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TRIBOLOGICAL PROPERTIES OF THERMOPLASTIC ELASTOMER USED IN 3D PRINTING TECHNOLOGY

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Abstract. The use of thermoplastic elastomers (TPE) in 3D printing technology enables the use of this technology to produce prototype seals with an unusual shape or design solution. Tribological tests were carried out on a pin-on-disc test stand. The influence of contact pressure and sliding velocity on the friction coefficient of the TPE-steel friction pair under mixed lubrication conditions was analyzed. Based on the obtained tribological test results, it was found that the coefficient of friction of the thermoplastic TPE elastomer on steel in the presence of hydraulic oil (mixed lubrication) at a sliding velocity below 1 m/s does not exceed μ = 0.25. The obtained friction coefficient values are comparable to the results for other elastomeric materials used for technical seals. It was found that the influence of contact pressure on the value of the friction coefficient in the tested friction pairs is varied and depends, for example, on the sliding velocity. It was recommended to carry out research on the assessment of durability (wear intensity) and structure (porosity) of the material in elements manufactured using 3D printing to obtain full knowledge of the possibility of using these materials in the area of technical aircraft seals.

Keywords: thermoplastic elastomers (TPE), wear, friction, 3d printing, aircraft seals.

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1. Introduction

3D printing technology is considered one of the most dynamically developing manufacturing technologies in recent times. Starting from home applications, manufacturing spare parts or everyday use, to printing details from titanium and aluminium, sliding bearings, gears, etc. This technology is used not only in the production of consumer products but also in medicine, automotive and many other sectors to create prototypes, moulds and versions of final products. 3D printing technology is very widespread, and its importance has become particularly visible now in applications for military purposes in the army. Parts of drones, airplanes, and even entire devices are printed (Garcia-Gascon et al., 2022). In space, the use of 3D printers can also be seen to print consumable parts, which delivery to the space station is more expensive than the raw materials for printing and often impossible on the required date (Bourseau et al., 2023). 3D printing has revolutionized the processing of biomaterials, enabling the construction of complex structures with high resolution and precision. Various biomaterials have been produced using 3D printing, including polymers, hydrogels, ceramics, composites and metals (Bhatti & Singh, 2023).

Additive technologies have been known since the 1980s. It was then that the possibilities of this technology were first presented by Pierre A. L. Ciraud, laying the foundations for the first type of popularly called 3D printing. In 1984, he presented a method of producing any geometric shapes by sintering powder fed through a feeder at precisely defined points in the working field (Ślusarczyk, 2017). This method is today called SLS – Selective Laser Sintering.

Recent years have brought significant development of the FFF (Kujawa et al., 2013) – Fused Filament Fabrication technology, which has significantly resulted in a drop in the prices of both machines for this process and the semi-finished product – a plastic wire with a precisely defined diameter. This method involves feeding molten plastic through the so-called extruder that moves along a programmed path, feeding material at specific points, layer by layer, building the desired detail. As the prices of 3D printing machines decreased and the method developed, users of this technology began to place higher and higher demands on the materials used in this process. Print density, percentage infill options and additives began to be analyzed (Bagheri et al., 2022). Currently, in addition to standard polymer materials for 3D printing, such as ABS copolymer, polylactide (PLA) or high-impact polystyrene (HIPS) (Igus, n.d.-a), highly flexible materials are also used, such as thermoplastic elastomer (TPE), e.g. FiberFlex 40D (Igus, n.d.-a), which allows the printing of elastically deformable machine elements. This means it is possible to use 3D printing technology to produce individual seals with complex geometric shapes as well as unusual seals in prototype devices. In such a case, it seems necessary to know the mechanical and tribological properties of the materials used in sealing, as for other materials (Leśniewski, 2009) – knowledge of these features allows predicting the behaviour of elements, as well as the possibility of using various equations/dependencies to determine effectiveness or efficiency (Kim et al., 2020). Both producers and researchers focus their attention on the mechanical properties of materials (Igus, n.d.-a) and elements manufactured by the discussed method, and in particular on research on the impact of technological parameters on the mechanical properties of products. Few publications concern research on friction and wear of polymer materials used in 3D printing. The results presented there concern primarily basic materials such as PLA (Grygier et al., 2022), ABS (Murashima et al., 2017; Perepelkina et al., 2017) or special materials based on polyamide PA (Igus, n.d.-b) used for sliding elements of machines. The influence of 3D printing technological parameters on the tribological properties of these materials is most often determined (Dawoud et al., 2015; Hong et al., 2017). However, there is no presentation of tribological tests of elastomeric materials used in 3D printing, carried out in the presence of various lubricants.

The aim of this study is to present the tribological characteristics of the TPE thermoplastic elastomer that cooperates slidingly with steel. The results of the presented test concern friction resistance in the presence of typical hydraulic mineral oil during mixed lubrication, depending on the sliding velocity and contact pressure. The presence of a lubricant meant that for most measurement points, the amount of wear of the polymer material was immeasurable at the assumed friction distance. Since 3D printing technology is generally used to produce prototypes of devices for which high durability is not necessarily important, the study focused on the analysis of friction resistance, which contributes to energy losses and the heating of friction elements. This is particularly important in the case of thermoplastic materials, whose properties are strongly temperature-dependent. Knowledge of these properties is as important as the construction of mathematical models (Leśniewski & Krawiec, 2006) or other equations that allow determining and predicting the durability or efficiency of machines (Kim et al., 2020).

2. Research of the kinetic friction coefficient

2.1. Research method

Kinetic friction tests for the polymer-steel combination were carried out on the T-01 tribotester (pin-on-disc type) produced by the Łukasiewicz Research Network – Institute of Operational Technology in Radom. The device diagram is shown in Figure 1. The system is powered by an AC motor, and an inverter is used to regulate its speed. The drive is transferred from the engine to the rotating spindle (4) thanks to the gearbox.

The polymer sample in the form of a pin (1) with dimensions φ8x5 mm was mounted in the frame (2), and the steel counter-element in the form of a disc (3) rotated at a set speed *n* [rpm] so that the relative sliding velocity had the assumed value *v*. The load was applied by weights (9) causing the sample to press against the counter-element. The dead weight of the arm and the sample and frame is balanced by the counterweight (8) so that the only pressure exerted on the sample comes from the weights (9). When the steel disk (3) begins to rotate, the frictional force between the disk and the sample generates a torque that tries to rotate the arm (7) around the axis of the bearings (11). Thanks to the bearings (11), the arm can rotate vertically and horizontally. However, the rotation is stopped by a force sensor (10) placed along the direction of the friction force. In this way, the pressure force of the

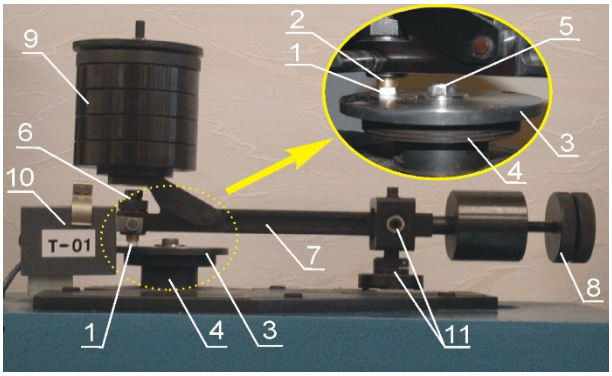

Figure 1. Tribotester pin-on-disc for tribological tests (Capanidis & Wieleba, 2003): 1 – polymer sample, 2 – frame, 3 – steel counter-element, 4 – spindle, 5 – fastening screw, 6 – clamping nut, 7 – arm, 8 – counterweight, 9 – weights, 10 – force sensor, 11 – bearings enabling rotation of the arm 7

Figure 2. The method of lubrication – felt material touching counter-element during the experiment

arm on the force sensor is equal in value to the friction force between the sample and the counter-element. The friction force F_T was measured by a force sensor (10), connected to the recording system.

Tribological tests were carried out under mixed lubrication conditions in the presence of Hydrol LHM-HLP 68 hydraulic oil. The oil was distributed on the surface of a rotating steel disc using a soaked felt element. The lubrication method is shown in Figure 2.

2.2. Materials used for research

The following materials were used to achieve the goals of this study:

- Polymer test samples were made of FiberFlex 40D thermoplastic elastomer (TPE) (Igus, n.d.-a). The printing temperature was 220 °C, the table temperature was 70 °C, and the heating temperature after printing was 110 °C. The FiberFlex 40D filament allows you to print an element quickly and cheaply with high impact strength and resistance to low temperatures. It is also characterized by high chemical and abrasion resistance. It has a hardness of 40D on the Shore scale and allows printing at a speed of 45 mm/s. The filament is characterized by an elongation of 680%. It is used for the production of rubber parts (seals, often bent elements), flexible elements such as hinges, phone cases and housings, toy elements (tires, rubber figures) and jewellery (bands).
- The disc, which was a counter-element to the polymer sample during tribological tests, was made of C45 steel with a hardness of 42 HRC and a surface roughness of $Ra \approx 0.5$ µm.
- Hydrol LHM/HLP 68 hydraulic oil was spread on the surface of the rotating steel disc using a soaked felt element. This oil is intended mainly for use in highly loaded power transmission systems and hydraulic drive and control systems, i.e. hydraulic transmissions, regulating and steering mechanisms and other similar devices in which difficult working conditions occur and there is an increased ambient temperature and humidity. This oil is produced based on high-quality mineral base oils and a package of enriching additives improving anti-wear, anti-corrosion and antioxidant properties. Quality class according to ISO 11158 – HM, viscosity: ISO VG: 68.

2.3. Conditions of conducting the experiment

The experiment was carried out in conditions reflecting the operating area of seals of elements used in the aviation and mining industries, i.e. gears and control mechanisms. The tests were carried out under the following friction conditions:

- average contact pressure p = 0.2–0.8 MPa,
- sliding velocity v = 0.5–1.5 m/s (159–477 rpm)
- ambient temperature T_o = 24 °C,
- friction conditions: mixed lubrication in the presence of Hydrol LHM-HLP 68 hydraulic oil.

3. Results

A rotatable plan was used to carry out the experiment (Capanidis, 2007; Kukiełka, 2002; Mańczak, 1976) at five levels of values for two independent variables (p, v). The test results are presented in Table 1.

Table 1. Results of tribological tests of the TPE elastomer during friction on steel – measured and calculated values of the friction coefficient (mixed lubrication, T_o = 24 °C)

No	p [MPa]	v [m/s]	μ	$\mu_{(calculated)}$
1	0.288	0.646	0.174	0.164
2	0.200	1.000	0.219	0.244
3	0.500	0.500	0.184	0.184
4	0.288	1.354	0.369	0.330
5	0.712	0.646	0.209	0.206
6	0.500	1.000	0.200	0.196
7	0.500	1.000	0.213	0.196
8	0.500	1.000	0.185	0.196
9	0.500	1.000	0.200	0.196
10	0.500	1.000	0.180	0.196
11	0.500	1.500	0.246	0.287
12	0.800	1.000	0.156	0.171
13	0.712	1.354	0.217	0.186

In order to describe the research results obtained in the rotatable plan, regression functions of the measured output values were used in the form of a second-order polynomial for two variables (Capanidis, 2007; Mańczak, 1976):

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_1^2 + a_4X_2^2 + a_5X_1X_2, \quad (1)$$

where: a_0, ..., a_5 – polynomial coefficients, X_1, X_2 – variables (p, v).

Polynomial coefficients were determined using the least squares method. The obtained functions were subjected to statistical evaluation (Kukiełka, 2002; Mańczak, 1976), including the determination of the value of the multidimensional correlation coefficient R and the value of the standard deviation, as well as the significance test F. This test is used to verify the hypothesis about the equality of variances of the examined variable in two populations. The values of the regression function coefficients and their statistical evaluation are presented in Table 2. This function was then used to draw spatial and contour graphs of changes in the friction coefficient µ depending on the pressure p and velocity v, which facilitates the analysis of the impact of these parameters on friction resistance. The analysis of both these parameters (p, v) simultaneously allows for a more accurate determination of the friction and wear parameters (Leśniewski, 2019).

The course of the friction coefficient value depending on changes in the value of contact pressure p and sliding velocity v during mixed lubrication of TPE elastomer on steel is presented in the form of a regression function graph in Figure 3.

Table 2. Regression function describing the coefficient of friction of the TPE elastomer on steel and its statistical evaluation

Regression function coefficients			Statistical evaluation of functions
	Y = μ(calculated)		Standard deviation σ = 0.0526
a_0	0.03493	+	
a_1	0.36807	*X1+	Correlation coefficient R = 0.9085
a_2	0.09509	*X2+	
a_3	0.13414	*X1*X1+	Test F = 6.62 > $F_{critical}$ (for α = 0.01 $F_{critical}$ = 5.67)
a_4	0.15964	*X2*X2+	
a_5	–0.62311	*X1*X2	

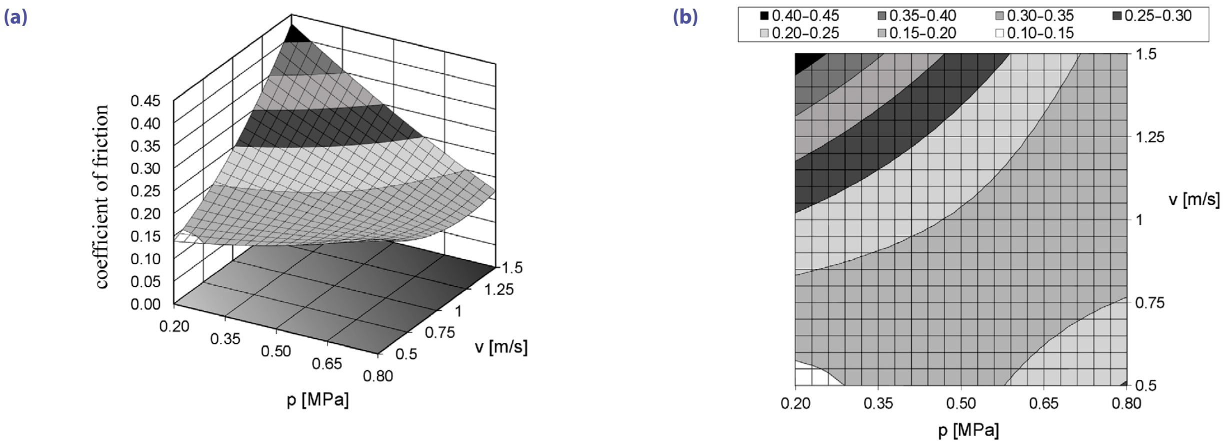

Figure 3. The effect of contact pressure *p* and sliding velocity *v* on the friction coefficient of elastomer TPE – steel couple in mixed lubrication conditions

The lowest friction resistance of the tested sliding node occurs at a contact pressure *p* not exceeding 0.5 MPa and a sliding velocity *v* up to 0.8 m/s. Increasing the contact pressure between the sliding elements at low sliding velocity contributes to a slight increase in the friction coefficient. In turn, at higher sliding velocity, increasing the pressure reduces the friction coefficient. The reasons for this phenomenon can be found in the reduction of oil viscosity and better lubrication of the friction surfaces. This is related to the significant heating of the interacting elements as a result of friction and an increase in their temperature (including the oil). The energy dissipated by friction as heat is approximately proportional to the product *pv*. This effect is not visible at low velocity, probably due to the significant share of adhesive interactions between the sliding materials.

4. Conclusions

The use of elastomeric polymers in 3D printing technology enables the use of this technology to produce prototype seals with an unusual shape or design solution. Tribological tests carried out on the friction of TPE thermoplastic elastomer on steel in the presence of hydraulic oil (mixed lubrication) confirmed the possibility of using this material in the area of prototype motion seals. The research results made it possible to formulate the following conclusions and observations:

- The coefficient of friction of the TPE thermoplastic elastomer on steel in the presence of hydraulic oil (mixed lubrication) at a sliding velocity below 1 m/s does not exceed μ = 0.25. The obtained values of the friction coefficient in similar conditions are comparable to other elastomeric materials used for technical seals.
- The impact of contact pressure on the value of the friction coefficient is varied and depends, among others, on sliding velocity. At low velocity (v < 0.8 m/s), increasing the contact pressure contributes to an increase in the friction coefficient, while at higher sliding velocity (v > 0.8 m/s), increasing the contact pressure causes a decrease in the friction coefficient. This is probably caused by an increase in the temperature of the oil and a decrease in its viscosity.

The conducted research concerned determining the influence of basic movement parameters, i.e. pressure and sliding velocity on the value of the coefficient of friction of the TPE thermoplastic elastomer on steel. To fully understand the possibility of using this material in the area of motion seals, durability tests (wear intensity) as well as the tightness of the material structure in elements manufactured using 3D printing technology should be carried out.

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Author contributions

Conceptualization and methodology: TL, WW and MO; investigation: TL and WW; resources: TL, TA and KB; data curation: JK; writing – original draft preparation: WW and TL; writing – review and editing: JK; visualization: WW and TL; supervision: TL. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare no conflict of interest.

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