1. INTRODUCTION

Brakes are one of the most significant parts in any vehicles, such as cars, trucks, trains and aircrafts [1, 2]. Disk brake is the most common type of brakes. It is based on the use of friction between the elements of the brake. These brakes usually consist of brake pads that can be pressed to a brake disc connected to the wheel [3]. Cast iron is widely used for manufacturing of such brakes. This material has good thermal conductivity and anti-vibration capacity [3]. The disadvantage of cast iron brakes is high level of noise and wear rate.

Various materials are used for manufacturing of brake pads. The efficiency of these brake systems depends mostly on the tribological properties of the materials used, as well as on the conditions of their usage [3]. A wide range of research has been carried out on ceramic composite materials and their tribological and mechanical properties for better understanding of the behaviour of such materials in braking systems [2].

In this paper, the experimental research of metallic and ceramic materials was carried out in order to select the optimal tribopairs that could be used for manufacturing of brake systems for trucks and off-road vehicles providing them with high safety and efficiency without increasing the cost.

2. MATERIALS FOR BRAKES

Materials for brake pads can be classified into semi-metallic, metallic, organic and ceramic types [4].

Metallic pads are noisy and produce a lot of dust. Wear rate of such brakes is high [5].
Nowadays, brakes manufacturers use some organic and non-asbestos materials in order to decrease the negative ecological impact and produce environment-friendly brakes [6-10]. These brakes produce less noise, but wear rate is also high.

C/SiC composites are used in braking systems, because they have a lot of advantages, such as low density, high temperature resistance, good tribological properties and low wear rate [11, 12]. The disadvantage of such brakes is their cost. Ceramic composites are expensive. Also, the tribological properties of ceramic pads depend on the temperature. The influence of the temperature in brake systems on the friction processes was studied by V. Dygalo et al. in [13] and N. Benhassine et al. in [14].

Another important issue for brakes is vibrations and their influence on the contact pressure and area, since friction between the elements of brakes depends on these parameters, and, therefore, such effects should be considered during the design process [15, 16]. Also, the contact area and, therefore, the tribological properties depend on the initial surface roughness and the accuracy of manufacturing and assembling of brake system elements [17-19].

3. EXPERIMENTAL RESEARCH

A wide range of measurement machines and methods has been developed for investigation of tribological properties [20].

In this paper, the experimental research of the materials for the design of brakes was carried out with the use of the universal friction machine MTU-1 that is based on a vertical milling machine “JMD-X1” and contains the original friction assembly unit that allows us to save the parallelism of the contacted surfaces [21, 22].

The scheme of the experiment was plate-on-plate. The lower samples were made of C/SiC, the upper samples were made of two types of steel: C22 and 37Cr4. The rotational speed of the upper sample was 300 and 650 rpm, whereas the lower sample was fixed. No lubricants were used. The load on the upper sample was 150, 400 and 600 N. The influence of braking pressure and braking speed on the tribological properties of C/SiC in brakes was investigated by Fan et al. in [23]. Dynamic friction coefficient was measured and analysed during the experiments.

The first set of experiments was carried out during 10 minutes for the tribopairs C/SiC – steel 37Cr4 with the following conditions: rotational speed was 300 rpm, starting load was 400 N.

Figure 1 shows the photographs of the samples after the first experiment.

![Figure 1. C/SiC (left) and 37Cr4 (right) samples after the first experiment](image1)

In figure 2, the graph of friction coefficient versus time for the tribopair C/SiC – steel 37Cr4 during the first experiment is shown.

![Figure 2. Graph of friction coefficient versus time during the first experiment](image2)

As can be seen from the graph in figure 2, the running-in of a friction pair occurs rather quickly, and at a small load the dynamic friction coefficient, having reached a plateau at the level of approximately 0.4, does not depend on time. This indicates a slight destruction of the surface layer and minimal wear.

The second set of experiments was carried out during 15 minutes for the tribopairs C/SiC – steel C22 with the following conditions: rotational speed was 300 rpm, starting load was 150 N.

In Figure 3 the samples after the second experiment are shown.
The third set of experiments was carried out for the tribopairs C/SiC – steel 37Cr4 with the following conditions: rotational speed was 650 rpm, starting load was 600 N.

In Figure 5 the samples after the third experiment are shown.

In Figure 6, the graph of friction coefficient versus time for the tribopair C/SiC – steel 37Cr4 during the third experiment is presented.

It can be observed from the graph that after the running-in, the oxide films are destroyed, the particles of oxides are dispersed and act as an additional abrasive without leaving the contact zone, which leads to the continuing growth of the friction coefficient. The average coefficient of friction is 0.75.

The last set of experiments was carried out during 15 minutes for the tribopairs C/SiC – steel C22 with the following conditions: rotational speed was 650 rpm, starting load was 600 N.

In Figure 7 the samples after the last experiment are presented.

It can be noticed from the graph in figure 4 that this tribopair at the beginning of the experiment behaves unstably, which is associated with a low hardness of C22. Surface running-in is observed during the entire experiment. Plastic deformation is observed on the surface of the sample made of C22, which increases the friction coefficient. The wear rate of such a pair will be high enough, the average coefficient of friction is 0.6.
In Figure 8, the graph of friction coefficient versus time for the tribopair C/SiC – steel C22 during the last experiment is shown. The graph in Fig. 8 shows that this tribopair after running-in also has an increase in the coefficient of friction, which is associated with the destruction of the surface layer. Further, wear particles act as abrasive, but the friction coefficient has small changes. The average coefficient of friction is 0.8.

4. CONCLUSION

The results of the experiment show that friction coefficient in the tribopair C/SiC – steel 37Cr4 increased in the beginning and then remained virtually constant during the experiment whereas in the tribopair C/SiC – steel C22 it increased during the whole experiment. This could be explained by the fact that in the second tribopair wear particles do not leave the contact area and charge the material acting as an abrasive. However, friction coefficient in the tribopair C/SiC – steel C22 is greater than friction coefficient in the tribopair C/SiC – steel 37Cr4, which means that use of steel C22 can help us reduce the braking distance, but wear of braking system parts is higher in that case.

REFERENCES

[1] Z. Wang, J. Han, J. P. Domblesky, Z. Li, X. Fan, X. Liu: Crack propagation and microstructural transformation on the friction surface of a high-speed railway brake disc, Wear, Vol, 428–429, pp. 45–54, 2019.

[2] S. Fan et al.: Microstructure and tribological properties of advanced carbon/silicon carbide aircraft brake materials, Composites Science and Technology, Vol. 68, pp. 3002–3009, 2008.

[3] A. Borawski: Simulation Study of the Process of Friction in the Working Elements of a Car Braking System at Different Degrees of Wear, Acta Mechanica et Automatica, Vol.12, No.3, 2018.

[4] C. Pinca-Bretotean et al.: Friction and wear characteristic of organic brake pads material, IOP Conf. Series: Materials Science and Engineering, Vol. 477, paper 012009, 2019.

[5] X. Xiao, Y. Yin, J. Bao, L. Lu, X. Feng: Review on the friction and wear of brake materials, Advances in Mechanical Engineering, Vol. 8, pp. 1–10, 2016.

[6] M. Kandeva, V. Balabanov, E. Zadorozhnaya, Zh. Kalitchin, P. Svoboda: Environmental protection by self-organisation of tribo-systems with self-lubricating materials in dry friction. Part I. Investigations at different loads, Journal of Environmental Protection and Ecology, Vol. 18, No. 3, pp. 1050-1069, 2017.

[7] G. Akincioğlu, H. Öktem, I. Uygar, S. Akincioğlu: Determination of Friction-Wear Performance and Properties of Eco-Friendly Brake Pads Reinforced with Hazelnut Shell and Boron Dusts, Arabian Journal for Science and Engineering, Vol. 43, pp. 4727–4737, 2018.

[8] K.K. Ikpambese, E.A. Lawrence: Comparative Analysis of Multiple Linear Regression and Artificial Neural Network for Predicting Friction and Wear of Automotive Brake Pads Produced from Palm Kernel Shell, Tribology in Industry, Vol. 40, No. 4, pp. 565-573, 2018.

[9] B. Dan-asabe, A. Stephen: Mathematical Modelling and Optimization of the Compressive Strength, Hardness and Density of a Periwinkle-Palm Kernel and Phenolic Resin Composite Brake Pad, Tribology in Industry, Vol. 40, No. 1, pp. 108-116, 2018.

[10] Y. Lyu, J. Wahlström, M. Tu, U. Olofsson: A Friction, Wear and Emission Tribometer Study of Non-Asbestos Organic Pins Sliding Against AlSiC MMC Discs, Tribology in Industry, Vol. 40, No. 2, pp. 274-282, 2018.

[11] S. Fan et al.: Wear mechanisms of the C/SiC brake materials, Tribology International, Vol. 44, pp. 25–28, 2011.

[12] G. Byeong-Choon, C. In-Sik: Microstructural Analysis and Wear Performance of Carbon-Fiber-Reinforced SiC Composite for Brake Pads, Materials, 10, 701, 2017.

[13] V. Dygalo, I. Zhukov: The thermal loading estimation of the friction pairs of a vehicle automated brake system, IOP Conf. Series: Materials Science and Engineering, Vol. 386, paper 012012, 2018.

[14] N. Benhassine, A. Haiahem, B. Bou-Said: A comparative study of the transient thermomechanical behavior of friction of the ceramic brake discs: Temperature field effect, Journal of Mechanical Science and Technology, Vol. 33, Issue 1, pp. 233–240, 2019.
conditions, Tribology in Industry, Vol. 40, No. 3, pp. 392–400, 2018.

[16] A.E. Tyurin, G.M. Ismailov, E.V. Beloenko, A.V. Baranov: Monitoring vibrations and microdisplacement for "pin on disc" tribology studies, Journal of Physics: Conference Series, Vol. 803, No. 1, paper 012167, 2017.

[17] G. Riva, G. Perricone, J. Wahlström: Simulation of Contact Area and Pressure Dependence of Initial Surface Roughness for Cermet-Coated Discs Used in Disc Brakes, Tribology in Industry, Vol. 41, No. 1, pp. 1–13, 2019.

[18] M. Bolotov, I. Grachev, E. Kudashov: Investigation of parts assembly error, taking into account the deviation of the shape of their surfaces, MATEC Web of Conferences, 224, paper 01098, 2018.

[19] M.A. Bolotov, V.A. Pechenin: Model of precision parts assembly, in: Proceedings of the International Conference of DAAAM Baltic Industrial Engineering, 2016-April, Tallinn, Estonia, pp. 98-103.

[20] A.Y. Grigoriev, D.M. Gutsev, A.P. Zozulya, I.N. Kovaliova, V.G. Kudritskii, N.K. Myshkin, M.S. Semenyuk: Reciprocating MTU-2K7 millitribometer, Journal of Friction and Wear, Vol. 35, No. 6, pp. 455-459, 2014.

[21] S. Perepelkina, P. Kovalenko, R. Pechenko: Investigation of Tribological Properties of Metallic Materials with the Use of the Universal Friction Machine “MTU-1”, Procedia Engineering, Vol. 176, pp. 301-309, 2017.

[22] S. Perepelkina, P. Kovalenko, R. Pechenko, K. Makhmudova: Investigation of friction coefficient of various polymers used in rapid prototyping technologies with different settings of 3D printing, Tribology in Industry, Vol. 39, No. 4, pp. 519-526, 2017.

[23] S. Fan et al.: Effect of braking pressure and braking speed on the tribological properties of C/SiC aircraft brake materials, Composites Science and Technology, Vol. 70, pp. 959–965, 2010.