

# A systemic approach to testing the tribological properties of selected materials of agricultural machines

## Systémový prístup k skúšaniam tribologických vlastností vybraných materiálov poľnohospodárskych strojov

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### Abstract

The contribution brings the evaluation of selected materials regarding wear resistance under conditions of two experiments. The following materials had been chosen for these experiments: steel E295, steel C 45 after heat treatment, steel C 45 after quenching and steel 16MnCr5 after carburizing and quenching. The experiment was performed on a test device belonging to the category of "pin – disk" test devices. The resistance of selected materials was evaluated regarding energy consumption, and it was compared to sizes of weight loss. It was observed that the material C 45 after heat treatment reached the highest values of wear resistance in conditions of adhesive wear without lubrication. The material 16MnCr5 indicated the best results in conditions of abrasive wear.

**Keywords:** abrasive wear, adhesive wear, agricultural machines' materials, tribology

### Abstrakt

V príspevku boli zhodnotené vybrané materiály z hľadiska odolnosti proti opotrebeniu v podmienkach dvoch experimentov. Pre tieto konkrétne experimenty boli vybrané tieto materiály: oceľ E 295, oceľ C 45 v stave po zušľachtení, oceľ C 45 v stave po kalení a oceľ 16MnCr5 v stave po cementovaní a kalení. Vlastný experiment bol realizovaný na skúšobných zariadeniach, ktoré patria do kategórie skúšobných strojov „čap – kotúč“. Odolnosť vybraných materiálov bola hodnotená z hľadiska spotreby energie a bola porovnávaná s veľkosťami úbytkov hmotnosti. Bolo zaznamenané, že najvyššie hodnoty odolnosti proti opotrebeniu v podmienkach adhézneho opotrebenia bez mazania boli dosiahnuté u materiálu C 45 v stave po zušľachtení a v podmienkach abrazívneho opotrebenia u materiálu 16MnCr5.

**Kľúčové slová:** abrazívne opotrebenie, adhezívne opotrebenie, materiály poľnohospodárskych strojov, tribológia

## Detailný abstrakt

V príspevku boli zhodnotené vybrané materiály z hľadiska odolnosti proti opotrebeniu v podmienkach dvoch experimentov. Z pohľadu charakteristického opotrebenia súčiastok poľnohospodárskych strojov boli vybrané pre potreby experimentálneho hodnotenia dva druhy skúšok, a to skúšky adhézneho opotrebenia bez mazania a skúšky abrazívneho opotrebenia na brúsnom plátne. Skúšky boli realizované na renovovaných pracoviskách. Pre tieto konkrétne experimenty bol vybraný materiál bez tepelného spracovania, oceľ E 295, oceľ C 45 v stave po zušľachtení, oceľ C 45 v stave po kalení a oceľ 16MnCr5 v stave po cementovaní a kalení. Materiály vzoriek boli vybrané na základe štúdia a následného štatistického zhodnotenia materiálov používaných na výrobu súčiastok typu hriadeľ v poľnohospodárskych strojoch. Vlastný experiment bol realizovaný na skúšobných zariadeniach, ktoré patria do kategórie skúšobných strojov „čap – kotúč“. Vlastné skúšky patria do kategórie skúšok porovnávacích. Odolnosť vybraných materiálov bola hodnotená z hľadiska spotreby energie a bola porovnávaná s veľkosťami úbytkov hmotnosti. Bolo zaznamenané, že najvyššie hodnoty odolnosti proti opotrebeniu v podmienkach adhézneho opotrebenia bez mazania zistené pomocou koeficientov tribologickej únosnosti  $K^*$  a  $K_N$  boli dosiahnuté u materiálu C 45 v stave po zušľachtení a to  $K^*=3.141$  a  $K_N=2.026$ . Najnižšie hodnoty boli zaznamenané u ocele 16MnCr5 v stave po cementovaní a kalení s najvyššou hodnotou tvrdosti a to  $K^*=2.371$  a  $K_N=1.529$ . V podmienkach abrazívneho opotrebenia boli vzorky hodnotené podľa pomernej odolnosti proti abrazívnemu opotrebeniu  $\psi$  ako aj z pohľadu energetického. Najvyššia hodnota pomernej odolnosti  $\psi$  bola zaznamenaná u materiálu 16MnCr5,  $\psi = 2,2124$ . U tejto vzorky boli namerané aj najvyššie hodnoty tvrdosti. Najnižšiu hodnotu pomernej odolnosti  $\psi$  mala vzorka materiál E295,  $\psi = 1,1667$ . Z porovnania vybraných ukazovateľov je možné konštatovať veľmi dobrú vzájomnú koreláciu výsledkov pomernej odolnosti  $\psi$  vypočítanej z úbytkov hmotnosti a intenzity opotrebenia  $I$  určenej z energetických ukazovateľov. Z porovnania veľkosti intenzity opotrebenia  $I$  a zdanlivej hustoty energie trenia  $e^*$  možno konštatovať, že pri najnižšej intenzite opotrebenia má vzorka materiál 16MnCr5 v stave po cementovaní a kalení, mal najvyššiu hodnotu  $e^*$ , a to  $65,29 \text{ J}^* \text{mm}^{-3}$ . Najnižšiu hodnotu zdanlivej hustoty energie trenia z celého súboru vzoriek má porovnávací materiál RFe100 a to  $29,700 \text{ J}^* \text{mm}^{-3}$ . Porovnaním odolnosti základných materiálov používaných na výrobu súčiastok poľnohospodárskych strojov si možno urobiť obraz o ich odolnosti proti opotrebeniu v daných podmienkach.

## Introduction

Friction as an important physical effect required a lot of theoretic and experimental work to be understood (Vocel et al., 1976). A systemic approach is necessary for the complex solution of friction and related attrition in both theoretic and experimental sphere. Regarding tribological properties of materials, important is the right choice of material or material pair, geometric shape, roughness, etc. (Kučera et al., 2008;

Kučera, 2008; Brendel et al., 1984). Regarding tribometry, it is a question of the test device, choosing own test methods as well as the right shape and size of test samples, preparation of samples, etc. (Kučera, 2006; Kadnár et al., 2011; Rusnák et al., 2011; Tököly et al., 2009). Choosing an appropriate approach to solve the friction problem and related wear is also very important (Czichos, 1978; Kadnár et al., 2008; Kučera, 2004; Tököly et al., 2010).

The energy required to separate a particular friction exposed material is a critical factor affecting the processes of friction and wear. It is therefore appropriate to assess these processes using the energy balance equation. A method for determining erosion wear has been developed from the quantitative assessment of friction and wear processes in energy terms (Brendel et al., 1978; Fleischer et al., 1980). The advantage of this energy method is the generality of results. This method can be easily applied parallel to Kragelský molecular mechanical theory. The core of the problem of the wear energy theory is the determination of density of friction energy (Blaškovitš et al., 1990; Fleischer, 1978).

The problem is even more complicated in case of a need to renovate the worn surface.

As we deal with the tribological node with weld deposits, there are increased demands on the knowledge of material properties, effects of alloying elements and the impact of welding technology on welded layers properties (Blaškovitš et al., 2006; Kadnár et al., 2010; Kučera, 2006).

The article deals with the prediction of properties of selected materials on the base of tribological experiments results. The objective of the article was to assess the selected materials in terms of wear resistance as well as in terms of energy and to compare the results obtained in conditions of two experiments.

In the submitted article, we would also like to point to certain aspects of systemic approach to material selection, preparation of samples and testing methods in relation to agricultural machinery.

## Materials and Methods

The technical level of machines and their operating reliability depends on the proper functioning of tribological nodes, which significantly affect the quality of work, performance and operating costs. Increasing the life of functional parts of agricultural machinery is in close connection with the knowledge of principles and factors of metal material wear.

We have analyzed the materials used for manufacturing the components of “shaft or pin” type. The selected materials were compared with each other.

A great attention to the selection of appropriate materials was paid. The 186 different components of shaft or pin type of various agricultural machines (tractors, harvesters, straw cutters, mobile machines, etc.) with worn functional parts of cylindrical shape were analysed and 20 different types of steel are used for the production of those components (according to the Slovak technical Standards – STN) were found:

- 3 types of steel grade E 295, S 355J0, E 355,
- 4 types of steel grade C15E, C45, C55, C60,
- 2 types of steel grade 37MnSi5, 42MnV7,

- 6 types of steel grade 37Cr4, 16MnCr5, 20MnCr5, 34Cr4, 36Mn5, 67SiCr5,
- 4 types of steel grade 25CrMo4, 42CrMo4, 30Cr2V, 42CrV6,
- 1 type of steel grade 18NiCr5-4.

The reference list also showed that:

- 16.7 % of components were made of heat unprocessed steels,
- 11.8 % of components were heat-treated, their exposed surfaces were induction hardened,
- 38.2 % of components were made of heat-treated steels,
- 30.1 % of components were carburized on exposed functional surfaces.

Heat-treatment itself or its combination with another type of heat processing was used for 52.7 % of components.

From the group of materials, the following types of steel were selected for purposes of the experimental wear resistance test:

- steel E 295 as a representative of steels used in untreated (natural) state;
- steel C 45 as a representative of steels used in state after heat treatment and steels with induction hardening on exposed surfaces;
- steel 16 MnCr5 as a representative of steels used for components with carburized and hardened surfaces.

### **Selection of test methods and test devices**

When selecting the method of testing, test device and evaluation of experimental results, we have taken into account the specific work conditions of agricultural machinery and the variety of wear of surfaces.

On this basis, we decided for:

- adhesive wear test without lubrication,
- abrasive wear test on the grinding cloth.

The chosen wear testing methods belong to the group of comparison tests with test specimens.

### **Adhesive wear test without lubrication**

Tests were performed on a test device of type TE 97/A – Fig. 1 and Fig. 2, which belongs to the category of “pin-disk” devices with a flat contact of friction node elements. The test device is suitable for comparison tests of selected materials. Fundamentally, test samples of pin shape are imprinted to facing surfaces of a rotating disk using a hydraulic cylinder and constant force. Pins were manufactured from basic materials E 295, C 45 and 16 MnCr5. The counter part was made of material C15. Chemical composition of used materials is shown in Table 1.

Ten testing specimens were prepared from each material. After heat treatment, the samples were lathed into the final dimension  $\varnothing 8 * 50$  mm.

Table 1: Chemical composition of used materials (in weight %)

Tabuľka 1: Chemické zloženie použitých materiálov (v % hmotnosti)

	C	Mn	Si	Cr	Ni	Cu	(P + S)
E295	0.38	0.9	0.9	–	–	–	0.1
C15	0.13–0.2	0.6–0.9	0.17–0.37	max. 0.25	–	max. 0.3	0.08
C45	0.45	0.65	0.27	0.25	0.3	0.3	0.08
RFe100	0.06	0.45	0.15	–	–	–	0.04
16MnCr5	0.14–0.19	1.1–1.4	0.17–0.37	0.8–1.1	–	–	–

### Test parameters

Test parameters were chosen based on the selection of test parameters of adhesive wear without lubrication used in the tribological laboratory so that they allow the fullest extent of comparison of tribological properties of the supplied samples.

pressure in the hydraulic circuit	1.47 MPa
compressive force on the pin	74.3 N
surface speed of the test radius	$3.2 \text{ m} \cdot \text{s}^{-1}$
exposure time	15, 30, 45, 75 s
material of the counter part	steel C 15
dimension of the sample	$\text{Ø } 8 * 50 \text{ mm}$

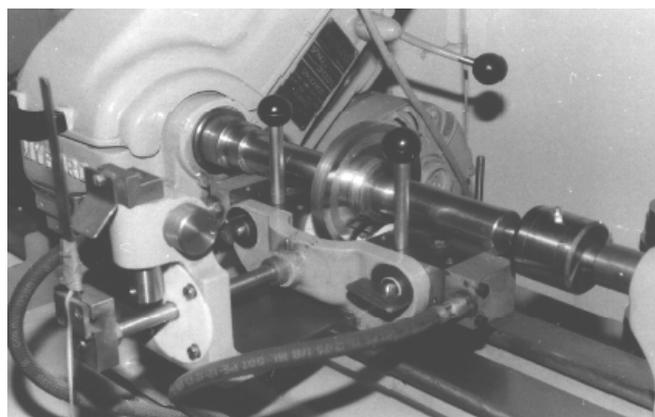


Figure 1: View of active part of device TE 97/A

Obrázok 1: Detailný pohľad na aktívnu časť TE 97/A

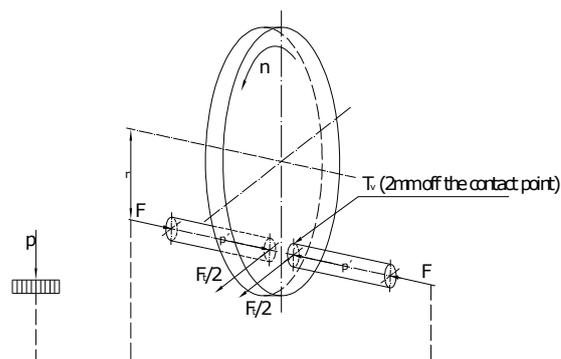


Figure 2: Illustration of working principle of device TE 97/A  
 Obrázok 2: Ilustrácia podstaty pracovného procesu TE 97/A

The characteristics of the samples for wear test on the device TE97/A are shown in Table 2.

We observed the mass loss as a function of time on the device TE 97/A (Fig. 1). Results were obtained by weighing the samples on analytical scales before and after the test.

$$\Delta m = m_o - m_1, \text{ g} \quad (1)$$

We detected the wear rate at the exposure time of 15, 30, 45, 75 seconds. The results are shown in Table 4.

### Evaluation of tribological capacity

In laboratory conditions, the mass loss of weld deposits  $W_o$  was observed on devices, which enable observing the value of friction force  $F_T$  during loading by constant force  $F_N$  at given time  $t$ . Time  $t$  is proportional to friction path  $L$ .

Then, we may calculate the friction work  $A$ , J as follows:

$$A = \int_0^t F_T \cdot v \cdot dt \quad (2)$$

When relating the friction work to unit weight (volume) of worn weld metal, we get the relation:

$$K^* = \frac{A}{W_o}, \text{ N}^* \text{m}^* \text{kg}^{-1} \quad (3)$$

The value  $K$  is known as the coefficient of tribological capacity and represents the amount of friction work required to separate a unit amount of material.

If we relate the values of wear  $W_0$  and friction work  $A$  to etalon material, then it may be stated:

$$K_N = \frac{K_{sample}^*}{K_{etalon}^*} = \frac{\frac{A_{sample}}{W_{0sample}}}{\frac{A_{etalon}}{W_{0etalon}}} = \frac{A_{sample}}{A_{etalon}} \cdot \frac{W_{0etalon}}{W_{0sample}} \quad (4)$$

$A_{sample}$  – friction work of sample, J

$A_{etalon}$  – friction work of etalon material, J

$W_{0sample}$  – wear of sample, g

$W_{0etalon}$  – wear of etalon material, g

The value  $K_N$  is known as the coefficient of relative tribological capacity of material. This criterion  $K_N$  takes into account the physical fundamentals of separation of particles from the surface of material in the process of friction. It thus allows assessing the quality of materials for tribological application in specific conditions.

Table 2 shows the results of measurements of hardness on the faces of samples.

Table 2: Characteristics of samples for wear test on device TE97/A

Tabuľka 2: Charakteristika vzoriek pre skúšky opotrebenia na zariadení TE97/A

Sample no.	Basic material	Heat treatment	Surface hardness (HV30)
1	E 295	-	160 ±10
2	C 45	Quenching 850 °C / water, tempering 650 °C / 1h / air	259 ±3
3	C 45	Quenching 850 °C / water, tempering 170 °C / 1h / air	626 ±16
4	16 MnCr5	Carburized, quenching 830 °C / water, tempering 170 °C / 1h / air	860 ±10
5	C 15	-	170 ± 3

### Abrasive wear test on the grinding cloth

Tests were performed on the test device with grinding cloth – Fig. 3 and Fig. 4, which belongs to the category of “pin-disk” test devices with a surface contact of friction node elements. The test device is suitable for comparison tests of selected materials. The principle of the test is that pin-shaped samples (test particles) are loaded with constant force and pressed to the grinding cloth on the rotating disk. Pins were made

of selected materials (E 295, C 45, 16 MnCr5). In accordance with standard, the etalon was made of the DIN RFe100 material, as a reference material (Table 1).

Ten testing specimens were prepared from each material. After heat treatment, the samples were lathed into final dimension  $\text{Ø } 10 * 50 \text{ mm}$ .



Figure 3: Test device

Obrázok 3: Skúšobné zariadenie

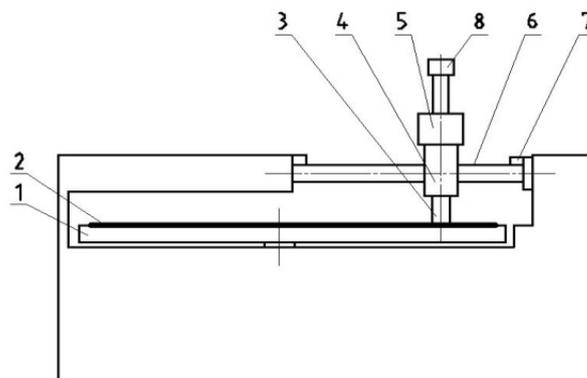


Figure 4: Scheme of the two body abrasive wear tester

Obrázok 4: Principiálna schéma zariadenia

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1 – disk, 2 – grinding cloth, 3 – test particle, 4 – holder, 5 – tensiometer, 6 – motion screw, 7 – limit switch, 8 – weight

### ***Test parameters***

length of friction path	50 m
disk diameter	480 mm
radial movement of sample	3 mm
specific pressure	$0.32 \text{ N} \cdot \text{mm}^{-2}$
type of grinding cloth	A99 – G
dimension of sample	$\text{Ø } 10 * 50 \text{ mm}$

The weight of the samples was evaluated before and after the test. The samples were weighed on the analytical scales MEOPTA (accurate to 0.0005 g) after a thorough degreasing and drying.

According to a valid methodology for the test device, relative resistance to abrasive wear  $\psi$  is determined by:

$$\psi = \frac{\Delta m_e}{\Delta m_{vz}}, - \quad (5)$$

where:

$\Delta m_e$  – mass loss of etalon material (standard), g

$\Delta m_{vz}$  – mass loss of sample, g

Besides mass losses, the size of friction force was measured and recorded as well. Total friction work consumption as well as other indicators were determined based on the size of friction force.

The density of friction energy represents the amount of friction work in relation to a friction-stressed amount of mass (Brendel et al., 1984; Fleischer, 1973, 1980).

Adding the mean shear stress and replacing the friction-stressed amount of mass with removed mass, we get the equation for calculating the apparent density of friction energy. Subsequently, transforming this expression, we get the basic energy equation of wear

$$e_t = \frac{A_t}{V_t}, \text{ MPa} \quad (6)$$

where:

$A_t$  – friction work, J

$V_t$  – friction-stressed amount

If we add the mean shear stress  $\bar{\tau}$  and replace the friction-stressed amount of mass  $V_t$  with removed mass  $\Delta V$ , we get the equation for calculating the density of friction energy

$$e_t^* = \frac{\bar{\tau} s_t S_a}{\Delta V}, \text{ J}^* \text{mm}^{-3} \quad (7)$$

where:

$S_a$  – nominal contact area,  $\text{m}^2$

$s_t$  – friction path, m

Using the profilegram of the surface, the real contact area of the surface  $S_r$  can be determined from its geometrical characteristics.

Using the equation for the intensity of wear

$$I_h = \frac{\Delta V}{S_a s_t} \quad (8)$$

and subsequently, if we transform this expression, we get the basic energy equation of wear

$$I_h = \frac{\bar{\tau}}{e_t^*} \quad (9)$$

The density of friction energy, the intensity of wear and mean shear stress are the indicators that rate the critical energy level characterizing the friction process. The advantage of this energy method of wear process evaluation is the possibility of generalization of applicable results.

The intensity of wear means the amount of material that is separated from the nominal contact area of a path. We can compare each group of materials (wear products) in different conditions and times using the dimensionless intensity of wear. This comparison is possible from a qualitative as well as quantitative point of view.

Hardness was measured on the faces of the samples, i.e. at the point of interaction with the test disk. A durometer MEOPTA – VICKERS with pyramid load  $F = 295.3 \text{ N}$  was used to take measurements.

The relative resistance of examined materials ( $\psi$ ) is set as a criterion for assessment of abrasive wear resistance test results. The density of friction energy and the intensity of wear are the results of energy consideration and calculation. The density of friction energy represents the amount of frictional work required to separate a certain amount of mass of the material.

The characteristics of the samples for wear testing on grinding cloth are shown in Table 3.

Table 3: Characteristics of the samples for wear testing on grinding cloth

Tabuľka 3: Charakteristiky vzoriek pre skúšky opotrebenia na brúsnom plátne

Sample no.	Basic material	Heat treatment	Surface hardness (HV30)
1	E 295	-	160 ±10
2	C 45	Quenching 850 °C / water, tempering 650 °C / 1h / air	259 ±3
3	C 45	Quenching 850 °C / water, tempering 170 °C / 1h / air	626 ±16
4	16 MnCr5	Quenching 830 °C / water, tempering 170 °C / 1h / air	860 ±10
5	RFe100	-	100 ±3

## Results

### Results of adhesive wear test without lubrication on device TE97/A

Table 4 shows the calculated values of the coefficient of tribological capacity  $K^*$  and the coefficient of relative tribological capacity  $K_N$ .

Table 4: Results of adhesive wear test without lubrication on device TE97/A

Tabuľka 4: Výsledky skúšok adhézneho opotrebenia bez mazania na zariadení TE 97/A

Sample no.	Wear w (g) at exposure time t (s)				$K^*$ , J*kg <sup>-1</sup>	$K_N$
	15	30	45	75		
1	0.0028	0.0028	0.0058	0.0069	2.464	1.589
2	0.0002	0.0011	0.0018	0.0066	3.141	2.026
3	0.0012	0.0018	0.0018	0.0080	2.446	1.578
4	0.0003	0.0022	0.0049	0.0113	2.371	1.529
5	-	-	-	-	1.55	1

The coefficients  $K^*$  and  $K_N$  of the sample no. 5 (material C 15) are the reference (etalon) values of the tribological laboratory.

Based on the measured losses of weight and calculated coefficients  $K^*$  and  $K_N$  shown in Table 4, we may state the following:

The highest values of weight losses were observed at the exposure time of 75 s.; the results at other exposure times are characterized by a relatively high variance and instability. As we deal with the material pair “steel – steel“ and with test without lubrication, the transmission of abrasion particles between surfaces occurs at the point of their contact (Kučera et al., 2008). From this point of view, the calculated coefficients  $K^*$  and  $K_N$  seem to be more appropriate for assessing the wear resistance of various materials.

The highest values of the coefficients of tribological capacity and relative tribological capacity of materials were observed in the sample no. 2 (steel C 45) in state after heat-treatment, with the second lowest hardness (259 HV). On the other side, the lowest values of the coefficients  $K^*$  and  $K_N$  were observed in the sample no. 4 (steel 16 MnCr5) in state after carburizing and quenching, with the highest hardness (860 HV).

### Results of abrasive wear test on the grinding cloth

Based on the results of the experiment and subsequent calculations, it is possible to compare the relative abrasive wear resistance with energy characteristics of the friction process of various materials.

Following the standards, relative wear resistance  $\psi$  is a decisive criterion for the assessment of test materials tested on the grinding cloth.

The highest value of relative resistance  $\psi$  was observed in the material 16 MnCr5, the sample no. 4. This sample also showed the highest values of hardness. The lowest value of relative resistance  $\psi$  was observed in the sample no. 1 (material E295).

A very good mutual correlation of results of relative resistance  $\psi$  (calculated from weight losses) and intensity of wear  $I$  (determined from energy indicators) can be stated according to the comparison of selected indicators in Table 5.

Table 5: Results of abrasive wear test on the grinding cloth

Tabuľka 5: Výsledky skúšok abrazívneho opotrebenia na brúsnom plátne

Sample no.	Average weight loss (g)	Mean value of friction force $F$ (N)	Density of friction energy $e^*$ (MPa)	Intensity of wear $I$ (-)	Mean shear stress $\bar{\tau}$ (MPa)	Coefficient of shear friction $f$ (-)	Relative resistance to abrasive wear $\psi$ (-)
1	225 $\pm$ 3	21.74	37.144	7.4*10E-6	0.2339	0.860	1.1667
2	204 $\pm$ 10	24.67	47.356	6.6*10E-6	0.3125	0.976	1.3053
3	180 $\pm$ 5	25.28	54.508	5.8*10E-6	0.3165	0.989	1.4827
4	120 $\pm$ 5	20.15	65.2988	3.9*10E-6	0.2582	0.802	2.2124
5	266 $\pm$ 8	20.28	29.700	8.6*10E-6	0.2550	0.798	1.0

By comparing the value of the intensity of wear  $I$  with the density of friction energy  $e^*$ , we may state that the sample no. 4 (material 16 MnCr5 in state after carburizing and quenching) had the highest value of  $e^*$  (65.29 MPa) at the lowest intensity of wear. The lowest value of the density of friction energy (29.700 MPa) from the whole set of samples was observed in the sample no. 5 (etalon material RFe100).

From the comparison of the density of friction energy and average weight loss (Table 5) can be stated that consumed energy is inversely proportional to the measured loss.

It can be stated from the calculated and measured results that the hardness of the material is the decisive criterion under the conditions of given experiment in terms of relative resistance  $\psi$  as well as in terms of energy.

## Conclusions

From the observation that was carried out during many experiments, we find it necessary to mention the importance of systemic approach in each sequence of given experiment. This involves:

- selection of material,

- difficulty of experiment,
- availability of test devices,
- methods of results assessment,
- application of results, etc.

In this article, the assessment of tribological properties of materials under the conditions of intensive adhesive wear without lubrication and abrasive wear is performed according to weight losses (in abrasive wear test even using relative resistance to abrasive wear). This assessment is supplemented with energy indicators such as the intensity of wear and density of friction energy. The coefficient of tribological capacity of material has been the decisive indicator in abrasive wear. The material of samples is compared to reference (etalon) material as well as to each other. By comparing the resistance of basic materials used for manufacturing components for agricultural machinery we can determine their resistance to wear in given conditions. It is now necessary to extend the research of this issue in the sphere of non-stationary processes and to use all available methods of mathematical modeling and simulation of these processes.

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### References

- Balla, J., Škarbala, A., (1990) Modelovanie procesu abrazívneho opotrebenia v pôde. In: Zborník Intertribo '90, Vysoké Tatry. Bratislava: DT ČSVTS
- Blaškovič, P. et al., (1990) Hodnotenie tribologickej únosnosti návarov. In: Zborník Intertribo '90, Vysoké Tatry. Bratislava: DT ČSVTS.
- Blaškovitš, P., Čomaj, M., (2006) Renovácia naváraním a žiarovým striekaním. Bratislava: STU v Bratislave.
- Brendel, H. et al., (1984) Tribotechnika. Praha: SNTL.
- Czichos, H. (1978) Tribologi. A System Approach to the Science and Technology of Friction. Amsterdam: Elsevier.
- Fleischer, G. et al. (1980) Verschleiss und Zuverlässigkeit. Berlin: VEB technik.
- Fleischer, G., (1973) Energetische Methode der Bestimmung des Verschleisses. Schmierungstechnik, 4(9), 269–274.
- Kadnár, M. et al., (2011) The design and verification of experimental machine for real journal bearing testing. Technički vjestnik, 18 (1), 95–98.
- Kadnár, M., Rusnák, J., (2008) Ekologické oleje aplikované do oblasti klzných uložení : metódy, prístroje a interpretácia. Nitra : Slovenská poľnohospodárska univerzita.
- Kadnár, M., Kučera, M., Kadnár, J., Rusnák, J., (2010) Chemical analysis of wear products in friction marks. Acta Technologica Agriculturae, 13(2), 53-56.

- Kučera, M., (2004) Analysis of the information from the test of tribological characteristics of selected materials. In: *Nové trendy v konštruovaní a v tvorbe technickej dokumentácie 2004*, 27. máj 2004, Nitra. Nitra: SPU v Nitre.
- Kučera, M., (2006) Tribological experiment and analysis of products of wear-out. In: *Nové trendy v konštruovaní a v tvorbe technickej dokumentácie 2006*, 25. máj 2006, Nitra. Nitra: SPU v Nitre.
- Kučera, M., (2008) Prediction of characteristics for pairs of materials in conditions of limit friction. *Acta Technologica Agriculturae*, 11(1), 11–15.
- Kučera, M., Pršan, J., Kadnár, M., (2008) Analysis of friction marks and wear products. *Acta Technologica Agriculturae*, 11(2), 43–49.
- Kučera, M., Kadnár, M., Pršan, J., (2009) Resistance tests of selected materials on grinding cloth. In: *Nové trendy v konštruovaní a v tvorbe technickej dokumentácie 2009*, 21. máj 2009, Nitra. Nitra: SPU v Nitre.
- Rusnák, J. et al., (2011) Measurement of titanium surface roughness created by non-conventional cutting technology. *Research in Agricultural Engineering*, 57(Special is.), 57–60.
- Tököly, P., Bošanský, M., Tanevski, M., (2009) The possibility of FEM at structural analysis of non-involute gearing. *Machine Design 2009 : 49th anniversary of the Faculty of Technical sciences*, Novi Sad, May 18th 2009. 217–222.
- Tököly, P., Bošanský, M., Vanya, A., (2010) The determination of the thickness of tooth face surface layer from the aspect of wear resistance. *Machine Design*, 147–152.
- Vocel, M. et al., (1976) *Tření a opotřebení strojních součástí*. Praha: SNTL.