Tomasz KOZIOR[*], Czesław KUNDERA[*]

ASSESSMENT OF TRIBOLOGICAL PROPERTIES OF POLYMERS USED IN ADDITIVE TECHNOLOGIES SLS AND PJM

OCENA WŁAŚCIWOŚCI TRIBOLOGICZNYCH WYBRANYCH POLIMERÓW WYKORZYSTYWANYCH W TECHNOLOGIACH PRZYROSTOWYCH SLS I PJM

Key words:

SLS, PJM, Additive Technologies, Formiga P100

Słowa kluczowe:

SLS, PJM, Technologie Przyrostowe, Formiga P100

Abstract

The paper presents preliminary results of tribological research on materials used in two additive technologies photo-curing polymer resin PJM and selective laser sintering of polyamide powders SLS. A Tribometer T-15 type ring-disk was used to determine the impact of technological parameters, e.g., printing direction and building layer thickness on the selected tribological properties and wear processes for elements generally used as machine parts.

[*] Kielce University of Technology, Faculty of Mechatronics Mechanical Engineering, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland.

INTRODUCTION

The dynamic development of mechanisms of precision machinery, e.g., technical active seals, sleeve bearings, or motor connections of machines puts extremely high requirements on the reduction of friction and wear processes. Tribological processes occurring in the friction area determine the reliability and durability of such devices and have a direct impact on the proper work of the object **[L. 1, 2]**. In conventional manufacturing methods, the tribological properties of the materials are much easier to determine because of the isotropy in mechanical properties and their structure. Problems of durability arise when we are using additive technologies to manufacturing end-used parts exposed to wear without additional finishing operations, i.e. grinding, and polishing.

Additive manufacturing technologies are based on a layer manufacturing of physical models directly from a 3D three-dimensional solid model **[L. 3]**. The use of three-dimensional models makes the whole process of production much more flexible and competitive in relation to the conventional manufacturing technologies. Any design changes can be implemented quickly, without the need to setup technological machines, such as machining tools or forging dies. Because of the layer construction of the models, it is possible to produce end-used components, where: it is difficult or impossible using traditional technologies. With the development of additive technologies and improved accuracy, designers increasingly started using the above-mentioned technologies for the production of fully functional co-operating machine elements, i.e. seals, bearings, and mechanical connection elements **[L. 4]**. Most additive technologies, especially those where: plastics are used as input materials, present anisotropy in mechanical properties and accuracy. This phenomenon mainly depends on the technological parameters and placement models on the building platform. This problem causes that the wear process of machine parts produced by using "Three Dimensional Printing" can be different for the same element.

Selected tribological properties of materials used in SLS technology were described in **[L. 5]**, where: the authors used a tribometer (type ring-pin) to determined basic tribological parameters of the friction elements. Samples were manufactured using bronze powder (EOSINT M Cu 3201). Countersamples were made by using polyamide with glass fibre. The research was carried out in a heating chamber with controlled temperature.

This paper describes the preliminary study of the process of friction in a face contact surface of the ring-and-disk, using a T-15 tribometer. Rings (samples) for tests were made from different materials used in two commonly used additive technologies: PJM and SLS. The aim of the study was to determine the effect of process parameters, i.e. printing direction and building layer thickness on the wear processes of the rings (samples) and the coefficient of friction in a sliding connection.

TECHNOLOGY

In the study, two types of modern additive technologies that use input polymeric materials were used: photo-curing polymer resin PJM, and selective laser sintering SLS. For PJM technology, a Connex 350 machine (Stratasys Company) and VeroWhite material were used. In SLS technology, to prepare samples, Formiga P100 (EOS company) and material PA 2200 were used. The mechanical properties of the materials used to build the samples are shown in **Table 1 [L. 6, 7]**. The printing process of samples and tribological research were carried out at the Kielce University of Technology in the Laboratory of Unconventional Manufacturing Technology.

Table 1. Mechanical properties of materials: PA 2200 / Vero White [L. 6, 7]
Tabela 1. Właściwości mechaniczne materiałów: PA 2200/VeroWhite **[L. 6, 7]**

Mechanical Properties	Value	Unit	Standard
Young's modulus	1700/2495	MPa	EN ISO 527 / ASTM D-638
Notched Izod (23°C)	4.4/24	kJ/m^2	ISO 180/1A / ASTM D-256
Shore's hardness	75/83	-	ISO 868 / Scala D
Density	0.930/1.18	g/cm^3	EOS method / ASTM D792
Water absorption	1/1.5	%	D-570-98 24hr

Selective Laser Sintering SLS

SLS technology is one of the most commonly used method of rapid prototyping. In this technology, polyamide powder with a grain of a diameter equal to 0.056 mm is distributed on the working platform by a machine arm. Then a focused beam of a CO_2 laser by scanning a selected cross section of the model is sintered building a layer and combining it with the previously made surface. The process of building and cooling takes place in an atmosphere of inert gas (nitrogen) to prevent oxidation. After completion of the sintering process, a working platform is lowered by a value equal to the thickness of one layer, which is minimally 0.1 mm for PA 2200 material in SLS technology **[L. 8]**. Due to the used powder as a building material, SLS technology allows building models of very complex internal shapes. The powder, which has not been used during production, can be removed from the model in a cleaning stage by compressed air.

Photo-curing Polymer Resin PJM

PolyJet Matrix Technology (PJM) **[L. 4]** is based on photo-curing liquid polymer resins by used UV light. In the building process, printing heads sprayed thin drops of liquid polymer resin in the selected cross section of the model. Then a UV lamp initiates the polymerization process by scanning the newly formed layer. The main technological parameter presented in this technology is layer thickness, which has a significant impact on the accuracy and mechanical properties. The minimum layer thickness for a "single" material is equal 0.016 mm and 0.03 mm for the mixtures of materials, "digital materials" **[L. 9, 10]**.

SAMPLES

The samples for tests were designed using CAD software SolidWorks 2016 in accordance to tribometer T-15 instructions. This device was designed and manufactured at the Institute for Sustainable Technologies – National Research Institute in Radom. The samples were made in 3 variants. The samples angles between the building platform and sample-working surface (friction) were equal to 0°, 45°, and 90°. In the case of the first type of samples prepared using SLS technology, the layer thickness was equal 0.1 mm, and for the second type the layer thickness was 0.2 mm. In the PJM technology, the layer thickness was equal 0.03 mm. The geometrical dimensions of the samples and their placement on the machine platform are shown in **Figures 1** and **2**. Printing parameters are shown in **Table 2**.

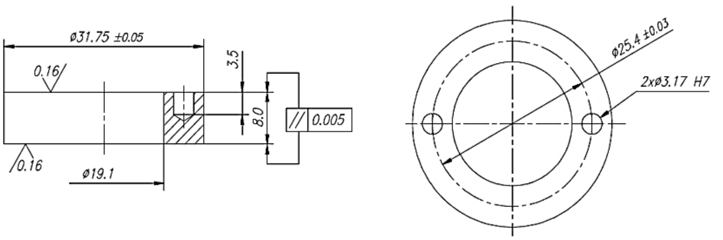


Fig. 1. Sample dimensions
Rys. 1. Wymiary badanych próbek

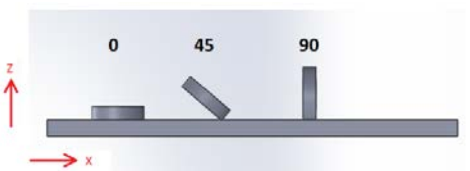


Fig. 2. Placement of samples on the machine platform
Rys. 2. Rozmieszczenie próbek na platformie maszyny

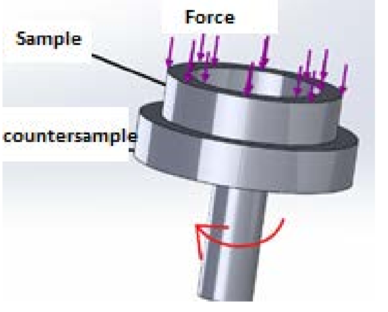
Table 2. Printing parameters
Tabela 2. Parametry „wydruku" próbek

Samples No.	Angle [°]	Layer thickness
1	0	0.1/0.2/0.03
2	45	0.1/0.2/0.03
3	90	0.1/0.2/0.03

METHODOLOGY OF THE RESEARCH

Tribological research was performed using a tribometer. The T-15 device consists of a testing machine, measurement and control systems, and a computer with software to analyse and record research results. The principle of T-15 work is shown in **Figure 3**. The rotating disc made of C45 steel is in contact with the fixed sample in a form of ring (**Fig. 1**), which is pressed by clamping arm with lever ratio of 3:1. During the research, samples can be loaded with a maximum force of 150 N.

a)



b)

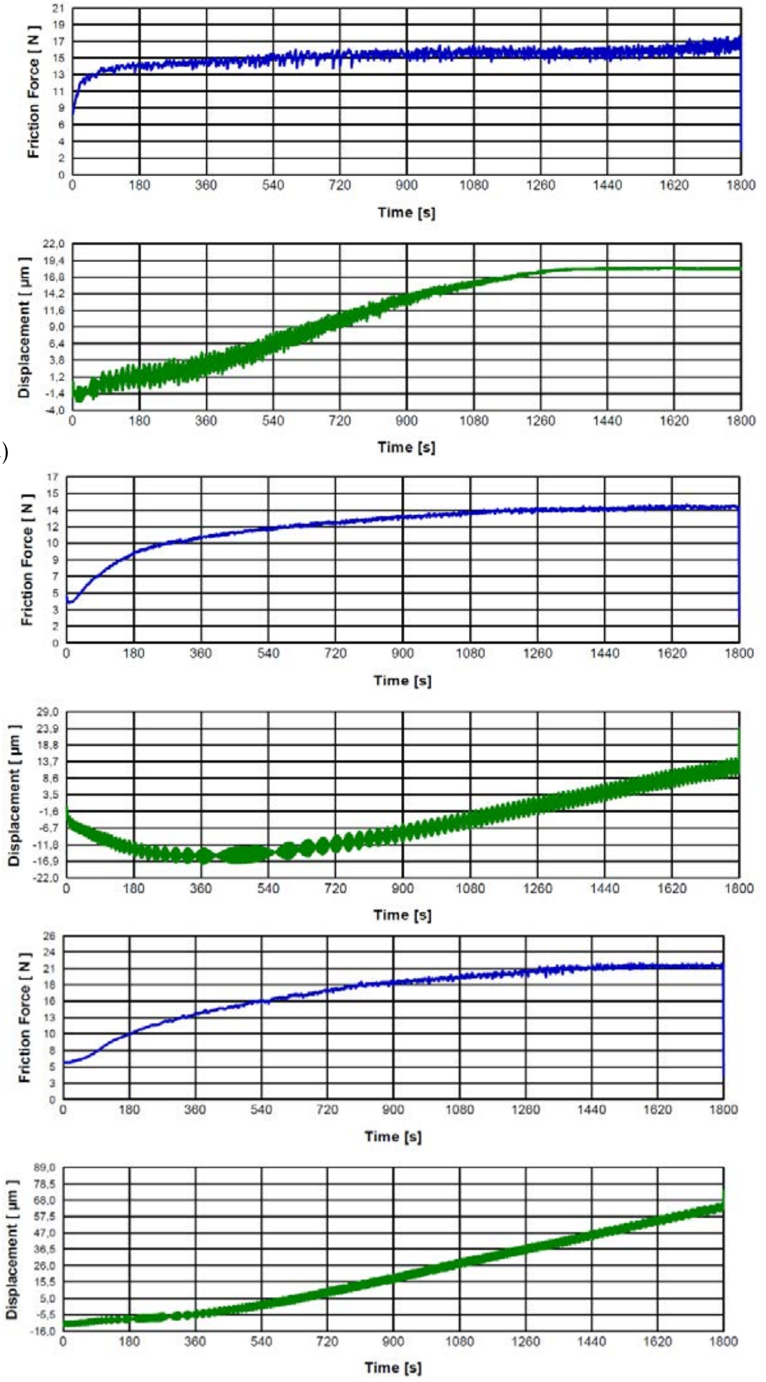
Fig. 3. Research device: a) Tester T-15, b) simplified tribological model
Rys. 3. Stanowisko badawcze: a) Tester T-15, b) uproszczony model tribologiczny

The apparatus allows one to measure: friction force, summary linear wear, temperature in the research chamber and near to the contact surface between sample and countersample. An additional advantage of the above-mentioned device is a closed chamber with adjustable temperature ranging from ambient temperature up to 200°C.

Research cycle parameters were determined separately for the samples made in SLS and PJM technology, due to the visible differences in the process of wear. For both technologies, the countersample speed was set at 150 [rpm**]**, and the test time was 1800 s. In the SLS technology, the loading force was equal to 150 N, and, for the PJM technology, the loading force was equal to 30 N. In both technologies, friction force, summary linear wear, and the temperature close to the friction contact surface were measured.

RESEARCH RESULTS

The test results are shown in **Figures 4–9** and **Tables 3–5**. In the case of SLS technology, the initial increase in friction force and its stabilization can be observed. In the PJM technology, the friction force remained at a similar level throughout the test. **Figures 4–6** show the test results obtained directly from the T-15 tester software.



a)

b)

c)

Fig. 4. SLS technology, layer thickness – 0.1 mm: a) 0°, b) 45°, and c) 90°

Rys. 4. Technologia SLS, grubość warstwy – 0,1 mm: a) 0°, b) 45°, c) 90°

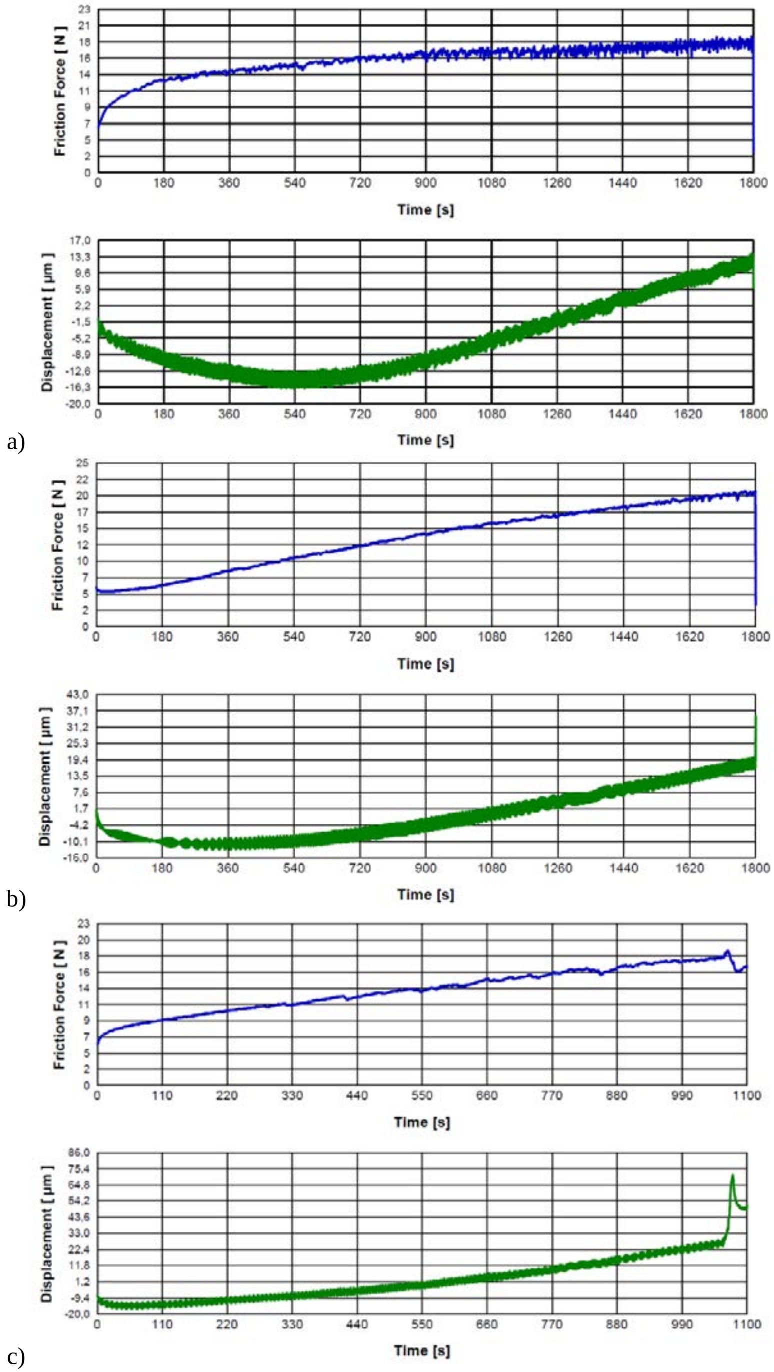
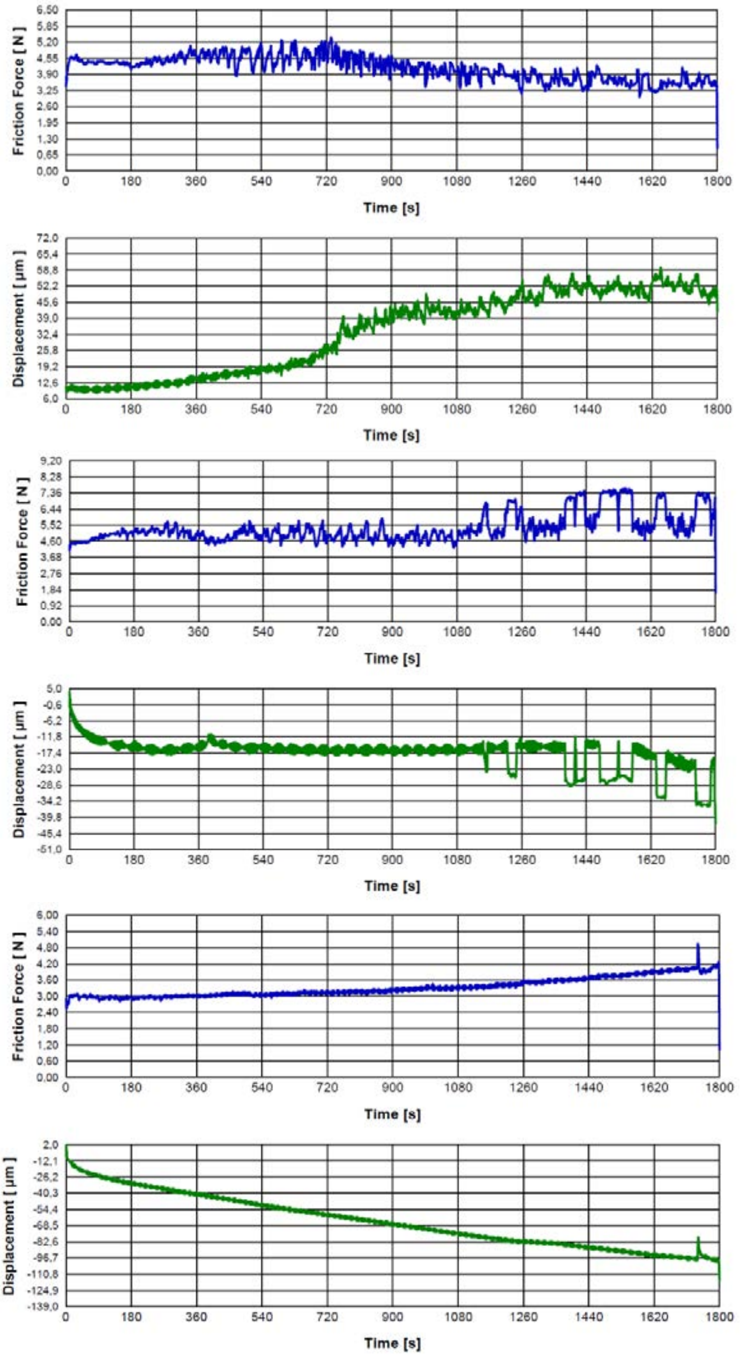


Fig. 5. SLS technology, layer thickness – 0.2 mm: a) 0°, b) 45°, and c) 90°

Rys. 5. Technologia SLS, grubość warstwy – 0,2 mm: a) 0°, b) 45°, c) 90°



a)

b)

c)

Fig. 6. PJM technology, layer thickness – 0.03 mm: a) 0°, b) 45°, and c) 90°

Rys. 6. Technologia PJM, grubość warstwy – 0,03 mm: a) 0°, b) 45°, c) 90°

Table 3. Maximum friction force [N]
Tabela 3. Maksymalna siła tarcia [N]

Samples No.	SLS 0.1 mm	SLS 0.2 mm	PJM 0.03 mm
1	17.4	19.3	5.23
2	14.2	20.6	7.48
3	21.8	18.7	4.93

Table 4. Maximum friction coefficient
Tabela 4. Maksymalny współczynnik tarcia

Samples No.	SLS 0.1 mm	SLS 0.2 mm	PJM 0.03 mm
1	0.116	0.128	0.174
2	0.095	0.137	0.249
3	0.145	0.125	0.164

Table 5. Linear wear of friction elements [µm]
Tabela 5. Zużycie liniowe pary ciernej [µm]

Samples No.	SLS 0.1 mm	SLS 0.2 mm	PJM 0.03 mm
1	2.6	16.8	0
2	17.2	12.4	35.75
3	12.3	16.3/1100s	115.75

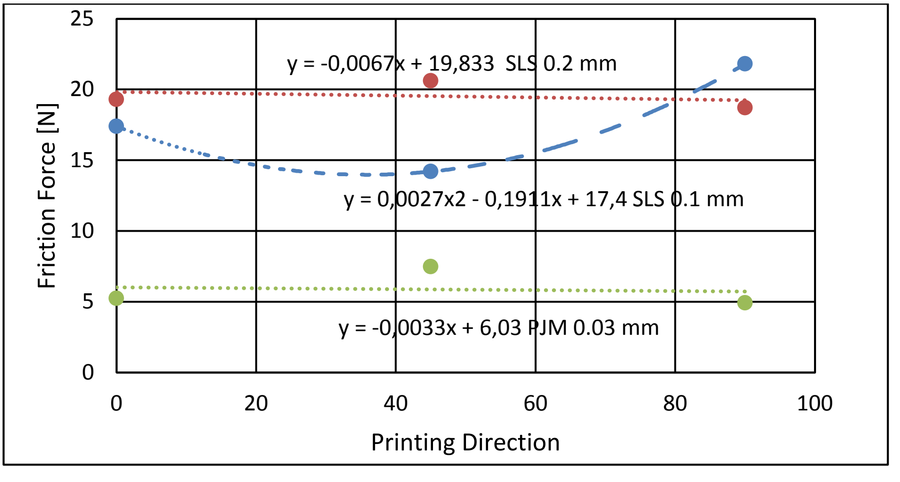


Fig. 7. Relation: friction force – printing direction
Rys. 7. Zależność: siła tarcia – kierunek wydruku

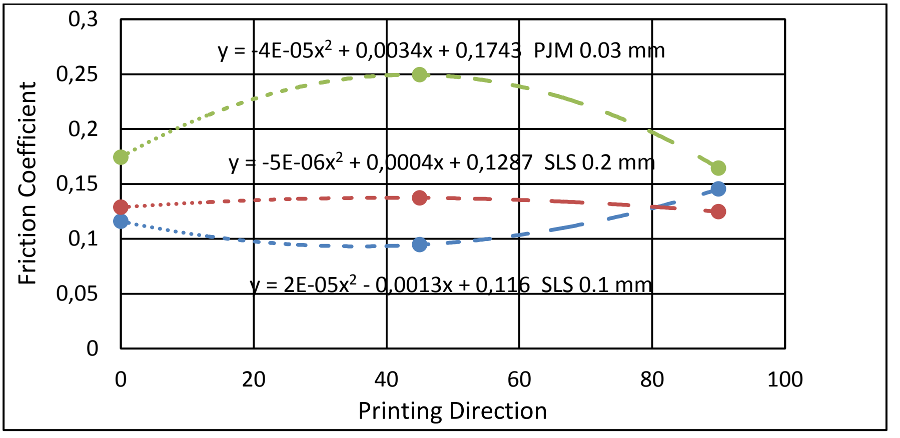


Fig. 8. Relation: friction coefficient – printing direction
Rys. 8. Zależność: współczynnika tarcia – kierunek wydruku

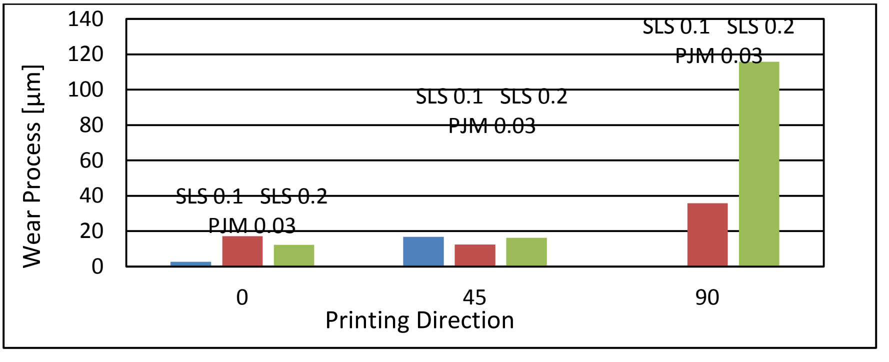


Fig. 9. Relation: wear value – printing direction
Rys. 9. Zależność: zużycie sumaryczne – kierunek wydruku

By analysing the research results, we can concluded that the location of the models on the building platform (printer) in SLS and PJM technologies has a significant impact in the process of the production of models exposed to wear processes, e.g., machine elements.

Samples manufactured by SLS technology are characterized by different tribological properties in comparison to the PJM technology. In polyamide samples, two stages of the friction are noticeable. The first is a normal wear process, which is independent of the printing direction. This stage takes about 600 seconds. The second stage is a noticeable reduction of wear processes and the increase in the formation wear products. In SLS technology, the temperature linear expansion of polyamide has a great impact on the wear processes. For SLS technology, the temperature increased by about 30°C during the test cycle. These phenomena affects the wear process, friction force, and the coefficient of friction. Sample No. 3 manufactured in SLS technology with layer thickness of 0.2 mm and the angle between building platform and wear surface of 90° has shown the weakest tribological properties. During the test cycle, after a period of time equal to 1100 s, the sample was destroyed. It could be caused by the weakest connection between layers and the placement of 90 degrees on the building platform. The same laser power for both layer thickness (0.1 and 0.2) probably was not inadequate for 0.2 layer thickness, which can cause the difference in the tribological research results. It means that laser power and speed should be recalculated for the new layer thickness.

In PJM technology for samples 2 and 3, one can distinguish only one characteristic, i.e. the wear increases in a linear function of time, and there is no stabilization after 1800 seconds. In the case of the placement of the samples of the building platform at an angle of 0 degrees during printing process, the process of wear is negligible, and a test cycle is similar to the samples made in the SLS technology.

In SLS technology, the lowest coefficient of friction is present in the sample at an angle of 45 degrees and a layer thickness of 0.1 mm. In the case of an increase or decrease in the building angle, the coefficient of friction increases. Samples made with a layer thickness of 0.2 mm present coefficients of friction at the same level regardless of the printing direction.

Samples made in PJM technology have shown the highest coefficient of friction for the angle of 45°. In case of an increase or decrease in the angle, the coefficient of friction decreases.

CONCLUSIONS

From the analyses of the research results of tribological tests on samples manufactured by both SLS and PJM technologies, the following general conclusions can be formed:

1) In SLS technology, the greatest wear process occurs in samples that had a placement angle of 45° and a layer thickness of 0.1 mm, and a placement angle of 0° and a layer thickness of 0.2 mm.
2) Layer thickness significantly influences the value of the coefficient of friction. The preferred variant for SLS technology, which had the lowest coefficient of friction, is when the samples are placed at 45° on the building platform, and the preferred variant for PJM technology is with a platform angle of 90°.
3) In PJM technology, the worst variant related to the wear process is where: the samples were inclined at an angle of 90 degrees to the building platform. The wear process in this variant is several times larger than in the other samples.
4) In the case of both technologies, a linear temperature rise in the friction zone is noticeable. In the case of SLS technology, after 1800s, the temperature

rose from 25°C to about 60°C. For PJM technology, the temperature rose from 25°C to about 35°C.

ACKNOWLEDGEMENTS

The study was conducted using research facilities purchased with EU funds in the framework of the 2007-2013 Development of Eastern Poland Operational Program, LABIN Project − Support for Innovative Research Facilities of the Kielce University of Technology in Kielce. Priority 1 – Innovative Economy, Measure 1.3 – Support for R&D Projects.

REFERENCES

1. Pawelec Z.: Charakterystyki tribologiczne kompozytów polimerowych w ruchu posuwisto-zwrotnym. Tribologia 3-2014.
2. Zwolak J., Kozik D., Kruczek B.: Badanie procesów zachodzących w sprzęgłach stosowanych w przekładniach zębatych power shift podczas sprzężenia ciernego. Tribologia 4-2015.
3. Leu M.C., Guo N.: Additive manufacturing: technology, applications and research needs. Frontiers of Mechanical Engineering, Vol. 8 Iss. 3, pp. 215-243, 2013.
4. Kundera Cz., Kozior T.: Assessment of the technological clearance in model of sliding bearing made by SLS technology. Mechanik, Vol. 2, pp. 345-354, 2015.
5. Seberstyen T., Takacs J., Tóth L., Franek F., Pauschitz A.: Tribological Aspects of Wear of Laser-Sintered Rapid Prototype Tools. Fundamentals of Tribology and Bridging the Gap Between the Macro and Micro/Nanoscales, Vol. 10, pp. 571-576, 2001.
6. EOS COMPANY.: Formiga P100 – User Manual, Monachium, 2008.
7. www.stratasys.com (available: 22.01.2016 r.)
8. Pilipović A., Valentan B., Brajlih T., Haramina T., Balić J., Kodvanj J., Sercer M., Drstvenśek I.: Influence of laser sintering parameters on mechanical properties of polymer products. International Conference on Additive Technologies ICAT, 2010.
9. Kundera Cz., Bochnia J.: Investigating the stress relaxation of photopolymer O-ring seal models. Rapid Prototyping Journal. Vol. 20, No. 6, pp. 533 – 540, 2014.
10. Chen Y., Zhezheng C.: Joint analysis in rapid fabrication of non-assembly mechanisms. Rapid Prototyping Journal, Vol. 17 No. 6, pp. 408 – 417, 2011.

Streszczenie

W pracy przedstawiono wstępne wyniki badań tribologicznych materiałów stosowanych w dwóch technologiach przyrostowych natrysku fotopolimeru PJM oraz selektywnym spiekaniu laserowym proszków poliamidowych SLS. Wykorzystano zestaw tribologiczny T-15 typu pierścień-tarcza w celu wyznaczenia wpływu parametrów technologicznych, tj. kierunku wydruku i grubości budowanej warstwy na wybrane właściwości tribologiczne oraz zużycie współpracujących elementów maszyn.