Vol. 39, No. 2 (2017) 192-197, DOI: 10.24874/ti.2017.39.02.05

Tribology in Industry

www.tribology.fink.rs

RESEARCH

# Investigation of Tribological Properties of Friction Pairs Duralumin – Fluoropolymer Used for Design and Manufacturing of Biomechatronic Devices

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Keywords:

*Duralumin – fluoropolymer*
*Friction coefficient*
*Tribological properties*
*Wear*
*Temperature in the contact area*
*Prostheses and orthoses*

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A B S T R A C T

*This paper deals with the processes occurring on the surfaces of materials during the interaction between metal and non-metal parts of various biomechatronic devices, such as prostheses, orthoses and exoskeletons. These mechatronic systems require careful selection of materials for design and manufacturing of their parts taking into consideration not only mechanical properties of the materials, but also their tribological characteristics. Friction pairs duralumin – fluoropolymer and stainless steel 100CrMn6 – fluoropolymer were chosen for the research as the samples. Experimental research was carried out with the use of the universal friction machine MTU-1. For this research, the scheme "plate-on-plate" was used without lubricants. Friction torque, friction coefficient and the temperature in the contact area versus the runtime were obtained as a result of the experiments. Furthermore, estimation of wear of contacting samples was performed. Analysis of the results allowed us to choose suitable materials for design and manufacturing of orthoses, prostheses and exoskeletons.*



## 1. INTRODUCTION

Recently, a wide range of various mechatronic devices has been developed for sufficient rehabilitation after injuries or diseases that cause dysfunctions of extremities. These devices, such as orthoses and exoskeletons, could be used for the recovery of lost functions of lower or upper limbs providing the opportunity of everyday training and relearning by reducing energy costs and muscular efforts [1-4]. In case of a lost extremity, a prosthesis could be used in order to improve the quality of life by replacing the missing limb [5]. Exoskeletons could be also used for industrial purposes where it is necessary to decrease the physical load or to enhance the muscular power of workers [6]. Most of these devices are wearable, which means that the weight of such systems plays a significant role and must be taken into consideration during the design. Another important issue related to the design of exoskeletons and orthoses is the choice of power supply. In order to increase the battery life batteries with high capacity might be used. However, this would increase the weight of the device, which makes it uncomfortable for the users and might increase the load on the parts of the system. This could increase friction in the joints of the device and, therefore, wear of the parts.

Requirements for the strength, weight, size and reliability of orthoses, exoskeletons and prostheses lead to the necessity of careful selection of materials for design and manufacturing of their parts. Not only the strength properties of the materials should be taken into consideration, but also it is necessary to consider the tribological properties of the friction pairs, which will increase the lifetime and energy efficiency of the device by reducing wear and friction losses in tribopairs [7].

## 2. MATERIALS FOR DESIGN OF ORTHOSES, PROSTHESES AND EXOSKELETONS

Various materials are used for design and manufacturing of mechatronic systems for robotic rehabilitation and assistance, such as stainless steel, alloys, polymers, rubber and fiber [8]. Some of these materials provide the structure with the required hardness; other materials are used for their elasticity and flexibility. All the materials have different tribological properties that have influence on wear and energy efficiency of the system.

Duralumin, stainless steel 100CrMn6 and fluoropolymer were chosen as the materials for this research. These materials could be used for the design of prostheses, orthoses and exoskeletons in order to reduce their weight, friction coefficient in tribopairs and wear of interacting parts.

Duralumin is widely used for design of friction pairs in prostheses, orthoses and exoskeletons due to its properties. First of all, the low weight of the structure reduces the load on the friction pairs, and secondly, duralumin is corrosion resistant, which reduces wear of the tribopair. Also, for duralumin parts it is easy to use a coating consisting, for example, of $Al_2O_3$ which does not require lubrication and is resistant to contamination [9, 10].

Fluoropolymer could be used for design of various mechatronic devices because of its low friction coefficient. In addition, fluoropolymer is resistant to chemical influence, radiation and corrosion. Fluoropolymers are also flame-resistant or self-extinguishing when ignited. They are chemically inert to aggressive environment, which allows us to use different kinds of lubricants in friction pairs [11].

Stainless steel 100CrMn6 could be used for the design of parts of orthoses and exoskeletons that require high hardness and wear resistance.

In this research, two sets of experiments were carried out in order to compare the friction processes in tribopairs fluoropolymer – stainless steel 100CrMn6 and fluoropolymer – duralumin. Friction torque, temperature in the contact area and friction coefficient were obtained as the results of experiments. Temperature in the contact area has a significant influence on the performance of parts and systems [12].

## 3. UNIVERSAL FRICTION MACHINE “MTU-1”

Recently, various measurement machines and methods have been developed for estimation of tribological properties [13-16]. Another important issue is estimation of the geometry and its deviation for the parts of complex shape, because the contact area and, therefore, friction in the tribopairs depend on these parameters [17]. In addition, the tribological properties depend on the surface roughness of interacting parts, which makes it important to choose the suitable finishing procedure for the parts of designed systems [18, 19].

In this paper, a universal friction machine MTU-1 was used for the experimental research of tribological properties of duralumin, steel 100CrMn6 and fluoropolymer (Fig. 1). The universal friction machine “MTU-1” 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. Overall dimensions of the machine allow us to place it on the laboratory bench. The machine is resistant to vibration, electromagnetic interference, dust, humidity and temperature fluctuations.

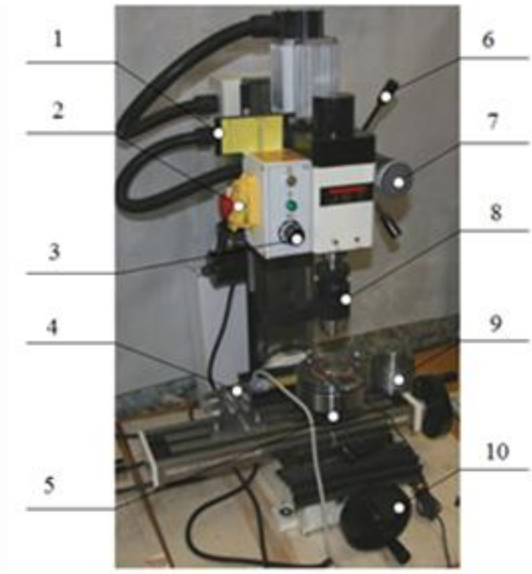


**Fig. 1.** Universal friction machine "MTU-1".

In Fig. 1, the following parts of the universal friction machine "MTU-1" are shown: 1 – table of rotation speed; 2 – power button; 3 – speed control button; 4 – friction torque measurement system with the elastic sensing element; 5 – strain gauge for axial load measurement; 6 – handle for fast loading; 7 – handle for fine loading; 8 – chuck for the upper sample; 9 – lubricant reservoir; 10 – handle for displacement of the coordinate table.

The testing method for "MTU-1" is based on a relative rotational movement of the upper sample on the lower stationary sample with or without lubricants using different test schemes, such as disc-on-disk, pin-on-disk, sphere-on-ring, plate-on-plate, etc. The upper sample rotation speed without the load is adjustable from 0 to 2500 rpm, the pressing force on the samples can be varied from 50 to 1000 N [20].

## 4. EXPERIMENTAL RESULTS

The first set of experiments was carried out using the test scheme plate-on-plate for the tribopairs fluoropolymer – steel 100CrMn6 with the following conditions: rotation speed was 300 rpm, starting load was 120 N. The forces and loads generated in orthoses were estimated by Silva et al. in [21].

In Fig. 2, the graph of the friction torque versus time for the tribopair fluoropolymer – stainless steel 100CrMn6 is shown.

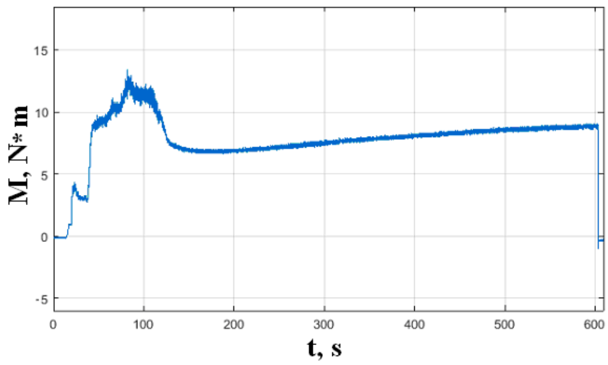


**Fig. 2.** Graph of the friction torque versus time for the tribopair fluoropolymer – steel 100CrMn6.

The analysis of the graph in Fig. 2 shows that at the beginning of the experiment the friction torque changed abruptly, which is caused by the beginning of the process of running-in in the tribopair.

In Figs. 3 and 4, the graphs of the temperature in the contact area and friction coefficient versus time of the experiment for the tribopair fluoropolymer – steel 100CrMn6 are shown.

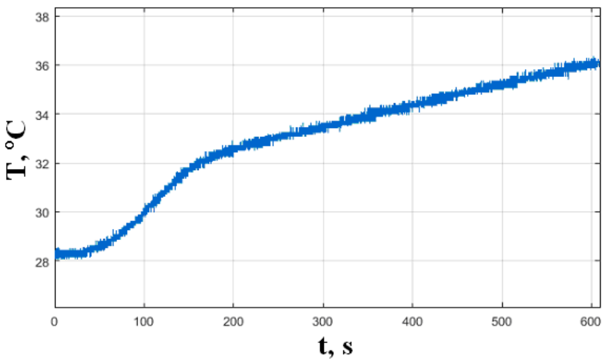


**Fig. 3.** Graph of the temperature in the contact area versus time for the tribopair fluoropolymer – steel 100CrMn6.

It could be observed from the graph in Fig. 3 that after approximately 100 seconds from the beginning of the experiment there is an inflection point. Apparently, the inflection point is due to the appearance of the partial reflow of the fluoropolymer surface at this point of time, which indicates the occurrence of a temperature flare at the contact point.

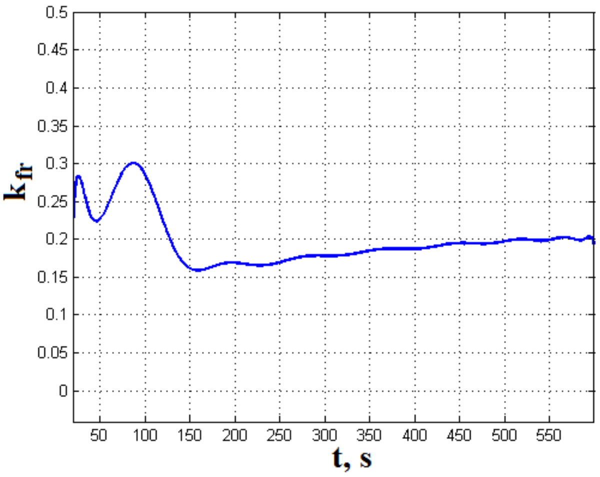


**Fig. 4.** Graph of friction coefficient versus time for the tribopair fluoropolymer – steel 100CrMn6.

The graph in Fig. 4 shows that the maximum friction coefficient is 0.3. It is observed during the running-in of the tribopair. After the running-in, friction coefficient sharply decreases.

Figure 5 shows the photographs of fluoropolymer surface after the experiments. The pictures in Fig. 5 clearly show both the areas of reflow of fluoropolymer and the areas of selective transfer during friction.

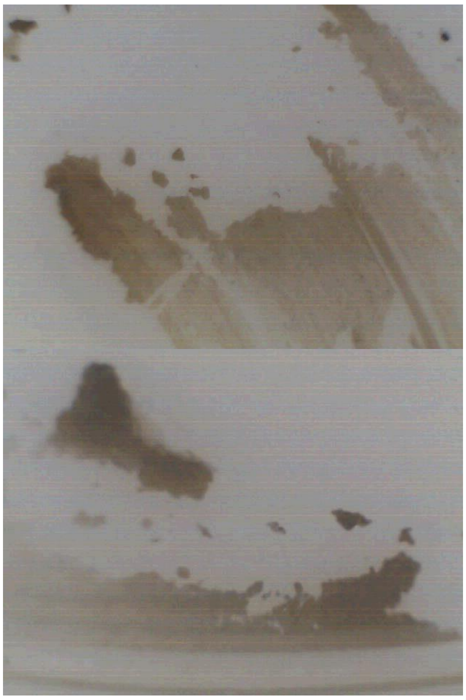

**Fig. 5.** Photographs of fluoropolymer surface after the experiment (the tribopair fluoropolymer – steel 100CrMn6, magnification is 88X).

It should be noted that the surface of the steel sample has virtually no changes, which is due to both the hardness and wear resistance of the steel.

The second set of experiments was devoted to the study of tribological properties of the tribopair duralumin – fluoropolymer. Experimental conditions were the following: rotation speed was 300 rpm, starting load was 150 N.

In Fig. 6, the graph of the friction torque versus time for the tribopair duralumin – fluoropolymer is presented. The graph shows that the friction torque remained approximately constant during the experiment, with small fluctuations. This is due to low friction coefficient of fluoropolymer and sufficient viscosity of duralumin.

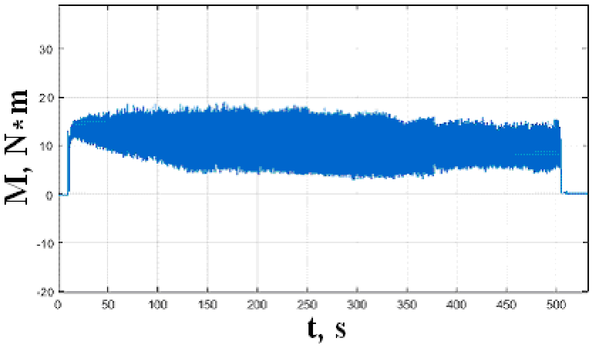


**Fig. 6.** Graph of the friction torque versus time for the tribopair duralumin – fluoropolymer.

In Figs. 7 and 8, the graphs of the temperature in the contact area and friction coefficient versus time for the tribopair duralumin – fluoropolymer are shown.

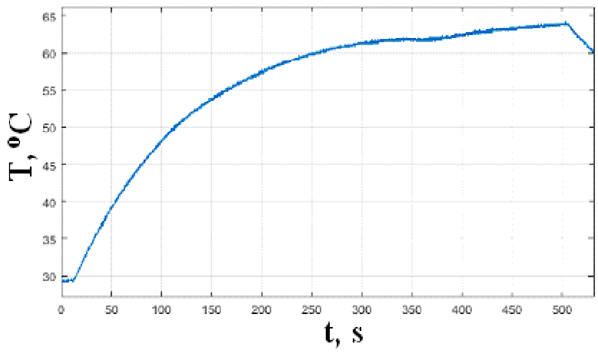


**Fig. 7.** Graph of temperature in the contact area versus time for the trobopair duralumin – fluoropolymer.

It could be observed from the graph in Fig. 7 that the temperature in the contact area gradually increases, which indicates the absence of scuffing in the tribopair.

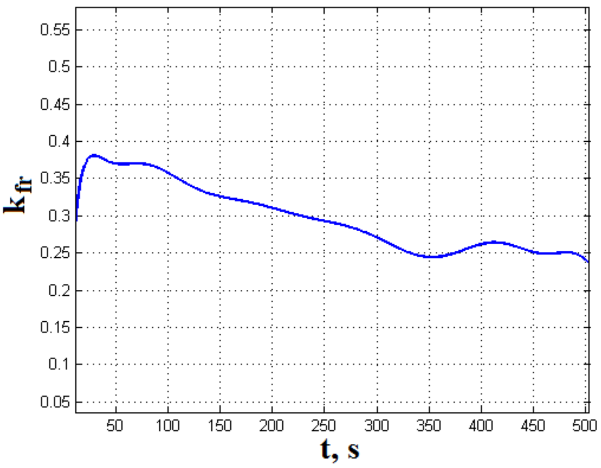


**Fig. 8.** Graph of friction coefficient versus time for the tribopair duralumin – fluoropolymer.

It could be noticed from the graph in Fig. 8 that friction coefficient smoothly decreases during the experiment. This could be explained by the absence of significant wear on the surfaces of the samples. The maximum value of friction coefficient in this experiment is 0.38.

In Fig. 9, the photograph of the surface of fluoropolymer after the experiment is shown.

**Fig. 9.** The surface of fluoropolymer after the experiment (the tribopair duralumin – fluoropolymer, magnification is 87X).

It could be seen from the photograph in Fig. 9 that there are areas of running-in on the surface, but their quantity and size are not significant.

## 5. CONCLUSION

The analysis of the results of the experiments shows that the tribopair duralumin – fluoropolymer has lower friction coefficient than the tribopair fluoropolymer – stainless steel 100CrMn6. The friction process in the tribopair duralumin – fluoropolymer is more stable and does not cause abrupt changes of friction coefficient and friction torque. Friction coefficient in the tribopair duralumin - fluoropolymer smoothly decreases after running-in, which makes it possible to predict the behaviour of the tribopair with high accuracy. The results of the research allow us to make a conclusion that the use of the tribopair duralumin – fluoropolymer, especially with a coating on duralumin or with the use of a boundary lubrication, is more convenient and advantageous for design and manufacturing of friction pairs of prostheses, orthoses and exoskeletons.

In future work, it is necessary to define the optimal roughness parameters for contacting surfaces of the parts in order to reduce wear and friction in the tribopairs of exoskeletons, orthoses and prostheses and to increase their energy efficiency.


## Acknowledgement

This work was supported by the Government of the Russian Federation, grant 074-U01.


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