TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

THE INFLUENCE OF SOME FACTORS ON THE SIZE OF THE FRICTION COEFFICIENT IN THE CASE OF SOME TEST SAMPLES MADE OF POLYMERIC MATERIAL AND MANUFACTURED BY 3D PRINTING

Elisaveta CRĂCIUN, Andrei Marius MIHALACHE, Margareta COTEAȚĂ, Laurențiu SLĂTINEANU

Abstract:. *By changing the 3D printing conditions, it is possible to change the various physical-mechanical elements of the materials of the manufactured parts. A simple equipment was designed and materialized to determine the friction force generated when moving a test sample made of polylactic acid on a strip under a normal force of known magnitude. The experimental results were processed mathematically using specialized software. Empirical mathematical models were determined to highlight the influence exerted by eight input factors in the investigated process on the magnitude of the friction coefficient. It was found that the normal force and the sliding speed are the main factors that affect the value of the friction coefficient.*

Key words: *friction coefficient, experimental equipment, polylactic acid, influence factors, empirical mathematical model.*

1. INTRODUCTION

In the last two decades, polymer materials have been increasingly used in industry and other fields. As new polymeric materials are discovered and studied, it is found that they present some properties equal to or superior to those of metallic materials, such that such materials can have advantages in manufacturing, operation, and maintenance. There are situations where polymer parts have actually replaced metal parts.

Thus, Kerns considered that the arguments for replacing parts made of metallic materials with those made of polymeric materials are based on the reduction of the weight of the parts, the increase of the operating speed, or the improvement of other operating properties of the parts [1]. It is necessary to mention, however, that the increase in the operating speed is limited to a certain extent, due to the increase in the amount of heat released, which could negatively affect some properties of interest of the polymeric materials.

Processes by which parts can be manufactured from polymeric materials are injection molding, extrusion, thermoforming, spraying, stamping, cutting, welding, bonding, etc. [2, 3] and, in recent decades, 3D printing.

In the case of a part made of polymeric material, 3D printing involves the gradual formation using a filament of melted material and applied by taking into account predefined paths in order to finally arrive at a shape corresponding to that of a 3D model developed using design software.

It is found that other processes have been developed, analyzing in more detail the 3D printing processes of polymer mass parts apart from the one based on the use of a molten polymer material filament.

Fused filament fabrication (FFF) is a widespread 3D printing method due to its simplicity, relatively low costs, and versatility in using different types of thermoplastic materials. The method is applied in various fields, including rapid prototyping, but also in the production of household objects, toys, or customized components.

The main parameters that must be taken into account when determining the printing conditions are the diameter of the filament used, the printing speed, the material filling density of the part, the printing direction, the working temperature, the speed and solidification time, the type of material used as raw material, the paths traveled by the print head, etc. The values of the printing parameters can be set according to the requirements that the part must meet, more specifically, the production tolerances, the required mechanical properties, and the final roughness of the surfaces. It is found that the roughness, the density of the printed tracks, the diameter of the molten material wire, and the type of material directly influence some frictional properties of the parts in contact [4-9].

Thus, Chisiu et al. studied the effect of the printing direction on the printing force and the friction coefficient for systems involving sliding movements [4].

Fouly et al. considered the possibility of changing the properties of a material that can be used to make artificial implants, such as polylactic acid, by adding natural fillers using some substances extracted from corn cobs [5].

Roy used a factorial experimental plan design to investigate the influence of printing parameters on the wear and friction coefficient of materials such as ABS and PLA [6].

In the present work, the method called fused filament fabrication was preferred for the manufacture of samples necessary for the study of friction processes. A filament of polymeric material is heated to a temperature at which it becomes plastic and easy to shape. The heated material is then extruded through a print head, gradually generating a model designed in specialized 3D design software. The print head moves in a three-dimensional space and deposits the molten material layer by layer to arrive at the part with the desired shape. After the material has been deposited, it rapidly cools and solidifies, thus maintaining the shape of the previously generated object.

In the framework of experimental research carried out previously, in which a manual displacement of a sample pressed on a strip was resorted to, it was found that the magnitude of the frictional force can be influenced by the magnitude of the relative displacement speed between the bodies in contact [10].

The main of reason of the research whose results were presented in this article was that, starting from some previous results, it is possible to highlight the influence exerted by several factors on the size of the friction coefficient in the case of test samples made of polymeric materials and manufactured by 3D printing. To this end, a Taguchi L18 factorial experiment was used to identify empirical mathematical models. This model was supposed to provide information on the influence that eight input factors in the investigated process exert on the size of the friction coefficient, one of these eight factors being the relative movement speed between the bodies in contact. The experiment was carried out in laboratory conditions using simple equipment designed for this purpose.

2. INITIAL CONSIDERATIONS

The objective of the research, the results of which are presented in this paper, was to identify empirical mathematical models that highlight the influence of different factors on the size of the friction coefficient in the case of samples made of polylactic acid by 3D printing. It is known that the physical-mechanical properties of the materials incorporated in the parts made of polymeric materials manufactured by 3D printing can be significantly modified by acting on the values of specific parameters that define the conditions of 3D printing.

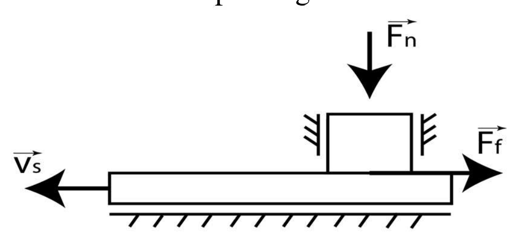

Fig.1. The principle scheme used in the experimental research.

For the experimental research, the principle scheme presented in Figure 1 was taken into account. It was used to move a cubic-shaped sample pressed on the upper surface of a strip with a normal force F_n, generated by a weight of a specified size. Knowing the size of the pull force F_f of the specimen, an evaluation of the

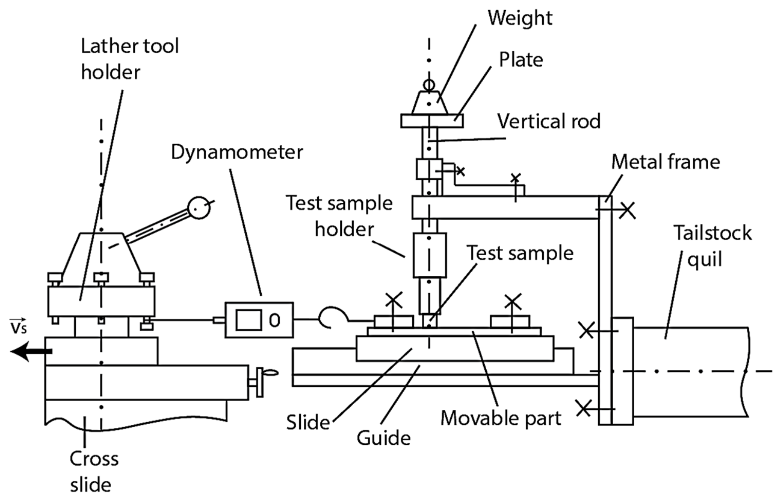

Fig. 2. Schematic representation of the equipment used in the experimental research.

size of the coefficient of friction μ was possible. As mentioned, previous research, however, has shown a certain dependence of the magnitude of the force F_f on the magnitude of the movement speed v_s of the test sample [10]. For this reason, the design of simple equipment was taken into consideration, which would ensure conditions for the change between certain limits of the speed of movement of the test sample.

It was appreciated that it is possible to change the speed v_s by using a universal lathe. It is known that on such a machine tool, different values of the feed rate can be obtained.

The main groups of factors capable of affecting the physical-mechanical properties of the test sample material and, therefore, the friction coefficient values are the chemical composition of the material used for printing the samples, the kinematic and dynamic characteristics of the movement of the test sample on a predetermined surface, the values of some parameters that characterize the process of printing.

As input factors in the investigated friction process, the test sample travel speed, the nature of the test sample material, the printing speed, the filling percentage of the test sample material, the thickness of the deposited layer, the magnitude of the normal force and the cooling conditions will therefore be considered.

3. EXPERIMENTAL CONDITIONS

As mentioned, the experimental research sought to identify empirical mathematical models that would highlight the intensity of the influence exerted by some factors on the magnitude of the friction coefficient μ in the case of test samples manufactured from polylactic acid by 3D printing. A schematic representation of the equipment used in the experimental research can be seen in Figure 2.

Intending to use the travel facilities provided by the feed motion of the apron of a universal lathe, experimental equipment adapted to an SNA 500X1000 type universal lathe was designed. In the case of lathes, in general, the feed rate is obtained as a product of the apron displacement per rotation of the main spindle with the rotation speed of the lathe main spindle.

Most of the components of the equipment can be placed on a metal frame that is mounted on the bushing corresponding to the spindle of the movable tailstock quill of the lathe. Thus, a bushing with balls is assembled on the metal frame, inside which a rod can move in a vertical direction. At the upper end of the frame, there is a plate on which a weight of known size is placed. This weight will contribute to the generation of the normal force F_n.

At the lower end of the rod, there is a bushing with a hole in which the 3D-printed polymer test sample can be located and clamped. A cubic test sample was considered, which would allow the use of surfaces characterized by different geometries due to the characteristics of the 3D printing process.

Under the action of the force F_n generated by the weight on the plate, the test sample is pressed on a short strip located on a sled of the equipment. Since the nature of the strip material may influence the magnitude of the friction force, it was proposed to use three strips of different materials, namely steel, polylactic acid (PLA), and high-impact polystyrene (HIPS).

Moving the slide on its guide is possible by ensuring a connection with the lathe tool holder on the apron of the universal lathe, using a cable for this purpose. The tool holder can move in a feed motion along with the lathe apron when the main spindle is driven in a rotary motion.

A digital dynamometer was placed between the equipment sled and the tool holder, which provides direct information on the value of the force with which the sled is pulled, i.e., the friction force F_f.

To reduce the possible influence exerted by friction between the various subassemblies of the equipment, a ball bushing was used to guide the rod vertically, and a device was used to locate and clamp the test sample on the slide of a ball guide. The experiments were conducted in accordance with the requirements of a Taguchi L18 factorial experiment with eight independent variables. One of these variables can take values across two levels, while the other seven independent variables will take values across three levels of variation. The use of a Taguchi L18 type experiment is related to the fact that, in general, such an experiment ensures obtaining acceptable empirical mathematical models from the point of view of their adequacy in relation to the experimental results, but starting from a minimum number of experimental tests. Another argument for using the Taguchi L18 type experiment is that it allows taking into account a relatively large number of input factors in the investigated process (8 factors).

Two different values were used for the moving speed v_s of the sled, accepting the hypothesis that the magnitude of the friction force F_f and, therefore, the coefficient of friction μ will have a monotonous variation (without maxima or minima) in relation to the change in the value of the speed v_s. The values of the velocity v_s were established by first performing some preliminary experimental tests.

As input factors in the investigated friction process, the moving speed v_s of the test sample support sled, the nature m of a couple of materials from which the test samples were made and the strip on which the specimen is pressed, the speed v_p of 3D printing, infill percent i, infill pattern i_p, layer thickness l, cooling conditions c were considered.

The values of the input factors in the friction process were entered in the first columns of Table 1. In this table, the coded value of the input factor size was mentioned first, according to the requirements of the Taguchi factorial experiment L18, but also the actual value used for each of the input factors in the form of a fraction.

Some explanations of the values of the input factors used in the development of experimental research are briefly presented below. Thus, 0% for the cooling conditions c means that no forced cooling of the test sample being generated is resorted to, judging that a natural cooling to the current temperature is sufficient. A value of 50% cooling c implies about half the operation of the cooling subsystem, which includes two fans attached to the extrusion nozzle, and a value of 100% requires a maximum intensity of the cooling process. Infill pattern i_p represents the density and design followed by the extrusion head for filling 3D printed test samples. In the framework of the research undertaken, from a wider range of infill pattern models, the grid (which gives the sample material strength and stability), gyroid (which provides the sample material with a certain hardness and flexibility), and lines (which leads to faster printing and less material consumption) were considered.

4. EXPERIMENTAL RESULTS AND THEIR PROCESSING

Software based on the least squares method was used to identify a mathematical model corresponding to the experimental results and process the experimental results (Table 1); this software was created within the Department of Machine Construction Technology at the "Gheorghe Asachi" Technical University in Iaşi [11]. The assessment of the adequacy of the determined mathematical model in relation to the obtained experimental results takes place by examining the value of Gauss's criterion [11, 12]. A smaller value of Gauss's criterion means a better fit of the mathematical model in relation to the experimental results used to determine it.

Table 1. Experimental conditions and results.

Exp. no.	Input factors, coded value/real value								Output parameters	
	Sliding speed v_s [mm/min]	Couple m of materials	Printing speed v_p [mm/s]	Infill percent i [%]	Infill pattern i_p	Layer thickness l [mm]	Cooling conditions c [%]	Normal force F_n [daN]	Friction force F_f [daN]	Friction coefficient μ
Column no. 1	2	3	4	5	6	7	8	9	10	11
1	1/ 0.448	1/ PLA-steel	1/ 20	1/ 20	1/ Grid	1/ 0.06	1/ 0	1/ 0.94	0.40	0.42
2	1/ 0.448	1/ PLA-steel	2/ 40	2/ 50	2/ Gyroid	2/ 0.1	2/ 50	2/ 1.5	0.48	0.32
3	1/ 0.448	1/ PLA-steel	3/ 60	3/ 80	3/ Lines	3/ 0.15	3/ 100	3/ 2.95	0.63	0.21
4	1/ 0.448	2/ PLA-PLA	1/ 20	1/ 20	2/ Gyroid	2/ 0.1	3/ 100	3/ 2.95	0.765	0.26
5	1/ 0.448	2/ PLA-PLA	2/ 40	2/ 50	3/ Lines	3/ 0.15	1/ 0	1/ 0.94	0.22	0.23
6	1/ 0.448	2/ PLA-PLA	3/ 60	3/ 80	1/ Grid	1/ 0.06	2/ 50	2/ 1.5	0.44	0.29
7	1/ 0.448	3/ PLA-HIPS	1/ 20	2/ 50	1/ Grid	3/ 0.15	2/ 50	3/ 2.95	0.18	0.06
8	1/ 0.448	3/ PLA-HIPS	2/ 40	3/ 80	2/ Gyroid	1/ 0.06	3/ 100	1/ 0.94	0.14	0.14
9	1/ 0.448	3/ PLA-HIPS	3/ 60	1/ 20	3/ Lines	2/ 0.1	3/ 100	2/ 1.5	0.23	0.15
10	2/ 1.12	1/ PLA-steel	1/ 20	3/ 80	3/ Lines	2/ 0.1	2/ 50	1/ 0.94	0.32	0.34
11	2/ 1.12	1/ PLA-steel	2/ 40	1/ 20	1/ Grid	3/ 0.15	3/ 100	2/ 1.5	0.62	0.41
12	2/ 1.12	1/ PLA-steel	3/ 60	2/ 50	2/ Gyroid	1/ 0.06	1/ 0	3/ 2.95	0.785	0.26
13	2/ 1.12	2/ PLA-PLA	1/ 20	2/ 50	3/ Lines	1/ 0.06	3/ 100	2/ 1.5	0.965	0.64
14	2/ 1.12	2/ PLA-PLA	2/ 40	3/ 80	1/ Grid	2/ 0.1	1/ 0	3/ 2.95	1.79	0.60
15	2/ 1.12	2/ PLA-PLA	3/ 60	1/ 20	2/ Gyroid	3/ 0.15	2/ 50	1/ 0.94	0.52	0.55
16	2/ 1.12	3/ PLA-HIPS	1/ 20	3/ 80	2/ Gyroid	3/ 0.15	1/ 0	2/ 1.5	0.50	0.33
17	2/ 1.12	3/ PLA-HIPS	2/ 40	1/ 20	3/ Lines	1/ 0.06	2/ 50	3/ 2.95	1.11	0.37
18	2/ 1.12	3/ PLA-HIPS	3/ 60	2/ 50	1/ Grid	2/ 0.1	3/ 100	1/ 0.94	0.305	0.32

With the help of the specialized software, an empirical mathematical model of the second-degree polynomial type was determined:

$$\mu = -0.485 - 3.698v_s + 2.720v_s^2 + 1.169m - 0.308m^2 + 0.04375v_p - 0.000558v_p^2 - 0.0142i + 0.000476i^2 - 0.298i_p + 0.0691i_p^2 + 7.812l - 47.517l^2 - 0.005c + 0.0000416c^2 + 0.593F_n - 0.08117F_n^2. \quad (1)$$

For this empirical mathematical model, the value of Gauss's criterion is S_G=0.02137408.

Since it is appreciated that a power function-type mathematical model provides more direct information regarding the influence of different factors on an output parameter of the investigated process, such an empirical mathematical model has yet to be determined:

$$\mu = 0.41v_s^{0.745}m^{-0.365}v_p^{0.01188}i^{-0.126} \cdot i_p^{0.003118} \cdot l^{-0.288}c^{-5.032}F_n^{0.769} \quad (2)$$

The value of Gauss's criterion for the empirical mathematical model of the power function type is S_G=0.1401008. This means that this mathematical model is still less appropriate in relation to the experimental results than the model defined by equation (1).

By using the empirical mathematical model constituted by equation (1), the graphic representations in Figures 3, 4 and 5 were made.

The analysis of the graphic representations in Figures 3, 4 and 5, as well as the mathematical model constituted by equation (2), leads to the observation that among the input factors whose increase generates an increase in the friction coefficient μ, the strongest influence is exerted by the magnitude of the normal force F_n, followed by the value of the sliding speed v_s. This finding is based on the fact that in the power-type function existing in equation (2), the highest values of the exponents correspond to the normal force F_n and the sliding speed v_s.

It is still noted that an increase in infill i leads to a decrease in the size of the friction coefficient μ, probably due to the increase in the density of the material and the increase, as such, in its resistance to deformation.

Some of the considered factors exert a reduced influence, which could mean that they practically do not exert influence on the magnitude of the friction coefficient μ since the values of the exponents attached to them have minimal values. Print speed v_p, infill pattern i_p, and cooling conditions c can be included in this category.

Experimentally, for the pairs of materials used in the experimental tests, the existence of a minimum value of the friction coefficient was found when the sliding speed increased (Figs. 4 and 5). In a simplified interpretation, the value of the friction coefficient should not be dependent on the magnitude of the sliding speed. However, in certain situations, it was found that, in the case of some plastic materials (or some elastic materials with non-linear sliding behavior) and the use of certain oils, it is worth noting a certain dependence of the value of the coefficient of friction on the magnitude of the sliding speed, possibly due to changes in the surface layer of the parts involved in the friction process. Such conditions can cause changes in the adhesion between the surfaces and, therefore, lead to changes in the value of the friction coefficient.

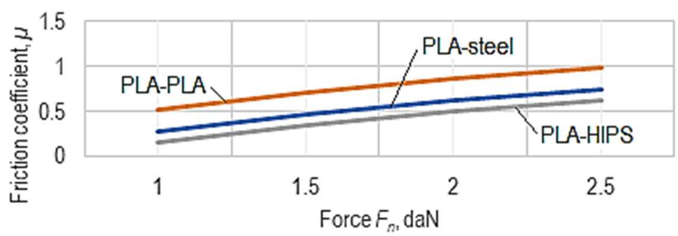

Fig. 3. The influence of the size of the normal force F_n on the value of the coefficient of friction μ, for the three couples of materials from which the test samples and the strips were made (v_s=0.448 mm/min, v_p=20 mm/s, i=20 %, i_p=2 for infill type gyroid, l=0.06 mm, c=0 %).

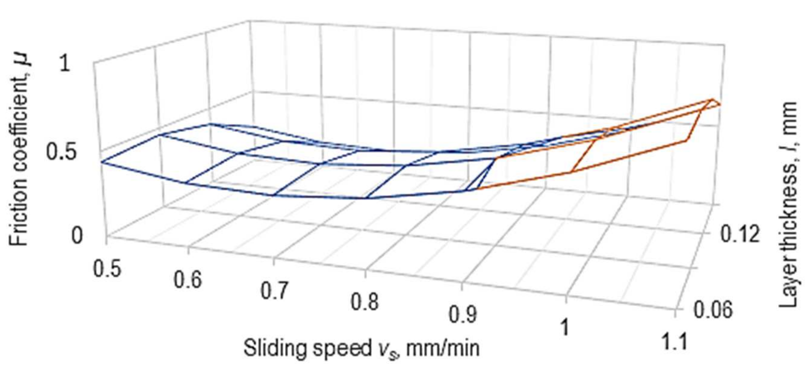

Fig. 4. The influence of the sliding speed v_s and normal force F_n on the magnitude of the friction coefficient μ in the case of the PLA-HIPS material couple (m=3, v_p=20 mm/s, i=20%, i_p=1, c=0 %, F_n= 2 daN).

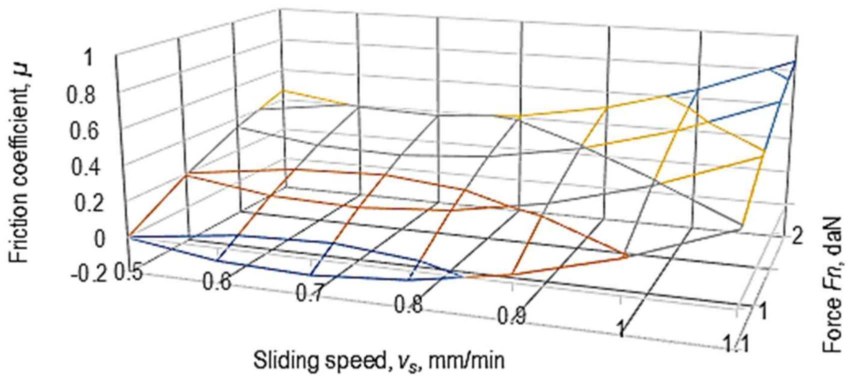

Fig. 5. The influence of the sliding speed v_s and the layer thickness *l* on the magnitude of the friction coefficient *μ* in the case of the PLA-HIPS material couple (*m*=3, v_p=20 mm/s, *i*=20%, i_p=2, *l*=0.06 mm, *c*=0 %).

5. CONCLUSIONS

The field of use of polymeric materials is growing. The appearance of new polymer materials and new technologies for manufacturing parts from polymer materials implies an intensification of research related to the knowledge of the operating properties of those materials. In this paper, the determination of an empirical mathematical model was aimed at highlighting the influence exerted by different factors on the size of the coefficient of sliding friction. For this purpose, simple equipment was designed and made that could be adapted to a universal lathe in order to benefit from the wide range of sizes of feed speeds with which it was possible to slide the test samples pressed on a strip of a certain material. The cubic-shaped test samples used were manufactured from polylactic acid by 3D printing. It was possible to determine the magnitude of the frictional force using the mentioned equipment. The experimental results were mathematically processed using specialized software. Two empirical mathematical models of the second-degree polynomial type and the power function type were determined. The analysis of the power function type mathematical model led to the conclusion that the magnitude of the friction coefficient increases to a significant extent when the normal force and the sliding speed increase. Essentially, an increase in the intensity of the cooling process, the thickness of the deposited layer, and the infill percent results in a decrease in the magnitude of the coefficient of friction. According to the power function type mathematical model, a change in the values of infill percent and printing speed does not exert influence on the size of the friction coefficient. In the future, it is intended to take into account other polymer materials for the samples used, as well as other factors likely to affect the friction coefficient values, such as the lubrication conditions and, respectively, the roughness of the surfaces involved in the friction process.

6. REFERENCES

[1] Kerns, J., 2016, *Replacing metal with plastic*, Machine Design, http://www.machinedesign.com.

[2] Singh, R., 2023, *Polymer processing*. https://www.me.iitb.ac.in/~ramesh/courses/ME206/polymer.pdf

[3] Baird D.G., Collias D.I.,. *Polymer processing. Principles and design*. Willey John Wiley & Sons, New York, 2014

[4] Chisiu G., Stoica N-A., Stoica A-M., 2021, *Friction Behavior of 3D-printed Polymeric Materials Used in Sliding Systems*, Materiale Plastice 58, 1, 176-185.

[5] Fouly A., Assaifan A. K., Alnaser I. A., Hussein O. A., Abdo H. S., 2022, *Evaluating the Mechanical and Tribological Properties of 3D Printed Polylactic-Acid (PLA) Green-Composite for Artificial Implant: Hip Joint Case Study*, Polymers, 14, 23, 5229.

[6] Roy R., Mukhopadhyay A., 2021, *Tribological studies of 3D printed ABS and PLA plastic parts*, Materials Today: Proceedings, 41, 4, 2021, 856-862.

[7] Perepelkina S., Kovalenko P., Pechenko R., Makhmudova K., 2017, *Investigation of friction coefficient of various polymers used in rapid prototyping technologies with different settings of 3d printing*, Tribology in industry, 39, 4, 519-526

[8] Portoacă, A.I., Ripeanu, R.G., Diniță A., Tănase M., 2023, *Optimization of 3D printing parameters for enhanced surface quality and wear resistance*, Polymers, 15, 3419.

[9] Slavkina V.E, Shitov A.O., Lopatina I.A., 2021, *The influence of 3D printing layer height on frictional properties of ABS plastic,* IOP Conf. Series: Materials Science and Engineering, ToPME 2020, 1129, 012072

[10] Crăciun E., Mihalache A.M., Hrițuc A., Coteață M., Dodun O., Nagîț G., Rîpanu M.I., Slătineanu L., 2023, *Determination of the friction coefficient magnitude in the case of polymer samples manufactured by 3D printing*, International Conference Polcom 2023, Bucharest.

[11] Crețu, G., Varvara, G. *Experimental research methods in machine manufacturing* (in Romanian), Publishing House Junimea, Iaşi, Romania, 1999.

[12] Worthing, A.G.; Geffner, J. *Treatment of Experimental Data* (in Romanian), Editura Tehnică, Bucharest, Romania, 1959.

Influența unor factori asupra mărimii coeficientului de frecare în cazul unor epruvete din material polimeric, fabricate prin imprimare 3D

Prin modificarea condițiilor de imprimare 3D, este posibilă modificarea diferitelor proprietăți fizico-mecanice ale materialelor pieselor fabricate. A fost proiectat și materializat un echipament simplu pentru a determina mărimea forței de frecare generate la deplasarea unei epruvete din acid polilactic pe o bandă, sub o forță normală de mărime cunoscută. Rezultatele experimentale au fost prelucrate matematic cu ajutorul unui software specializat. A fost determinat un model matematic empiric de tip polinom de gradul al doilea, pentru a evidenția influența exercitată de opt factori de intrare în procesul investigat asupra mărimii coeficientului de frecare. S-a constatat că forța de presare și viteza de alunecare sunt principalii factori care afectează valoarea coeficientului de frecare.

Elisaveta CRĂCIUN, Bachelor Student, “Gheorghe Asachi” Technical University of Iași, Department of Machine Manufacturing Technology, elisaveta.craciun@student.tuiasi.ro, tel. +40752390033

Andrei Marius MIHALACHE, Ph.D. Eng., Lecturer, "Gheorghe Asachi" Technical University of Iași, Department of Machine Manufacturing Technology, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, andrei.mihalache@yahoo.com, +40745356715.

Margareta COTEAȚĂ, Ph.D. Eng., Associate Professor, "Gheorghe Asachi" Technical University of Iași, Department of Machine Manufacturing Technology, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, mcoteata@tcm.tuiasi.ro, +40752141598.

Laurențiu SLĂTINEANU, Ph.D., Professor, “Gheorghe Asachi” Technical University of Iași, Department of Machine Manufacturing Technology, slati@tcm.tuiasi.ro, tel. +40723718675