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ABRASION RESISTANCE OF PLASTIC PARTS MANUFACTURED BY 3D PRINTING

BY

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Abstract. There are situations where parts manufactured by 3D printing processes must have a high abrasion resistance. To conduct experimental research on this subject, relatively simple test equipment for abrasive wear of pin-on-disk type was designed and materialized. The test pieces from the research material were pressed with known forces on the surface of a rotating abrasive paper disk. The test pieces were made of polyethylene terephthalate PET and polyethylene terephthalate carbon fiber reinforced PET CF15. As output parameters, the speed of decreasing the mass and the length of the test piece were used, respectively, for predetermined test durations. An experimental Taguchi L8 program was used, with 7 independent variables at two levels of variation. The experimental results were mathematically processed determined empirical mathematical models of the power function type. It was found that the strongest influence on the values of the output parameters was exerted by the average travel speed and by the granulation of the particles incorporated in the abrasive paper disk.

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Keywords: abrasion resistance; polyethylene terephthalate; pin-on-disk; experimental research; power function type empirical mathematical model.

1. Introduction

It is accepted that plastics are a class of non-metallic materials with an amorphous structure, which are obtained by melting together several constituents (resins, plasticizers, dyes, lubricants, supplementing materials, auxiliary materials) and which have a high capacity to be molded by plastic deformation at temperatures in the range of 140-180°C.

Let's take into account the behavior of plastics in heating. We find that thermoplastic material, which softens with increasing temperature and thermosetting or thermo-reactive materials, significantly changes some physical and mechanical properties after a cycle of heating-cooling due to the irreversible structural generation transformations. There are still other ways to classify plastics.

The main properties that differentiate plastics from other materials are low specific weight, low thermal and electrical conductivity, high corrosion resistance, good machinability by cutting, etc. Such properties have led to the widespread use of plastics to manufacture objects for a variety of purposes. It is important to use plastics when it is possible to replace metal materials with them, so when plastics provide better conditions for the use of parts than metal materials.

The last decades have been devoted to manufacturing plastic parts through additive manufacturing processes. The working principles of additive manufacturing processes allow the manufacture of plastic parts with a variation between relatively wide limits of working conditions, which also determines a change of some of their physical and mechanical properties.

Wear resistance is one of these important properties for the future use of plastic parts. The behavior of plastics in conditions of wear in general or abrasive wear, in particular, has been an objective of the activity of researchers in the field of machine manufacturing.

Thus, Wang et al. studied the abrasion resistance of polyethylene terephthalate films coated with SiO_2/epoxy hybrid material (Wang *et al*., 2013). They experimentally found a 40-50% increase in abrasion resistance when a 3% tetraethoxysilane solution was used in the test piece preparation.

The use of abrasion-resistant plastic in designing a mold for materializing additive manufacturing processes was considered in a patent application to the World Intellectual Property Organization in 2017 (Matzner *et al*., 2017).

Booth *et al*. cite Kevlar as a material capable of providing high abrasion resistance and flexibility to parts made by additive manufacturing processes (Booth *et al*., 2017).

The use of polymers to manufacture products incorporating ceramic powders has been an issue investigated by Bae *et al*. (2017). They found that some such polymers provide good abrasion resistance to parts made by 3D printing processes.

In a document for a master's degree in industrial engineering at the Polytechnic University of Barcelona, Preto and Silva considered abrasion resistance as one of the important properties of parts made by 3D printing from some plastics (Preto and Silva, 2019).

Eutionnat-Diffo et al. conducted experimental research on the wear resistance of some conductive polylactic acid filaments used in the manufacture of smart textiles by 3D printing (Eutionnat-Diffo *et al.*, 2020). One of the research conclusions was that there are factors that go into the 3D printing process that can significantly influence the abrasion resistance of polylactic acid.

Korger et al. found that thermoplastic styrene compounds provide lower abrasion resistance when evaluating some properties of interest for the use of polymers used in the manufacture of garments by 3D printing processes (Korger *et al*., 2020).

Not all plastics used in manufacturing parts by 3D printing processes meet high abrasion resistance requirements (Minnella, 2020). This can be a research topic in the future, especially when it comes to ensuring high wear resistance.

The purpose of this article was to present research results on the wear behavior of cylindrical specimens of polyethylene terephthalate PET and polyethylene terephthalate carbon fiber reinforced PET CF15, manufactured by 3D printing processes and tested under different conditions.

2. Conditions for Experimental Research

One of the meanings of the concept of wearing an object during its use is the degradation of that object through loss of material. This loss of material can be the result of friction, cavitation, abrasion, etc. The research whose results are shown in this article has focused on the development of wear processes due to abrasion. In principle, abrasion refers to the action of abrasive grains which have a sufficiently high hardness and which are pressed against the surface of the test piece or part with which the abrasive grains come in contact when there is a relative movement between the part or test piece and the abrasive grains. The abrasive granules will cause the generation of micro-cutting processes, with the removal of small amounts of test pieces or part material, in the form of microchips.

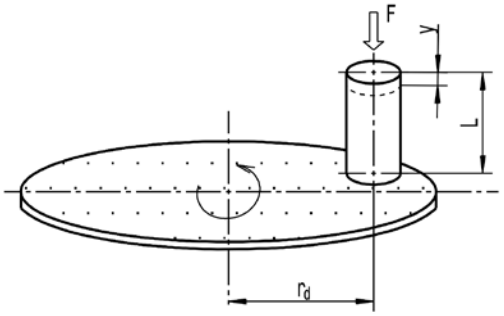


Fig. 1 − Principle of the working scheme used for the abrasion test of parts made of plastic and obtained by 3D printing.

Different working schemes for determining the abrasion wear resistance of different metallic or non-metallic materials can be met. In this article, we have considered a pin on disk scheme that involves pressing with different known forces a cylindrical test piece on the surface of a disk whose surface

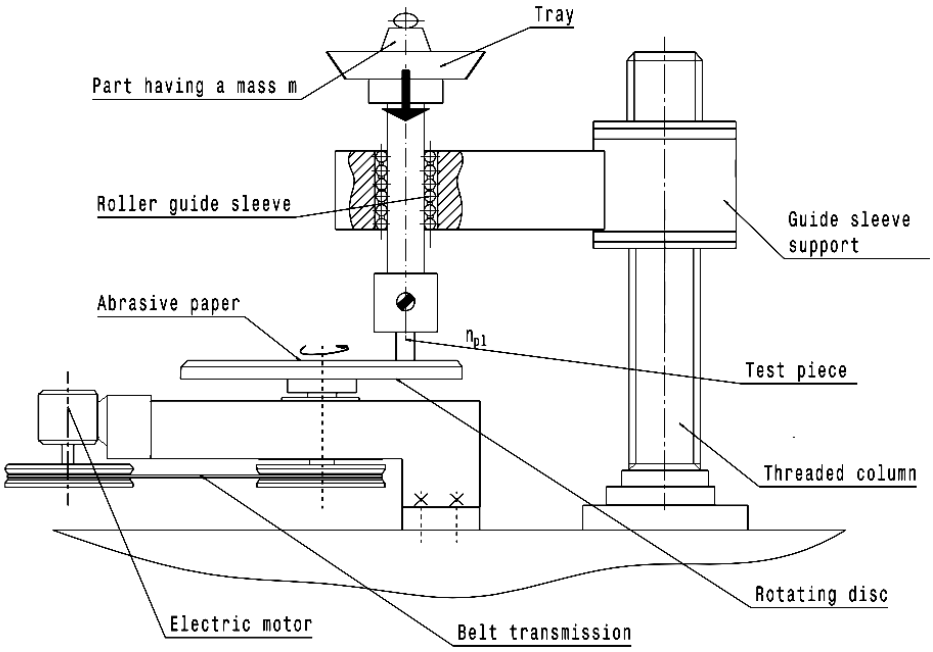


Fig. 2 − Schematic representation of the equipment used for the experimental study of the abrasion resistance of plastic test pieces made by 3D printing.

layer incorporates abrasive grains with certain average dimensions (Fig. 1).

The materialization of this scheme required equipment whose simplified representation can be seen in Fig. 2. It can be seen the use of a vertical cylindrical rod, at the upper end of which is a tray on which will sit a piece of known weight.

The test piece is placed at the lower end of the rod, passing through the inside of a roller guide bushing. The free front surface of the test piece is pressed against the surface of an abrasive paper disk placed on a metallic rotating disk. This abrasive paper disk is assembled using a velcro joint on the metal disk, driven in rotational motion by an electric motor. The roller guide bushing holder can be moved along a threaded column to adjust the initial position of the test piece relative to the rotating disk.

Knowing the rotational disk speed and the radius r_d of this disk at which the axis of symmetry of the test piece is located, an average travel speed of relative movement between the test piece and the abrasive paper disk (average travel speed v_t) can be determined. Suppose the mass m of the weight located on the tray and the value of the diameter of the cross-section through the cylindrical test piece are known. In that case, the value of pressure p exerted by the test piece on the surface of the abrasive paper disk can be evaluated.

Predetermined durations of the experimental wear tests and different weights of the weights placed on the tray were used.

The lengths of the test pieces before and after the experimental tests were determined using a digital caliper. An analytical balance of the type Partner Radwag AS20 was used to determine the mass of the test pieces before and after each experimental test.

To avoid the worn area of the abrasive paper disk influencing the wear performance results of the test pieces made of polyethylene terephthalate PET and polyethylene terephthalate carbon fiber reinforced PET CF15 by 3D printing, a new abrasive paper disk with known grain size was used for each experimental test.

Knowing the weights G of the placed parts placed on the tray and the diameter d of the cylindrical test pieces, it is possible to determine the pressure p, this being one of the input factors in the investigated process:

$$p=G/(\pi d^2/4). \quad (1)$$

3. Programming Experimental Tests

The experimental tests were initially programmed according to the requirements of a factorial experiment of the Taguchi L8 type, with seven independent variables at two levels of variation (Hrițuc *et al.*, 2021; Slătineanu, 2019).

As independent variables, there were used the pressure p exerted by the test piece on the abrasive paper disk (the two pressure values being 79617 Pa and 119426 Pa, respectively), the average peripheral speed v_t of rotation of the abrasive paper disk relative to the axis of symmetry of the test piece (with values of 93 and 186 m/min), the grain size g of the abrasive paper (with values of 180 and 320), the nature p_m of the material of the test piece (polyethylene terephthalate PET and polyethylene terephthalate carbon fiber reinforced PET CF15) and some values that characterized the conditions of 3D printing process (the thickness h of the layer deposited), the printing speed v_p, the orientation angle α of the print. Test duration of 20, 25, and 45 seconds were used, taking into account some results of the first experimental tests. The values of output parameters were determined by relating the losses of mass Δm and length Δl to the duration of the experimental tests.

Some of the conditions for performing the experimental tests and the results have been listed in Table 1.

Table 1

Working conditions and results of experimental tests (adopted from Hrițuc et al., 2021)

Input factors and output parameters	Experiment number:							
	1	2	3	4	5	6	7	8
Pressure p, Pa	79617	79617	79617	79617	119426	119426	119426	119426
Average trave; speed. v_t, m/min	93	93	186	186	93	93	186	186
Abrasive paper granulation, g	180	180	320	320	320	320	180	180
Layer thickness, h, mm	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
Printing speed v_p, mm/s	25	35	25	35	35	25	35	25
Printing orientation, α, ^{o}	90	0	0	90	90	0	0	90
Plastic material, p_m	PET CF15	PET	PET	PET CF15	PET	PET CF14	PET CF15	PET
Test duration, s	25	25	25	25	45	25	25	20
Mass lost, Δm, g	0.02742	0.09202	0.12161	0.04962	0.06015	0.01905	0.11538	0.16793
Mass erosion speed, $v_{\Delta m}$, g/s	0.00109	0.00368	0.00486	0.00110	0.00240	0.00076	0.00109	0.00839
Length variation, Δl, mm	1.52	9.24	10.28	6.1	6.32	4.15	9.59	14.29
Length erosion speed, $v_{\Delta l}$, mm/s	0.0608	0.3696	0.4112	0.244	0.140444	0.166	0.3836	0.7145

4. Processing of Experimental Results

The results of the experimental tests were processed using software based on the least squares method (Crețu, 1992). The use of empirical mathematical models of the power function type was preferred, given the wider use of such functions in modeling the various aspects related to cutting processes (for example, for modeling the cutting tool life, the sizes of the roughness parameters *Ra* and *Rz* , of the magnitudes of the components of the cutting force, etc. In this way, the following two empirical mathematical models were established to highlight the influence exerted by different factors on the speed of decrease of the mass $v_{\Delta m}$ and respectively of the length of the test piece $v_{\Delta l}$:

$$v_{\Delta m}=1.5099\cdot 10^{-7} p^{0.736} v_t^{1.203} g^{-1.202} h^{-0.404} v_p^{0.206} a^{-0.0151} p_m^{1.599}, \quad (2)$$

$$v_{\Delta l}=1.262\cdot 10^{-6} p^{0.652} v_t^{1.429} g^{-0.420} h^{1.011} v_p^{0.366} a^{-0.0298} p_m^{0.997}. \quad (3)$$

The two empirical mathematical models were used to plot the graphical representations in Figs. 3, 4, 5, and 6.

Following the analysis of the information provided by the two empirical mathematical models and the graphical representations in Figs. 3, 4, 5 and 6, the following comments were made.

Increasing the values of the factors to which positive values of the exponents attached to them in equations (2) and (3) have been assigned leads to an increase in the values of the values of the output parameters $v_{\Delta m}$ and $v_{\Delta l}$. This category includes the pressure *p*, average travel speed v_t, printing speed v_p. On

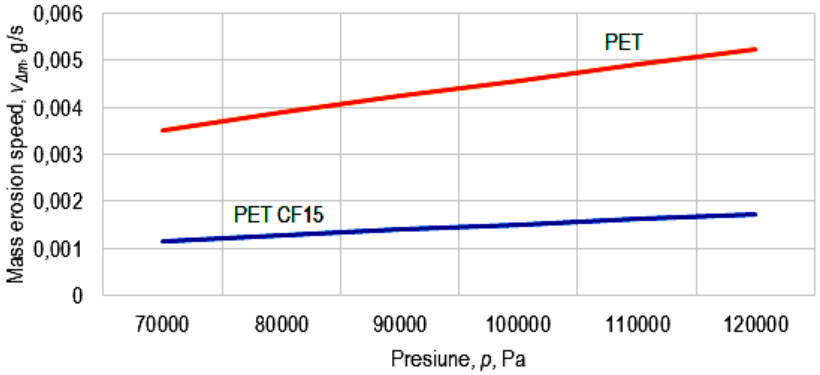


Fig. 3 – Influence exerted by the pressure p on the mass erosion speed $v_{\Delta m}$ (v_t=93 m/min, g=180, h=0.1 mm, v_p=25 mm/s, α=90°, p_m=1 for PET CF15, p_m=2 for PET).

the other hand, the increase of the values of the factors whose exponents have negative values in the mathematical relations (2) and (3) results in a decrease of the values of the two output parameters. Such factors are the granulation g of the abrasive material and the printing orientation angle α.

The above statements are not valid in the case of the input factor called

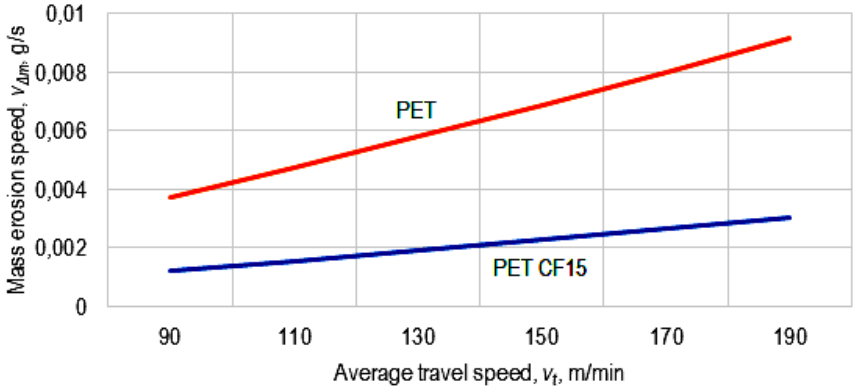


Fig. 4 – Influence exerted by average travel speed v_t on the mass erosion speed $v_{\Delta m}$ (p=79717 Pa, g=180, h=0.1 mm, v_p=25 mm/s, α=90°, p_m=1 for PET CF15, p_m=2 for PET).

"plastic material", for which the values 1 for PET material CF15 and 2 for PET material were used for the mathematical processing of the experimental results. A somewhat contradictory influence seems to be exerted by the thickness h of the deposited layer, whose exponents have a negative value in relation (2) and a positive value in relation (3), respectively. It is necessary to carry out additional experimental tests in the future to clarify the meaning of the variation of the

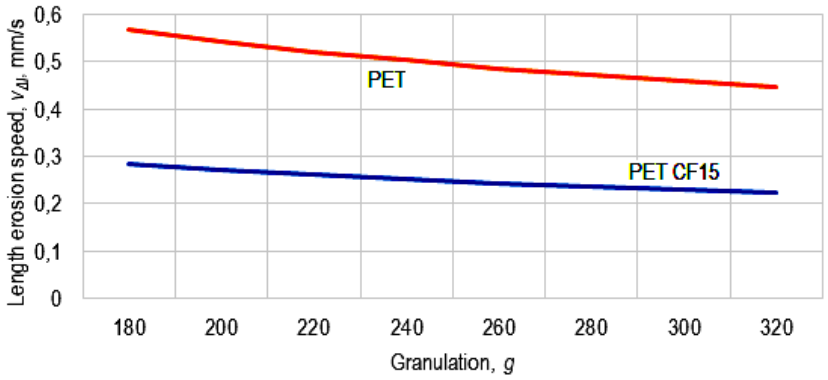


Fig. 5 – Influence exerted by the granulation of the abrasive paper on the length erosion speed $v_{\Delta l}$ (p=119426 Pa, v_t=186 m/min, h=0.2 mm, v_p=25 mm/s, α=90°, p_m=1 for PET CF15, p_m=2 for PET).

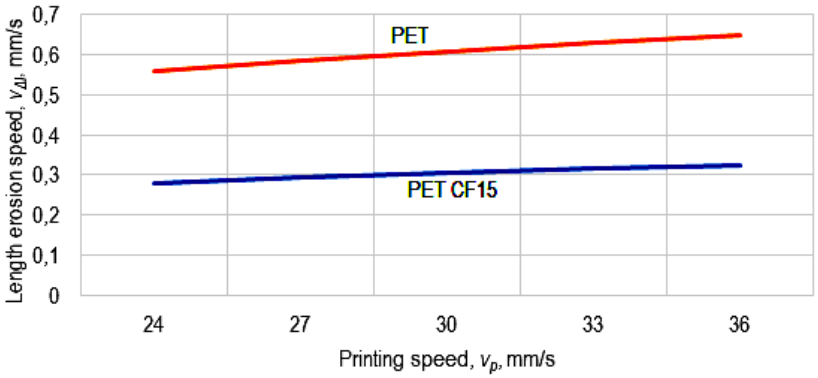


Fig. 6 – Influence exerted by the printing speed v_p on the length erosion speed $v_{\Delta l}$ (p=119426 Pa, v_t=186 m/min, h=0.2 mm, g=180, α=90°, p_m=1 for PET CF15, p_m=2 for PET).

influence exerted by this factor on the values of the output parameters $v_{\Delta m}$ and $v_{\Delta l}$.

Following the empirical model of the mathematical relation (2), the strongest influence is exerted by the average travel speed v_t, which corresponds to the highest absolute value of the attached exponent (1.203). In the case of the empirical mathematical model (3), the strongest influence is also exerted by the average travel speed v_t, to which the exponent with the highest absolute value (1.429) was associated.

The decrease in the erosion rate $v_{\Delta l}$ when increasing the granulation g can be justified because abrasive granules with smaller average dimensions will take by micro-cutting smaller quantities of the materials of the test pieces.

The printing orientation angle α exerts a relatively small influence on the erosion rate. The situation is highlighted in both empirical mathematical models by the low values of the exponents attached to this input factor.

5. Conclusions

One of the demands that plastic parts obtained by 3D printing processes could be subject to research is their wear resistance. In this paper, issues related to the behavior of such materials in abrasive wear have been addressed. A so-called simple pin on disk equipment was used. This involved pressing with known force some test pieces of two plastics (polyethylene PET and polyethylene with carbon fiber PET 25F, respectively) on the surfaces of two distinct abrasive paper disks. The programming of the experimental tests was initially performed starting from a factorial program of Taguchi L8 type, with 7 independent variables at two levels of variation. The experimental results were processed using software based on the method of least squares. It was decided

to determine mathematical models of the power function type to evaluate the influence exerted by the input factors in the investigated process on the erosion rate evaluated by mass loss and, respectively, by reducing the length of the test pieces. It was found that the strongest influence on the abrasion erosion rate is exerted by the average travel speed of the movement between the test piece and the disk on which the specimen is pressed. As expected, the increase in average travel speed results in an increase in the rate of erosion by abrasion. It has been confirmed that an increase in the grain size of the abrasive particles also leads to an intensification of removing material from the test piece by abrasion. In the future, a more detailed investigation will be carried out into some of the aspects in which contradictory results have been reported and the improvement of the equipment used to materialize the experimental tests.

REFERENCES

Bae C.-J., Ramachandran A., Chung K., Park S., *Ceramic Stereolithography: Additive Manufacturing for 3D Complex Ceramic Structures*, J. Korean Ceram. Soc., *54*, 6, 470-477 (2017).

Booth J., Whitley M., Rudd C., Kranz M., *Material Database for Additive Manufacturing Techniques*, U.S. Army, Technical Report RDMR-WD-17-64, 2017, available at https://apps.dtic.mil/sti/pdfs/AD1043719.pdf, accessed: 8.02.2022.

Crețu G., *Fundamentals of Experimental Research. Laboratory Handbook* (in Romanian). "Gheorghe Asachi" Technical University of Iași, România, 1992.

Eutionnat-Diffo P.A., Chen Y., Guan J., Cayla A., Campagne C. and Nierstrasz V. *Study of the Wear Resistance of Conductive Poly Lactic Acid Monofilament 3D Printed onto Polyethylene Terephthalate Woven Materials*. Materials, *13*, 2334 (2020).

Hrițuc A., Slătineanu L., Boca M.A., Sover A., Nagîț G., Dodun O., Coteaţă M., Mihalache A., *Abrasive Erosion Behavior of Some Plastic Parts Obtained by 3D Printing*, Macromol. Symp., *396*, 1, 2000288 (2021).

Korger M., Glogowsky A., Sanduloff S., Steinem C., Huysman S., Horn B., Ernst M., Rabe M., *Testing Thermoplastic Elastomers Selected as Flexible Three-Dimensional Printing Materials for Functional Garment and Technical Textile Applications*, J. Eng. Fibers Fabr., *15*, 1-10 (2020).

Matzner E., Dikovsky D., Melamed O., Der Lior, *3-D Printed Mold for Injection Molding*, International Application Published Under the Patent Cooperation Treaty (PCT), International Publication Number WO 2017/037713 Al, 2017.

Minnella S., *I Nuovi Materiali Utilizzati Nell'additive Manufacturing*, ANFIA (Associazione Nazionale Filera Industria Automobilistica), 2020.

Preto D.M., Silva D.V., *New Technologies to Accelerate Additive Manufacturing Processes on an Industrial Scale*, Universitat Politècnica de Catalunya. Escola Tècnica Superior d'Enginyeria Industrial de Barcelon, 2019.

Slătineanu L., *Fundamental of Scientific Research* (in Romanian), PIM Publishing House, Iași, Romania, 2019.

Wang J., Fu X., Ding J., Wu H.-M., Fu Y.Q., *Mechanical and Abrasion Properties of Polyethylene Terephthalate Films Coated with SiO_2/Epoxy Hybrid Material*, 2013, available at: https://www.researchgate.net/publication/287041857_Mechanical_and_abrasion_properties_of_polyethylene_terephthalate_films_coated_with_SiO2epoxy_hybrid_material, accessed: 8.02.2022.

REZISTENȚA LA ABRAZARE A PIESELOR DIN MATERIALE PLASTICE FABRICATE PRIN TIPĂRIRE 3D

(Rezumat)

Există situații în care este necesar ca piesele fabricate prin procese de tipărire 3D să aibă o rezistență ridicată la abraziune. Pentru a efectua cercetări experimentale în acest sens, a fost proiectat și materializat un echipament relativ simplu de testare la uzura abrazivă, de tip știft pe disk. Epruvetele din materialul cercetat au fost presate cu forțe cunoscute pe suprafața unui disk rotativ din hârtie abrazivă. Epruvetele au fost realizate din polietilen tereftalat PET și polietilen tereftalat armat cu fibră de carbon PET CF15. În calitate de parametri de ieșire, s-au folosit viteza de scădere a masei și respectiv a lungimii piesei epruvetei pentru durate de testare prestabilite. A fost utilizat un program experimental Taguchi L8, cu 7 variabile independente la două niveluri de variație. Rezultatele experimentale au fost prelucrate matematic, fiind determinate modele matematice empirice de tip funcție putere. S-a constatat că cea mai puternică influență asupra valorilor parametrilor de ieșire luați în considerare a fost exercitată de viteza medie de deplasare și de granulația particulelor dure încorporate în diskul de hârtie abrazivă.