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ANALYSIS OF TRIBOLOGIC PROPERTIES OF SELECTED STEELS

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Original scientific paper
This contribution brings an evaluation of basic material C 45 heat treated and hardened, 16MnCr5 as basic material carburized and hardened and weld deposits of selected additional hardened materials. Results obtained for basic material are compared with results on materials of surfaced layers. This enables us to predict certain characteristics of friction pairs under conditions of particular friction node. The tribologic experiment was carried out on device, which belongs to the category of "pin-disk" test devices. The resistance of the selected materials was evaluated concerning weight loss and energy issues. It was observed that combinations of material C508 + C64 and material RD1 give the best results for both categories of test samples under the experimental conditions. Wear resistance of this combination of materials was higher than 43 %. The wear resistance was calculated from energy consumed to remove one unit of metal from the surface.

Keywords: *adhesive wear; calculations; pin-disk test; wear resistance*

Analiza triboloških svojstava odabranih čelika

Izvorni znanstveni članak
U ovom se prilogu daje procjena osnovnog materijala C45 toplinski obrađenog i kaljenog, 16MnCr5 kao osnovnog materijala pougljičenog i kaljenog te materijala zavara izabranih dodatnih kaljenih materijala. Rezultati dobiveni za osnovni material uspoređeni su s rezultatima dobivenim na materijalima površinskih slojeva. To nam omogućuje predviđanje nekih karakteristika tarnih parova u uvjetima određenog tarnog čvora. Tribološki eksperiment proveden je na uređaju koji pripada kategoriji "trn-disk" uređaja za ispitivanje. Otpornost izabranih materijala procijenjena je u odnosu na gubitak težine i pitanja energije. Ustanovljeno je da kombinacije materijala C508 + C64 i materijala RD1 daju najbolje rezultate za obje kategorije ispitnih uzoraka u eksperimentalnim uvjetima. Otpornost na trošenje te kombinacije materijala bila je viša od 43 %. Otpornost na trošenje je izračunata je iz energije potrošene da bi se otklonila jedna jedinica metala s površine.

Ključne riječi: *adhezivno trošenje; otpornost na trošenje; proračuni; trn-disk test*

1 Introduction

Friction is an important physical effect and requires a lot of theoretical and experimental work to be well understood. A systematic approach is necessary for complex solution of friction and related attrition in both the theoretical and experimental spheres [1÷12]. Regarding tribologic properties of materials, the right choice of material or material pair, the geometric shape, roughness, etc. are all important [13]. For tribometry, it is a question of choosing the right test device and test methods as well as the right shape and size of the test samples and their preparation [14]. Choosing an appropriate approach to solve the problem of adhesive friction and related wear is also very important [15]. The specific working conditions of agricultural machinery affect its working life. This lifetime is sometimes short as a result of heterogeneous forms of breaking of the components and destruction of the components' surface. A relatively short working life of machinery and device components in agricultural production is caused by excessive wear, variability of the work regime, an aggressive environment [16]. For the purpose of solving the durability problem it is necessary to recognize basic factors and relations, which determine defects and decrease the operating reliability [17]. The problem is even more complicated in case of a need of replacing the worn surface. As it concerns here a tribologic node with weld deposit, the knowledge of material properties, the effect of alloying elements and the effect of the welding technique on weld deposit properties are all of the maximum importance [18]. Adhesive wear is a complicated process as surface layers of friction pairs of material are damaged during interaction of undulating bearing surfaces [19]. The nature of the deformation depends not only on the penetration depth of irregularities into the other part's surface but also on the radius of the particular penetrating irregularity [20]. In case of elastic deformation, faults in surface layers are of the high-cycle contact fatigue pattern. In case of plastic deformation, the surface attrition is determined by low-cycle contact fatigue. Adhesive wear is thus a result of micro-connections in the surface layers [21]. This paper deals with the possibility of predicting friction pair behaviour based on results of tribologic experiments

2 Materials, methods and samples

We paid great attention to the selection of appropriate materials. We analyzed 186 different components of shaft or pin type of various agricultural devices (tractor, harvester, straw-cutter, mobile machines, etc.) with worn functional parts of cylindrical shape [22] and we found that 20 different types of steel are used for production of these components:

3 types of steel class E 295, S 355J0, E 355
4 types of steel class C15E, C45, C55, C60
2 types of steel class 37MnSi5, 42MnV7
6 types of steel class 37Cr4, 16MnCr5, 20MnCr5, 34Cr4, 36Mn5, 67SiCr5
4 types of steel class 25CrMo4, 42CrMo4, 30Cr2V, 42CrV6
1 type of steel class 18NiCr5-4

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

- steel C45 as a representative of steel types used after heat treatment and inductive hardening,

- steel 16MnCr5 as a representative of steel used for production of components with carburized and hardened surface.

For the purpose of the experiment, material C45 and 16MnCr5 were selected as representatives of steel types used for manufacturing of "shaft-type" components with treated and hardened surfaces. These materials were compared with weld deposits made of additional material C508, C64, 54SiCr5 [17] and RD1. The samples were hard surfaced on materials C45 and 16MnCr5 of tubular shape using welding technique in shielding gas MIG/MAG, by the unifilar and by the two-wire process. Wire C 64 with higher content of carbon was used as additional cold wire. Chemical composition of used additional materials is as follows (% weight):
C 508 – 0,25 C; 0,9 Mn; 0,9 Si;
C 64 – 0,7 C; 0,7 Mn; 0,25 Si; 0,03 P; 0,06 (S+P); 0,22 Cu; 0,1 Cr; 0,1 Ni
RD 1 – 0,3÷0,5 C; 1,0÷1,5 Mn; 0,2÷0,5 Si; 0,9-1,5 Cr; 0,1÷0,3 Ti; 0,03 P; 0,03 S; 0,5÷0,8 Mo; 0,3÷0,5 V; 1,0÷1,5 W
54SiCr6 – 0,5÷0,6C; 0,5÷0,8 Mn; 1,3÷1,6 Si; 0,5÷0,7 Cr; 0,3 Cu; 0,5 Ni; 0,035 P; 0,035 S

Selection of test method, test device and evaluation method of results was performed following the definition of wear [23, 24] and adhesive process [25], which says that wear is an undesirable change in the surface or the size of a solid entity that is caused either by interaction of functional surfaces or by interaction of functional surface and medium, which starts the wear. Wear is demonstrated by the removal or transfer of surface elements by mechanical means. Based on this definition we decided to use adhesive wear test without greasing. Tests were elaborated on a test device of type TE 97/A – Fig. 1 which belongs to the category of "pin-disk" devices with flat contact of friction node elements.

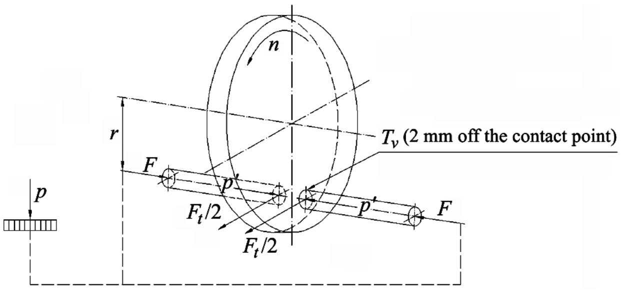

Figure 1 Illustration of working principle of device TE 97/A

The producer of the test device is Research Institute of Welding in Bratislava [RIW]. 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 material C45 and 16MnCr5 plus other weld deposit material as mentioned above. The counter part was made of material C15E, Fig. 3. Test conditions were chosen in accordance with test methodology elaborated by RIW. The method is based on measuring the energy consumption for defined wear. This technique is suitable for comparison of wear resistance of basic materials with wear resistance of weld deposits [21]. The following values for test parameters were selected for the adhesive wear test without greasing:

- contact pressure 1,4 MPa
- compressive force on the pin 74,3 N
- surface speed of the test radius 3,2 m/s
- exposure time 15, 30, 45, 75 s
- material of the counterpart dimension of the sample steel C15E 8×50 mm

Hard surfacing was performed on experimental welding machine ENZ-100 using CO_2 as shielding gas [18]. The samples for the adhesive wear resistance test were welded on a bar of 105 mm in diameter made of basic materials by the rotating welding technique. Samples with weld deposits 20÷25 mm in diameter were prepared this way. Surfacing parameters are listed in Tab. 1. After cooling, the samples were shaped into a ring which was then divided into 12 parts. Further lathe-turning prepared the active part of the sample which was imbedded into the counterpart and fixed. The thickness of the weld deposit on the surface after completion was 2 mm. Four pairs of test samples were prepared from each weld deposit. After heat treatment, the elements were modified and lathed to final diameter of 8 mm – Fig. 2.

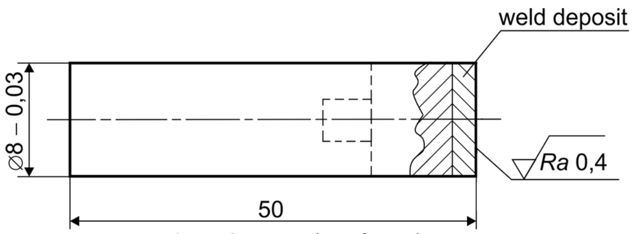

Figure 2 Preparation of test element

During the test, changes in friction force were recorded by a tensometric scanner RIW. The record of the course of friction force enables to determine maximum friction force, mean value of the friction force, frictional work and friction factor. The wear of the samples was detected by direct observation before and after the test. After proper degreasing and drying, samples were weighed on analytic scales MEOPTA with sensitivity 0,05 mg. The result of the wear test on device TE 97/A gives a diagram showing the extent of wear versus time of the test. This way of sample preparation guaranteed that the active part of the samples, especially in case of weld deposits, will correspond with real surfaces. Cross comparison of different sample materials was a possible thanks to the material of the counterpart being the same in each sequence of the test. The samples made of basic materials C45 and 16MnCr5 have the same shape as samples with weld deposits. The characteristics of test elements, the status of their heat treatment and temper are shown in Tab. 2. The hardness was measured on the front of the samples i.e. at the point of interaction of the sample with the testing disk. Hardness tester MEOPTA – VICKERS with a load of spire F = 295,3 N was used for measuring.

Table 1 Parameters of hard surfacing of samples for wear test without greasing AW – arc wire, CW – cold wire

Additive material			Speed of feeding (m/min)		Current hard surface flow (A)	Arc voltage (V)	Rotation speed of spindle (min^{-1})	Weld deposit rate (mm/min)	CO_2 consumption (l/min)
AW	*CW*	*∅AW/∅CW* (mm)	*AW*	*CW*					
C508	-	1,2 / 0	4,7	-	165	20	2,5	5	12
C508	C64	1,2 / 0,93	3,4	2,4	115	20	1,7	5	12
2×C508	-	2×1,2/ 0	2,0	-	145	20	2,2	5	12
54SiCr6	-	1,5/0	2,5	-	145	20	1,7	5	12
RD1	-	1,6/0	3,5	-	160	23	1,5	4,5	15

3 Results and discussion

For the tests without greasing, we derived the quantity of friction work from the value of the friction force at given time and its contribution to weight loss coefficient K^*. A value K^* is a coefficient of tribologic capacity of weld deposits (materials). It represents the quantity of friction work needed for detachment of a unit mass of material [29, 30]. Comparing the rate of wear and friction work to reference material we get a K_N value, which is referred to as the coefficient of relative tribologic capacity of weld deposit. Beside these, our test type enables definition of:

- ratio of friction coefficient to weight loss
- coefficient K^* to mass loss
- coefficient K_N to mass loss

Value K_N characterizes the physical nature of detachment of surface particles during friction. We observed mass loss as a function of time on device TE 97/A (Fig. 1). Results were obtained by weighing the samples before and after the test.

$$\Delta m = m_0 - m_1, \quad \text{g} \tag{1}$$

We detected the wear rate at exposure times of 15, 30, 45, 75 seconds. Fig. 4 presents the results of adhesive wear test without greasing on device TE 97/A.

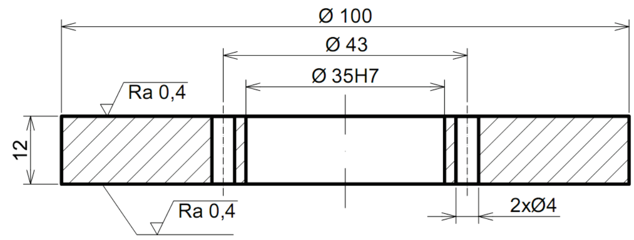

Figure 3 Illustration of shape and dimensions of the disk for adhesive wear test without greasing.

Table 2 Characteristics of samples for wear test without greasing

Sample no.	Basic material	Additive material	Heat treatment	Surface hardness (HV)
1	C 45	C 508	Hardening 850 °C/water,tempering 170 °C/1h./air	554
2	C 45	C 508+C64	Hardening 850 °C /water,tempering 170 °C/1h./air	598
3	C 45	2×C 508	Hardening 850 °C/water,tempering 170 °C/1h./air	527
4	C 45	-	Hardening 850 °C/water,tempering 170 °C/1h./air	606
5	16MnCr5	C 508+C64	Hardening 850 °C/water,tempering 170 °C/1h./air	637
6	16MnCr5	54SiCr6	Hardening 860 °C/oil,tempering 170 °C/1h./air	675
7	16MnCr5	RD 1	–	530
8	16MnCr5	–	Carburized, Hardening 830 °C/oil,tempering 200 °C/1h./air	842

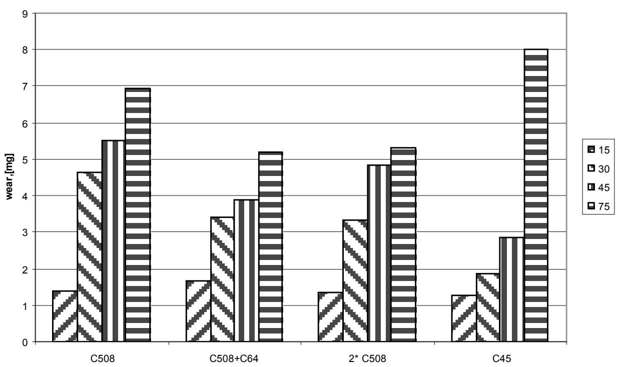

Figure 4 The wear vs exposure time for selected group of test steel C 45

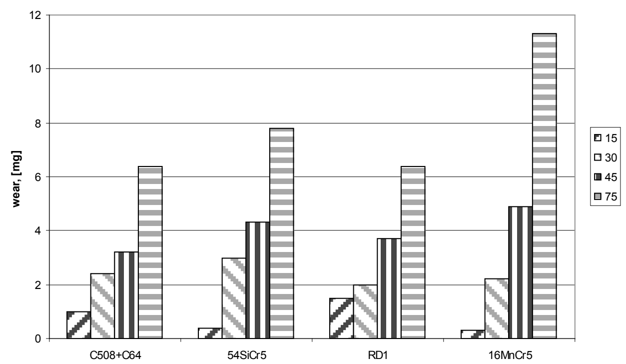

Figure 5 The wear vs exposure time for selected group of test steel 16MnCr5

To simplify the evaluation of results, two groups of samples were formed. The first group involves hardened samples meaning that basic material was hardened and weld deposits for this material were heat treated, and inductively hardened as well. The second group involves carburized and hardened materials whereby only the basic material carburized and hardened. Weld deposits for this material, except RD 1, were hardened after being made.

Based on results shown in Fig. 4 and Fig. 5 it is possible to describe the behaviour of test samples under experimental conditions. As shown in Fig. 4 the highest wear rate from the whole group of samples was measured for sample no. 4 and exposure time of 75 s. The lowest wear was measured for the same sample and exposure time of 15 s. The wear rate of all samples at 15 s was approximately the same. For other exposure times the wear rates are as shown in the figure. The highest overall wear rate (sum of wear rates for all exposure times) was reported for sample no. 1 and the lowest wear rate was measured in case of sample no. 4. For samples no. 2 and 3 we measured approximately the same wear rate as for sample no. 4. Based on Fig. 5 we state that the highest wear rate was again reported for the basic material, sample no. 8 and exposure time of 75 s. The lowest wear rate was reported for the same sample and of 15 s exposure time. The wear rate of other materials at exposure time of 75 s is substantially lower. For exposure time of 30 s and of 45 s the wear rate of all samples is very similar. The lowest was measured in case of sample no. 7 and the highest for sample no. 8. The highest overall wear rate (sum of wear rates for all exposure times) was measured for sample no. 8 and the lowest for sample no. 5. The wear rate of sample no. 7 is approximately the same as for sample no. 5. In laboratory conditions, mass loss of weld deposits m_0 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 the friction path L. i.e. $\mathrm{d}L = v\mathrm{d}t$ and then we may calculate work W as follows:

$$W = \int_0^t F_T v \, \mathrm{d}t. \tag{2}$$

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

$$K^* = \frac{W}{m_0}, \ \mathrm{J \cdot kg^{-1}} \tag{3}$$

If we relate values of the wear m_0 and friction work W to etalon material, then it may be stated:

$$K_N = \frac{K_s^*}{K_r^*} = \frac{\frac{W_s}{m_{0s}}}{\frac{W_r}{m_{0r}}} = \frac{W_s}{W_r} \cdot \frac{m_{0r}}{m_{0s}}, \tag{4}$$

where: W_s – friction work of the sample, J; W_r – friction work of reference sample, J; m_{0s} – wear of sample, g; m_{0r} – wear of reference sample, g.

Tab. 3 shows calculated values of the coefficient of tribologic capacity of weld deposits K^* and the coefficient of relative tribologic capacity of weld deposits K_N. The K_N criterion allows for the physical basis of detachment of particles from the surface during the friction process and enables assessment of weld deposits for tribologic use. To assess the suitability of weld deposits using coefficients of tribologic capacity we proceeded with two material groups. Tab. 3 shows the power consumed for detachment of unit of material in the process of friction and wear. This energy involves the transfer of abrasive elements from pin on disk and vice versa as well as the transfer back. The highest K coefficient value was reported for sample no. 7, which is weld deposit made with tubular wire RD1, in spite of its hardness being the lowest among all. The lowest K coefficient value was reported for sample no. 8, basic material 16MnCr5, in spite of its hardness being the highest. As shown in table 3 hardness is not determining in the process of friction and wear as far as power consumption is concerned. Considering sample no. 8 with its structure and chemical composition, we state that the structure based on martensite puts up less resistance against abrasion than for material of sample no. 7 which is RD 1, which is made of tough structure with complex carbides. The same applies to sample no. 4 vs sample no. 2. K coefficient values for other materials are given in Tab. 3.

Table 3 Chart of hardness as measured, K^*, K_N

Sample no.	Material	Heat treatment	Hardness / HV	K^* / (J·kg^{-1})×10^8	K_N / –
1	C 508	Hardening	554÷620	2,382	1,536
2	C 508+C 64	Hardening	598÷626	3,841	2,478
3	2×C508	Hardening	527÷586	3,062	1,976
4	C 45	Hardening	606÷644	2,446	1,578
5	C 508+C 64	Hardening	637÷671	2,898	1,869
6	54SiCr6	Hardening	675÷752	2,558	1,650
7	RD 1	–	493÷530	3,124	2,015
8	16MnCr5	Cemented and hardening	842÷897	2,371	1,529
etalon	C15 E	–	160÷180	155	1

Table 4 Chemical composition (% weight)

Weld deposit	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Ti	W
C508	0,28	0,66	0,65	0,02	0,02	0,58	0,03	0,02	-	0,17	-	-
2×C508	0,28	0,82	0,82	0,017	0,014	0,72	0,05	0,02	0,01	0,08	-	-
54SiCr6	0,44	0,78	0,64	0,02	0,02	0,71	0,08	0,01	0,01	0,21	-	-
C508+C64	0,32÷0,35	0,70÷0,75	0,59÷0,67	0,017÷0,026	0,017÷0,021	0,6÷0,7	0,05÷0,06	0,01÷0,02	0,01	0,08÷0,021	-	-
RD 1	0,31	1,01	0,29	0,02	0,13	0,95	-	0,56	0,43	-	0,015	1,06

Tab. 4 indicates that chemical composition of samples with weld deposits made of RD1 enables the formation of complex carbides in the structure of the steel. This leads to higher wear resistance with regard to power consumption needed for detachment of metal components.

4 Conclusion

This paper presents the results of tribological experiments performed using the device TE 97/A. This device belongs to the category of "pin – disc" devices. The tests of friction and wear without lubrication are performed using this device. The tests basically simulate a short-term absence of the lubricant in the friction node. Basic materials C45 and 16MnCr5 were used for the tests – these materials are used for manufacturing agricultural machinery components. These materials were compared to selected materials of welded layers in two groups. The experiments were assessed in terms of hardness, weight loss and energy consumption for each sample of material. The results of experiments demonstrate the suitability of material assessment for tribological purposes in terms of energy consumed in the process of wear. It was shown that the hardness of material is not the decisive determinant affecting the wear resistance in given conditions. Based on the results we may conclude that the chemical composition and especially the structural state of the surface layers had a significant effect. Probably for this reason the best results were achieved in layers welded with additional material RD1 and with combination of materials C508+C64.

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