, especially at temperatures close to the value of 200 °C. The mentioned decreasing trend of the coefficient of friction, almost exclusively, depends on the temperature of the heat treatment of one contact element which is made of material EN C45. However, the intensity of the decreasing of the coefficient of static friction obviously depends on the material properties of the second contact element and tribomechanical characteristics of the considered contact pair.

With the coefficient of static friction of the contact pair of steel EN C45 - steel EN X160 CrVMo12 1, the biggest difference is recorded between the value of the coefficient of static friction at ambient temperature and the values of the coefficient of static friction after heating in relation to the coefficient of static friction of all other considered contact pairs. In relation to the value of the coefficient of static friction measured at room temperature, with increasing temperature to $T_1 = 100^{\circ}\text{C}$, the coefficient of

static friction decreases from a value of $\mu_{av} = 0.408$ to the value of $\mu_{av} = 0.237$ (Fig. 4), namely, expressed as a percentage to the value of $k_{\mu} = 58.1\%$ (Fig. 5). With a further increase in the temperature range from $T_1 = 100^{\circ}\text{C}$ to $T_2 = 200^{\circ}\text{C}$ the intensity of the decrease of the coefficient of static friction μ_{av} is significantly reduced from 0.237 to 0.204. Further heating of the considered contact element from temperature $T_2 = 200^{\circ}\text{C}$ to temperature $T_3 = 280^{\circ}\text{C}$ leads to a slight increasing of the values of the coefficient of static friction from $\mu_{av} = 0.204$ to $\mu_{av} = 0.217$.

A significant decrease of the coefficient of static friction is recorded for the contact pair of steel EN C45 – steel EN S235 JRG2, where the hardness for the second contact element is 130HV. With increasing heat treatment temperature, constant decreasing of the coefficient of static friction μ_{av} observed from the initial measured value of $\mu_{av} = 0.375$ to the value of $\mu_{av} = 0.197$ that is measured on $T_3 = 280^{\circ}\text{C}$. As observed from the diagram in Fig. 5, the decreasing value of the coefficient of static friction in percentage is $k_{\mu} = 52.5\%$. With the contact pair of steel EN C45 - Grey iron 26, a decreasing of the coefficient of static friction is also recorded. In this case, at preheating temperature of the slider $T_2 = 200^{\circ}\text{C}$, the coefficient of friction decreases from the value of $\mu_{av} = 0.441$ to the value of $\mu_{av} = 0.285$, expressed as parameter k_{μ} this value is 64.6 %, compared with the value of the coefficient of friction at ambient temperature. During the heating of the contact element to temperature $T_3 = 280^{\circ}\text{C}$, there is a slight increase in the coefficient of static friction from value $\mu_{av} = 0.285$ to value $\mu_{av} = 0.295$.

In the case of considering the contact pairs of steel EN C45 - steel EN X160 CrVMo12 1 and steel EN C45 - Grey iron 26, the increasing of the coefficient of static friction with increasing temperature from 200 °C to 280 °C is very small, so it cannot be reliably claimed that the mentioned temperature range leads to significant changes in the coefficient of friction. Based on analysis (diagram in Fig. 4), it can be concluded that the biggest decrease in the coefficient of static friction is recorded for the contact pair of steel EN C45 – steel EN X160 CrVMo12 1, wherein the second contact element (substrate) is made of material whose hardness is 190HV and whose chemical composition contains a significant percentage of chromium (Cr=11.8%). The

smallest decrease of the coefficient of friction is recorded for the contact pair of steel EN C45 – Al. During the experimental testing of the above mentioned contact pair for temperatures from 20°C to 280°C, the coefficient of friction is reduced from a value of $\mu_{av} = 0.305$ to the value of $\mu_{av} = 0.215$, which is on the diagram in Fig. 5, presented as a decrease to the value of $k_{\mu} = 70.3\%$.

Based on the measured results of the coefficient of static friction in terms of the previous heat treatment of one contact element, it is very likely that the decreasing of the coefficient of static friction is largely dependent on the chemical composition and the hardness of the contact elements. Establishing correlation between these values (hardness of contact elements, their chemical composition and intensity of the decreasing of the coefficient of static friction) would require much more extensive experimental studies. Based on the results, the authors assume that in the case of the majority of metal materials, the heat treatment of one contact element leads to a significantly reduced coefficient of static friction. In relation to literature reference [10] and experimental results performed in this paper, it can be assumed that the surface layer of a previously heat treated contact element made of steel (EN C45) has a thin layer of iron oxide that, in contact with materials with lower or approximately the same hardness, provides a smaller decrease of the coefficient of static friction. Appearance of oxidation is possible at ambient temperature, but, metals that are exposed to temperatures above 200°C extensively produce an oxidation layer, which is precisely the case in the studies described.

5. CONCLUSION

Based on the research results, it can be concluded that the previous heat treatment of one contact element (pre-heating and cooling) in the temperature range 20°C - 280°C leads to a significant decreases in the coefficient of static friction. The authors of the paper assume that these significant decreases of the coefficient of static friction are a consequence of the creation of oxides on one heat treated contact element, while the other contact elements are materials with relatively lower hardness. In this way conditions were created characterized by the type of contact

of different materials which, from a tribological point of view, is always a very favorable case from the aspect of minimization of the coefficient of friction. The authors of the paper also find that the heat treatment of one contact element in a temperature range from 20°C to 280°C represents a very simple and extremely practical and rational way for a significant reduction in the coefficient of static friction.

Further directions of research in this area can be based on more detailed determining of the impact of temperature effects on different macro and micro geometry of contact elements made from various materials.

REFERENCES

- [1] B. Jeremic, D. Vukelic, P. Todorovic, I. Macizic, M. Pantic, D. Dzunic, B. Tadic: *Static Friction at High Contact Temperatures and Low Contact Pressure*, Journal of Friction and Wear, Vol. 34, No. 2, pp. 114–119, 2013.
- [2] P. Todorovic, M. Blagojevic, Dj. Vukelic, I. Macuzic, M. Jeremic, A. Simic and B. Jeremic: *Static rolling friction coefficient at high temperature*, Journal of Friction and Wear, Vol. 34, No. 6, 2013., Accepted manuscript.
- [3] Elena Loredana Deladi: *Static Friction in Rubber-Metal Contacts with Application to Rubber Pad Forming Processes*, PhD thesis, University of Twente, Twente, 2006.
- [4] N.K. Myshkin, C.K. Kim, M.I. Petrokovets: *Introduction to tribology*, CMG Publishers, Seoul, 1997.
- [5] K.-H. Zum Gahr, K. Voelker: *Friction and wear of SiC fiberreinforced borosilicate glass mated to steel*, Wear, Vol. 225, No. 2, pp. 885–895, 1999.
- [6] P. Blau: *The significance and use of the friction coefficient*, Tribol. Int., Vol. 34, No. 9, pp. 585–591, 2001.
- [7] B. Ivkovic, M. Djurdjanovic, D. Stamenkovic: *The Influence of the Contact Surface Roughness on the Static Friction Coefficient*, Tribology in Industry, Vol. 22, No. 3&4, pp. 41–44, 2000.
- [8] U. Muller, R. Hauert: *Investigations of the coefficient of static friction diamond-like carbon films*, Surface and Coatings Technology, Vol. 174–175, pp. 421–426, 2003.
- [9] Boris Polyakov, Sergei Vlassov, Leonid M. Dorogin, Peteris Kulis, Ilmar Kink, Rynno Lohmus: *The effect of substrate roughness on the static friction of CuO nanowires*, Surface Science, Vol. 606, pp. 1393–1399, 2012.
- [10] C. Vergne, C. Boher, R. Gras, C. Levaillant: *Influence of oxides on friction in hot rolling: Experimental investigations and tribological modeling*, Wear, Vol. 260, pp.957–975, 2006.
- [11] Rodriguez-Baracaldo R, Benito JA, Puchi-Cabrera ES, Staia MH: *High temperature wear resistance of (TiAl)N PVD coating on untreated and gas nitrated AISI H13 steel with different heat treatments*, Wear, Vol. 262, pp. 380–9, 2007.
- [12] Mo JL, Zhu MH, Lei B, Leng YX, Huang N.: *Comparison of tribological behaviours of AlCrN and TiAlN coatings – deposited by physical vapour deposition*, Wear, Vol. 263, pp. 1423–9, 2007.
- [13] Huang ZP, Sun Y, Bell T.: *Friction behaviour of TiN, CrN and (TiAl)N coatings*, Wear, Vol. 173, pp. 13–20, 1994.
- [14] Staia MH, Alessandria MD, Quinto DT, Roudet F, Marsal Astort M.: *High temperature tribological characterisation of commercial TiAlN coatings*, J Phys: Condens Matter, Vol. 18, pp. 1727–36, 2006.
- [15] Hovsepian PEh, Lewis DB, Luo Q, Münz W-D, Mayrhofer PH, Mitterer C.: *TiAlN based nanoscale multilayer coatings designed to adapt their tribological properties at elevated temperatures*, Thins Solid Films, Vol. 485, pp. 160–168, 2005.
- [16] J. Hardell, E. Kassfeldt, B. Prakash: *Friction and wear behaviour of high strength boron steel at elevated temperatures of up to 800 °C*, Wear, Vol. 264, pp.788–799, 2008.
- [17] Kutschej K, Mayrhofer PH, Kathrein M, Polcik P, Mitterer C.: *Influence of oxide phase formation on the tribological behaviour of Ti–Al–V–N coatings*, Surf Coat Technol; Vol. 200, pp. 1731–7, 2005.
- [18] N. Fateh, G.A. Fontalvo, G. Gassner, C. Mitterer: *Influence of high-temperature oxide formation on the tribological behaviour of TiN and VN coatings*, Wear, Vol. 262, pp.1152–1158, 2007.
- [19] E. Lugscheider, O. Knotek, K. Bobzin, S. Barwulf: *On the structure and oxidation mechanisms in nanoscale hard coatings*, Surf. Coat. Technol., Issues 133–134, pp. 362–368, 2000.
- [20] B. Tadic, B. Jeremic, Dj. Vukelic, S. Mitrovic, M. Eric: *Development of tribometer and measurement results of static coefficient of friction sliding and coefficient of rolling friction by principle steep plane*, in: *12th International conference on tribology, SERBIATRIB '11*, Kragujevac, 11 – 13 May 2011, pp. 397-402.