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RESEARCH

Investigation of Friction Coefficient of Various Polymers Used in Rapid Prototyping Technologies with Different Settings of 3D Printing

S. Perepelkina[a], P. Kovalenko[a], R. Pechenko[a], K. Makhmudova[a]

[a]*ITMO University, Kronverksky pr. 49, 197101 Saint Petersburg, Russian Federation.*

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Corresponding author:

Svetlana Perepelkina
ITMO University, Kronverksky pr. 49,
197101 Saint Petersburg,
Russian Federation.
E-mail: svetlana.yu.perepelkina@gmail.com

A B S T R A C T

This paper deals with the research of friction coefficient in tribopairs made of the polymers that are the most commonly used in rapid prototyping technologies. Parts manufactured with the use of a 3D printer with different settings of printing were chosen as samples for the experimental research. Friction coefficient and the temperature in the contact area during the runtime were measured using a universal friction machine MTU-1. The machine allows us to carry out tribological experiments using different contact schemes with or without lubricants. For this research, the scheme "plate-on-plate" was chosen. No lubricants were used. Wear of the samples was estimated after the experiments. Analysis of the experimental data has shown that changing of 3D printing settings has significant influence not only on the strength and stiffness of the parts, but also on the quality of the surface that affects the tribological properties of the tribopairs. The results of this research allow us to choose optimal settings for 3D printing depending on the required tribological properties of the parts, such as friction coefficient and wear.

1. INTRODUCTION

Recently, rapid prototyping technologies, or 3D printing, also called additive manufacturing, have been widely used for design and manufacturing of various parts of systems and mechanisms [1]. These methods and technologies are used both in industry and academic institutions [2]. In medicine, additive manufacturing helps us design implants, individual prostheses, as well as the parts for various mechatronic systems for robotic rehabilitation, such as orthoses and exoskeletons [3].

A wide range of research has been carried out in the field of 3D printing in order to investigate mechanical properties of the parts manufactured with the use of such technologies. Strength, stiffness, weight and other properties of these parts depend on various conditions of 3D printing, such as layers' thickness and height, shell thickness, fill density, etc. The most commonly used materials for rapid prototyping technologies are ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid). Mechanical properties of 3D printed parts were investigated by Bellini et al. [4]. Song et al. paid attention to the measurements of the mechanical response of 3D printed parts made of PLA [5]. Mechanical properties of coloured PLA were described by Wittbrodt et al. [6]. Es-Said et al. considered the influence of layer orientation on the mechanical properties, such as tensile strength, modulus of rupture, and impact resistance, for the parts made of ABS [7]. Part orientation during 3D printing has its influence on the surface finish [1] and, therefore, it affects the tribological properties of the tribopairs. However, tribological properties of such parts have not been investigated well enough, which may lead to uncontrolled wear of tribopairs surfaces. Dawoud et al. investigated the tribological properties, such as friction coefficient and wear, for the samples 3D printed with the use of ABS [8]. Tribological behaviour of alumina added ABS composites was described by Panneerselvam et al. [9].

In this paper, the tribological properties of the samples made of PLA with the use of 3D printing with different settings is considered

2. RAPID PROTOTYPING AND ADDITIVE MANUFACTURING TECHNOLOGIES

Most rapid prototyping technologies are based on the addition of material layer by layer according to the previously developed computer model. There are a lot of methods and technologies for additive manufacturing. Basic methods are: three dimensional printing (3DP), fused deposition modeling (FDM), stereolithography (SL), powder bed and inkjet 3D printing, selective laser sintering or melting (SLS or SLM), direct metal laser sintering (DMLS), laminated object manufacturing (LOM) and ultrasonic consolidation (UC) [10]. The most common methods for additive manufacturing and rapid prototyping are 3DP and FDM. These methods are based on the melting of the filaments that are usually made of thermoplastics. After being melted by the hot extruder, the material is deposited layer by layer through the nozzle that can move in vertical and horizontal directions. After extrusion from the nozzle the material hardens immediately due to the temperature change. No binders between layers are required.

Other additive manufacturing technologies, such as selective laser sintering, can use powders made of various materials, including plastics, metals or ceramic. In these methods, lasers are used to fuse the particles of the powder, therefore, binders are not used. The use of binders is required for other methods working with powders, such as powder bed and inkjet 3D printing [10].

Another rapid prototyping method is stereolithography. This technology is based on the use of liquid materials that are sensitive to the influence of light or ultraviolet. Layers harden being irradiated by the laser or ultraviolet due to the phenomena of photopolymerization.

All these methods allow us to produce parts with different inner structure and mechanical properties [11]. This diversity can be obtained by the use of different settings and various materials for additive manufacturing. Using 3D printing or fused deposition modeling it is possible to change some parameters, such as layers' thickness, fill density, porosity, layers' orientation, etc. These parameters affect the surface finish and, therefore, not only mechanical properties, but also tribological behaviour of the parts.

3. UNIVERSAL FRICTION MACHINE "MTU-1"

Recently, a wide range of measurement machines and methods has been developed for the estimation of tribological behaviour in various conditions [12-17]. 3D printing technology allows us to manufacture parts with varying accuracy [18] and degree of filling of the inner layers of the part. Deviations of the shape and roughness of the surface have significant influence on various properties of the part, including its reliability and wear [19-21].

Roughness of the surface layers, as a rule, does not depend on the filling factor. Therefore, it is of interest to investigate the tribological properties of tribopairs after abrasion of the surface layers. In this case, the porosity of the inner layers affects the tribological behaviour of the tribopairs [22].

A universal friction machine MTU-1 was used for testing. (Fig. 1) [23].

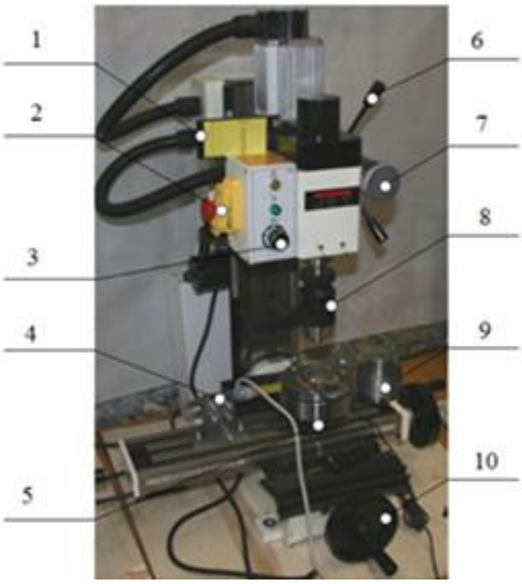


Fig. 1. Universal friction machine "MTU-1".

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

The structure of the universal friction machine "MTU-1" allows us to save the parallelism of the contacted surfaces, which increases the accuracy of measurements. The machine is resistant to the environmental influence, such as vibration, electromagnetic interference, dust, humidity and temperature fluctuations.

The testing method for "MTU-1" is based on a relative rotational movement of the upper sample to the lower stationary sample using different test schemes, such as disc-on-disk, sphere-on-ring, pin-on-disk, etc. The machine allows to carry out experiments with the use of lubricants, which makes it possible to use it not only for research of tribological properties of materials, but also for investigation of various lubricants that can reduce friction and wear of the parts [24,25].

The upper sample rotation speed without the load is adjustable up to 2500 rpm, the load on the samples can be varied from 50 to 1000 N [26].

4. EXPERIMENTAL RESULTS

Samples for the experimental research were made of various PLA plastics with different filling factor with the use of a 3D printer Picasso.

The samples for the first tribopair were made of plastic REC PLA with 100% filling. Experimental conditions: rotation speed is 300 rpm, starting load is 500 N. In Fig. 2, the samples for the first tribopair before the experiment are shown.

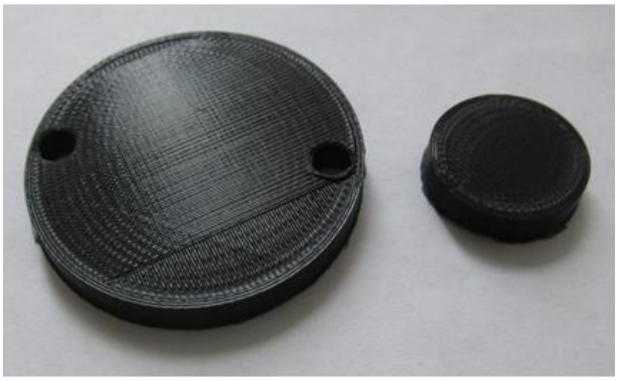


Fig. 2. Samples of REC PLA with 100 % filling.

Figure 3 shows the graph of friction torque versus time for the samples made of REC PLA with 100 % filling.

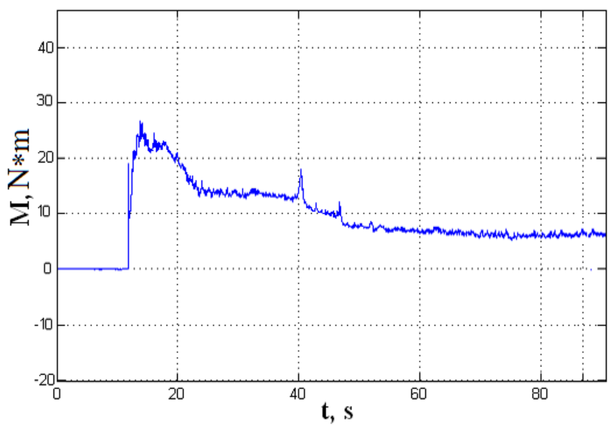


Fig. 3. Graph of friction torque versus time for REC PLA with 100 % filling.

It can be observed from the graph in Fig. 3 that at the beginning of the experiment friction torque changed sharply, which is connected with the beginning of the process of running-in in the tribopair due to plastic flow of the samples.

In Figures 4 and 5, respectively, the graphs of the temperature in the contact area and friction coefficient versus time of the experiment are presented.

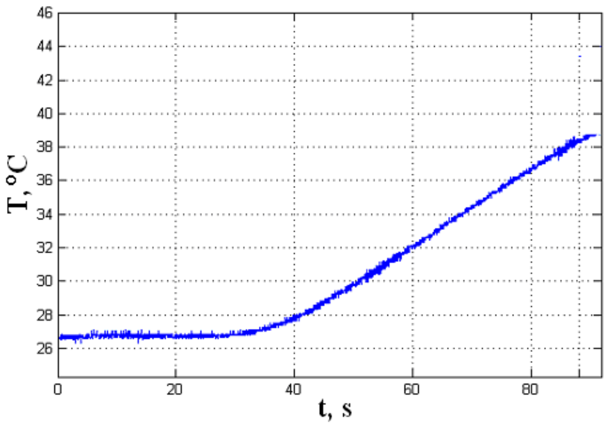


Fig. 4. Graph of the temperature in the contact area versus time of the experiment.

It can be seen from the graph in Fig. 4 that after approximately 40 seconds of the friction process the temperature in the contact area starts to rise. This is due to the jump of the friction torque, as well as the partial reflow of the material at the points of the real contact.

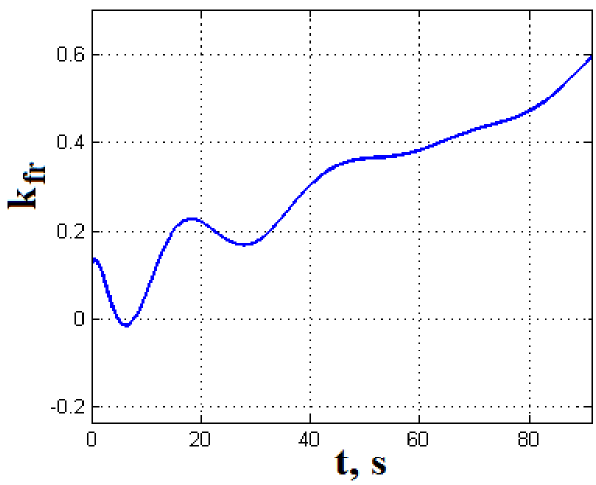
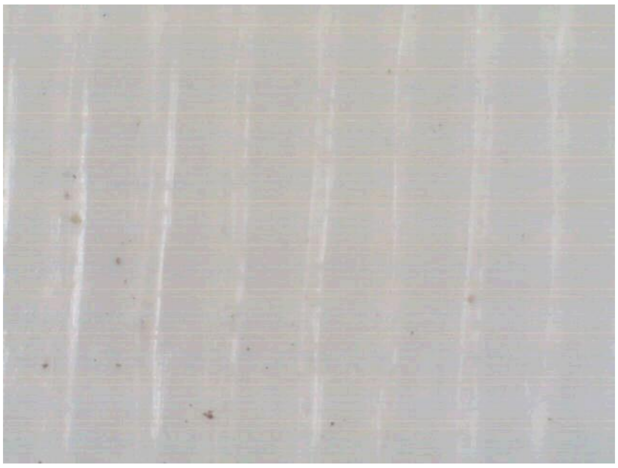


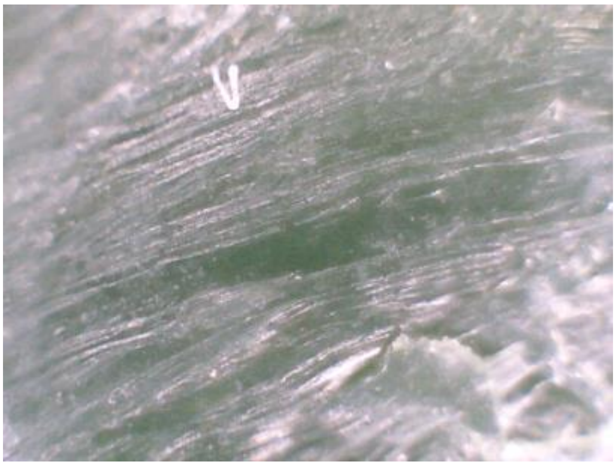
Fig. 5. Graph of the friction coefficient versus time.

It can be noticed from the graph in Fig. 5 that the maximum value of friction coefficient is 0.6. It is observed at the end of the experiment. The presence of extremum points on the graph is explained by the considerable plastic flow of the samples, as well as by the appearance and destruction of molecular cross-links between the samples.

Figure 6 shows the photographs of the surfaces of the samples before (Fig. 6, a) and after (Fig. 6, b) the experiment.



a)



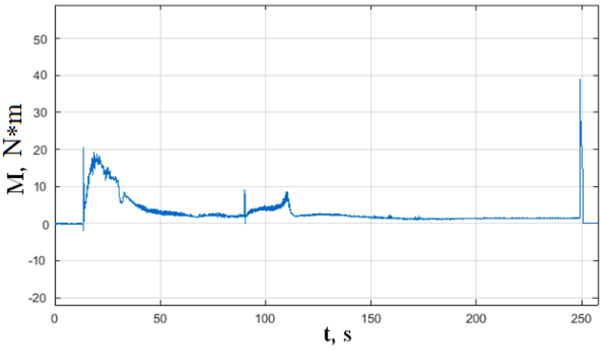
b)

Fig. 6. Photographs of the surface of the sample before (a) and after (b) the experiment (magnification is 88x).

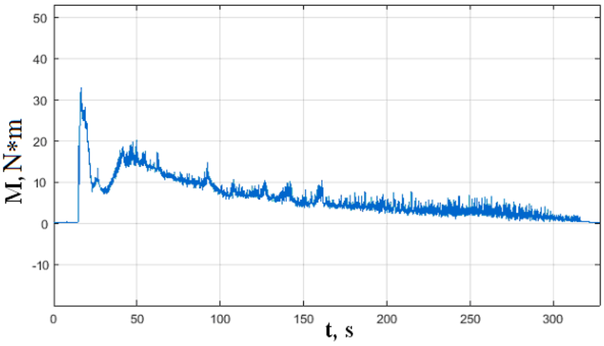
In Figure 6b, the areas of scoring and fusion of the surface are clearly visible.

The second set of experiments is devoted to the research of the tribopairs made of REC PLA with two different filling factors: 75 % and 100 %. The sample with 100 % filling has different layers' orientation from the sample investigated in the first set of experiments. Experimental conditions are the following: rotation speed is 300 rpm, the starting load is 250 N.

In Figure 7, the graphs of the friction torque versus time for two samples are shown.



a)

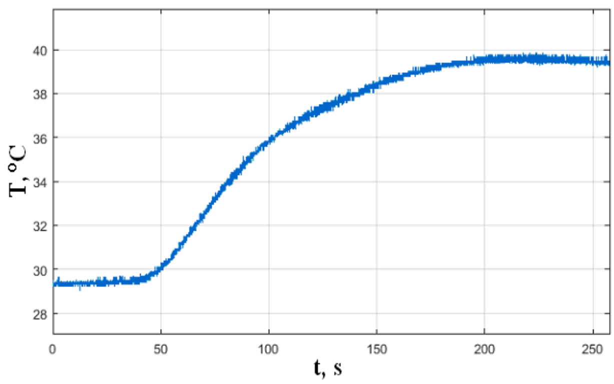


b)

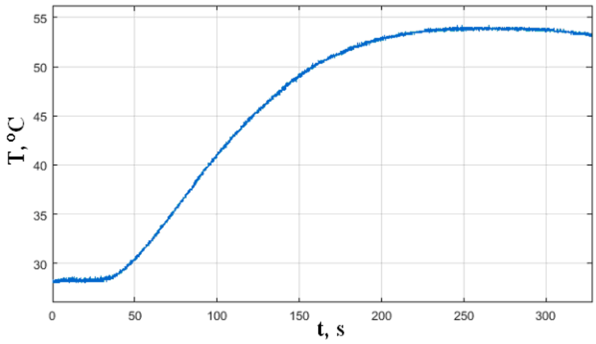
Fig. 7. Graphs of the friction torque versus time: a) for the sample with 75 % filling; b) for the sample with 100 % filling.

In Figure 7 a, the results for the sample with 75 % filling is presented. Figure 7 b shows the results for the sample with 100 % filling. It can be seen in Fig. 7 that the friction torque for the samples with 100 % filling after running-in changes smoothly, which is due to the more regular surface of the samples.

In Figure 8, the graphs of the temperature in the contact area versus time for the samples made of REC PLA with 75 % and 100 % filling are shown.



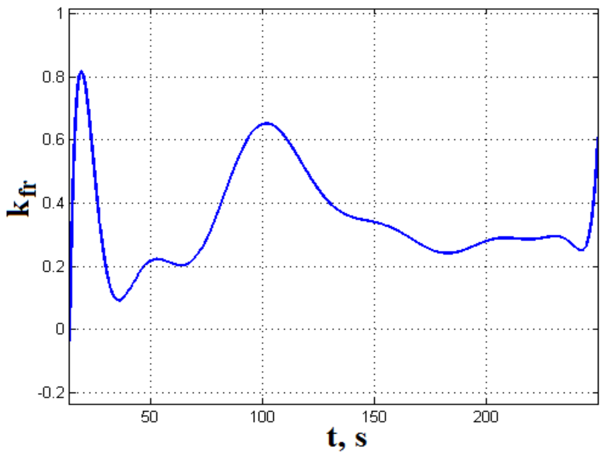
a)



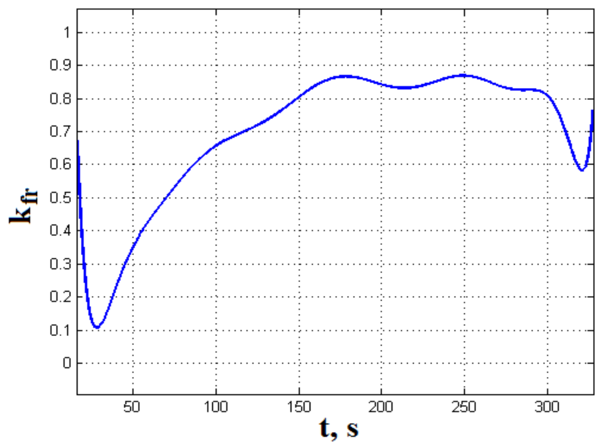
b)

Fig. 8. Graphs of the temperature in the contact area versus time: a) for the sample with 75 % filling; b) for the sample with 100 % filling.

It can be seen from the graph in Fig. 8 that the temperature in the contact area is gradually increasing, which indicates the absence of scuffing in the tribopair. For the sample with 100 % filling, the temperature in the contact area is higher, which is apparently due to a greater number of points of real contact in the tribopair.



a)



b)

Fig. 9. Graphs of friction coefficient versus time: a) for the sample with 75 % filling; b) for the sample with 100 % filling.

In Figure 9, the graphs of friction coefficient versus time for the samples with 75 % (a) and 100 % (b) filling are presented. It can be seen from the graph in Fig. 9 that friction coefficient for the sample with the filling factor 75 % has extremum points, which, apparently, is due to the porosity of the material. When the surface layer is abraded, the contact is between inner layers of the material. These inner layers have the porosity that is different from the porosity of the surface layer. Friction coefficient for the sample with 100 % filling changed more smoothly during the experiment. At the beginning of the experiment, friction coefficient decreased, which is due to the process of plastic flow in the tribopair. After that, friction coefficient increased, which is due to wear of the surface layers of the sample.

Figure 10 shows the photographs of the samples made of REC PLA with the filling factors 75 % (Fig. 10a) and 100 % (Fig. 10b) after the experiments.

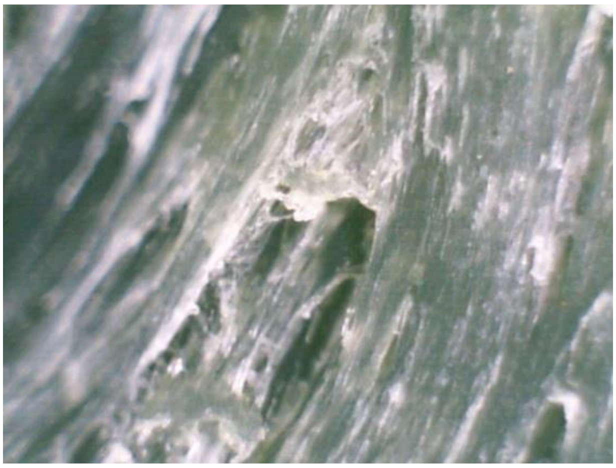
a)

b)

Fig. 10. Photographs of the samples made of REC PLA with a) 75 % and b) 100 % filling after the experiments.

It can be observed from the figure 10 that a sample with 75% filling has more uneven wear than a sample with 100% filling. This is due to the greater porosity of the sample.

Figure 11 shows the photographs of the surface of the samples after the experiment.



a)

b)

Fig. 11. Photographs of the surfaces of REC PLA samples with a) 75 % and b) 100 % filling after the experiments (Magnification is 88x).

In Figure 11, the areas of plastic flow and reflow of the material surface in the contact area can be noticed.

5. CONCLUSION

Experiments have shown that the tribological properties of the tribopairs made of plastics for 3D printing depend on the filling factor. The presence of plastic flow in the contact area increases friction coefficient; and the temperature in the contact area exceeds the melting point of the material. Porosity of the material has a significant influence on the process of friction and wear of the samples.

Friction coefficient in the tribopair with 100 % filling changes smoothly, which makes it possible to predict the behaviour of the tribopair more accurately. The results of the research allow us to make a conclusion that it is preferable to use parts with 100 % filling for design of tribopairs in mechanisms and systems. In future work, it is of interest to investigate the influence of layers' orientation on the tribological properties of 3D printed parts made of PLA and ABS.

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