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Abrasion resistance of some composite polymer materials

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Abstract. Plastic are non-metallic material characterized by an amorphous structure and manufactured by melting together several constituents, such as resins, plasticizers, dyes, fillers, etc. These materials can be deformed with relative ease at temperatures of 140-180 ° C. In turn, composite materials are constituted by a metallic or non-metallic mass reinforced with resistance elements in the form of long fibers, short and very short fibers, granules, fabrics, felt, etc. The use of parts made of composite materials in conditions characterized by the action of abrasive wear processes requires the knowledge of additional information regarding the behavior of these materials under such stresses. Samples of cylindrical form were made from two polymeric composite materials, namely Granite and PolyMide using a 3D printing process. For abrasive erosion testing, a pin-on-cylindrical surface pattern was chosen. As such, an abrasive testing device adaptable to a universal lathe was designed and achieved. The nature of the composite polymer material, the granulation of the abrasive paper, and the pressing force of the test sample on the abrasive cylinder were taken into account as input factors in the process. The output parameter monitored was the loss of material from the test sample as a result of the abrasion process. The experimental results were processed using specialized software. There were determined empirical mathematical models capable of highlighting the direction of action and the intensity of the influence exerted by some input factors in the testing process on the loss of material by the test sample as a result of the abrasion process. It was found that, for the conditions in which the experimental research was carried out, the strongest influence was exerted by the nature of the composite polymer material, followed by the magnitude of the pressing force of the test sample and by the granulation of the abrasive material.

Introduction

Plastics are considered as non-metallic materials that have an amorphous structure and are manufactured by melting together constituents such as resins, plasticizers, dyes, fillers, etc. Such materials still are characterized by the property of being shaped with relative ease, due to a high plasticity at temperatures in the range of 140-180 ° C. The composite materials can be defined as having a metallic or non-metallic mass, called *a matrix*. To increase strength to some mechanical stresses, composite materials include strength elements in the form of long fibers, short and very short fibers, granules, fabrics, felt, etc.

Wear is one of how a part deteriorates. There are several ways in which a part deteriorates through wear, and one of these is *abrasive wear*. In principle, abrasive wear occurs by removing material from the part as a result of the action of hard particles with sharp edges that are displaced and pressed against the surface of the part affected by the wear process. It can be appreciated that hard particles with sharp edges contribute to the materialization of micro-chipping processes, resulting, as mentioned, by removing small amounts of the material of the analyzed part.

There are known situations in which polymer parts are subjected to wear processes through abrasive erosion. The wear can contribute to reducing their capacity to perform the functions for which they were designed and manufactured. In such conditions, it is of interest to know how the abrasive erosion process can occur and, respectively, to identify ways to improve the abrasion behavior of polymer materials. One of the ways to increase the abrasion resistance of polymer materials was to include in their composition materials characterized by superior wear resistance, and in this way, it comes to the introduction of composite materials with polymer matrixes.

Mahapatra and Chaturvedi studied the effects of different input factors in the abrasive process on the abrasion behavior of untreated sugarcane fiber-reinforced composites [1]. In this case, they found that the main influencing factor is the fiber length.

Hermanth et al. addressed the problem of the abrasive wear resistance of some thermoplastic copolyester elastomer composites [2]. By carrying out experimental research, they found that the highest abrasion resistance was recorded in the case of a thermoplastic copolyester elastomer in which polytetrafluoroethylene microparticles were introduced.

Hsissou et al. developed research that aimed to identify possibilities for improving certain properties of some categories of composite materials with a polymer matrix by using fibers from organic or inorganic materials [3]. They thus found an increase in the abrasive erosion resistance of the investigated materials.

Zaccone et al. considered the research of the abrasive erosion behavior of a composite material containing carbon fibers introduced into an epoxy nanocomposite matrix in which layered silicate with nanoparticles is located [4]. The abrasive erosion process was generated by the impact of abrasive particles on the surface of the composite material test sample. The researchers found that the presence of the nanoclay particles contributes to a decrease in wear evaluated by mass loss from the test sample as a result of the abrasive erosion process.

In this article, the aim was to expose some aspects regarding the direction and intensity of the influence exerted by some factors on the removal of material by abrasion in the case of test samples made of composite polymer materials. An initial analysis allowed highlighting the existence of several ways to evaluate the abrasion resistance of materials. For the experimental research, an abrasive wear testing device of test samples made of polymer composite materials adaptable to a universal lathe was designed and manufactured. By mathematically processing the experimental results, it was possible to determine empirical mathematical models capable of highlighting the influence that some input factors in the testing process exert on the abrasion resistance evaluated by material loss in a certain time interval.

Initial considerations

The abrasion resistance of a material can be evaluated by monitoring the change in the mass or length of the test sample as a result of the removal of material by the abrasive grains in contact and displaced relative to the surface of a test sample made of the material under investigation.

If the abrasive grains are made of a sufficiently hard material if they have sharp edges, they exert pressure on the surface of the test sample, and have a certain position relative to this surface, the development of micro-chipping processes is possible.

The analysis of the various procedures for evaluating the abrasion resistance highlighted the use of abrasive papers, cardboard, or cloths as parts capable of exerting an abrasive effect. On their active surfaces, abrasive grains of different sizes were placed using sufficiently resistant adhesives. Usually, the samples of the material to be tested are pressed onto the part that has an active abrasive surface, the latter being at the same time in relative motion concerning the sample. Pressing the sample onto the active surface of the abrasive part is carried out under the action of a force of known magnitude.

Different reasons have led to the generation of distinct erosion testing schemes. There are as follows:

- Abrasive erosion testing by the *pin-on-disk method*, in which a cylindrical or parallelepipedal test sample is pressed onto the flat surface of a rotating disk. Such a method is characterized by the fact that the speed of relative motion between the test sample and the abrasive disk varies according to the radius at which the test sample is located. A disadvantage of the method derives from the fact that the removal of material from the test sample is non-uniform, being more intense in those areas where the speed of relative movement between the test sample and the abrasive grains is higher. To uniformize the wear conditions, it is possible to drive the test sample in a rotational movement around its axis perpendicular to the active surface of the disk, but this involves the use of a more complex solution of the testing equipment. Another disadvantage refers to the fact that the same area of the disk (in the shape of a circular crown) is used throughout the testing process. This could lead to a decrease in the abrasive process over time, due to the removal of some abrasive grains from the superficial layer corresponding to the active surface of the disk or simply the wear of the active surface of the disk;

- Abrasive erosion testing by the *pin-on-belt method*, based, in principle, on pressing and moving a test sample relative to the active surface of a so-called continuous belt, i.e., a belt with the ends glued and driven in motion due to the placement of the belt on two rollers, one of which is in rotational motion. A less convenient aspect of the method is that, in the case of a simple testing scheme, the same area of the abrasive belt is used throughout the abrasion resistance evaluation test. A reduction of such a disadvantage is possible by a periodic movement of the test sample along a transverse direction to the direction of movement of the abrasive belt, which would lead to a sinusoidal trajectory of the test sample movement along the abrasive belt. Also, this method does not lead to the complete removal of the inconvenient aspect of using the same area of the belt throughout the test. There still is the need to use a more complex equipment solution, which would make it necessary to ensure the transverse movement of the test sample to the movement of the belt presenting an abrasive surface;

- Abrasive erosion testing by *the pin-on-flat surface method*, which is similar, to a certain extent, to the previous method, with the only difference being that the abrasive belt is replaced by an abrasive sheet on which the test sample must move along a sinusoidal trajectory. In this case, one of the components could have a displacement along a rectilinear direction, while the other component could have a periodic relative movement along a direction perpendicular to the previous direction. This combination will lead to a sinusoidal trajectory of the test sample on the sheet presenting an abrasive active surface;

- Abrasive erosion testing by the *pin-on-cylinder method*, which involves the existence of pressure and relative displacement of the test sample on the outer surface of a cylindrical part in rotational motion and on which a sheet presenting an abrasive active surface has been placed. Such an abrasion testing scheme has the advantage of a certain constructive simplicity of the equipment used for its materialization and provides conditions for a more complete exploitation of the abrasive active surface of the sheet placed on the cylindrical part in rotational motion. The pin-on-cylinder method generates some difficulties, due to two main aspects, namely:

1) At the beginning of the test, the contact between the test sample surface and the abrasive surface of the paper takes place along a generatrix of the cylindrical surface of the mandrel on which the abrasive paper is placed and fixed and only after a certain removal of material from the test sample this contact is made on an area of a cylindrical surface. This could lead to a non-uniformity of the speed of removal of material from the test sample by abrasive wear;

2) If the evaluation of the intensity of the abrasion process is carried out by taking into account the decrease in the length of the test sample, it will be found that there are areas of the test sample with different lengths after the development of the abrasion process with the generation of an abrasive surface in the form of an area of a cylindrical surface.

The aforementioned aspects led to the adoption, as a test scheme, of the last variant of the mentioned methods. An abrasion testing device adaptable to a universal lathe was designed and used as such (Figs. 1 and 2). The device uses a mandrel located and clamped in the universal chuck of the lathe and in a live center located in the conical bore in the tailstock quill of the universal lathe. An abrasive sheet can be placed on the outer cylindrical working surface of the mandrel, with the abrasive sheet being secured using two collar-type clamps.

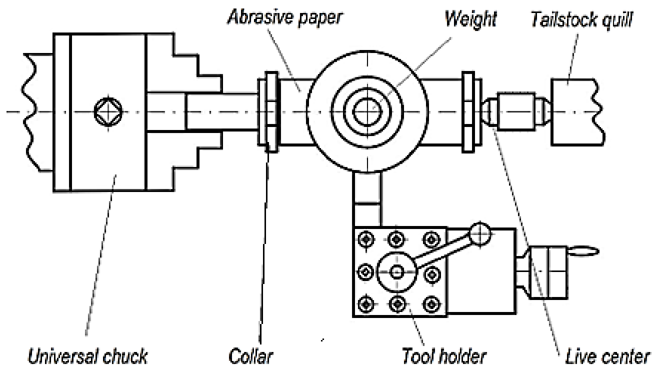

Figure 1 – Top view of the abrasive erosion testing device using the pin-on-cylinder method

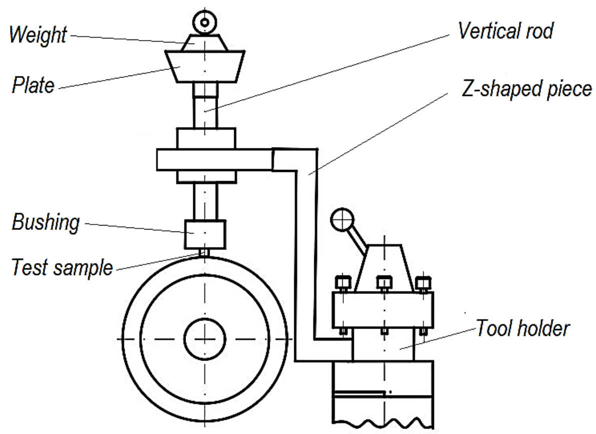

Figure 2 – Side view of the abrasive erosion testing device using the pin-on-cylinder method

The cylindrical test sample of the material to be tested is located and clamped using a screw in the lower area of the existing cylindrical bore in a bushing placed in a vertical position. The other end of the bushing is attached to a vertical rod fixed to a sled that can move on a roller guide mounted on a *Z*-shaped part. At the upper end of the vertical rod, there is a plate on which weights of different sizes can be placed, designed to contribute to the generation of distinct pressures for pressing the test sample on the abrasive cylindrical surface of the sheet placed on the mandrel.

One end of the *Z*-shaped part is fixed in one of the 4 slots of the universal lathe's tool holder. In this way, possibilities are provided for moving the test sample on the abrasive cylindrical surface together with the lathe carriage, at a preset speed corresponding to the longitudinal feed movement usually performed by the tools used on the lathe. Such a solution allows the use of feed rate values within relatively wide limits, as the rotation speed of the mandrel supporting the abrasive sheet can have values within a wide range, by using different rotation speeds of the main spindle of the lathe.

The movement of the abrasive material test sample as a result of using the feed motion of the lathe provides conditions for a more complete exploitation of the active abrasive surface of the paper placed on the mandrel.

It was considered that by using a roller guide for moving the sled supporting the vertical rod, the friction forces would be reduced, the magnitude of which could affect the values of the pressure exerted by the test sample on the active surface of the abrasive sheet.

A certain inconvenience may be generated by the problem of joining or overlapping the ends of the sheet of abrasive paper located and clamped on the mandrel. Intending to use sufficiently thin sheets of abrasive paper, it was considered, in this case, that the possible disadvantage generated by the existence of unevenness due to the overlapping of one end of the sheet on the other end of the sheet could be neglected.

The abrasion behavior of the test sample material could be influenced by factors or groups of factors such as the following:

- the nature and physical-mechanical properties of the test sample material;
- the nature and physical and mechanical properties of the material from which the abrasive grains are made, the adhesive for fixing the abrasive grains to the cardboard sheet, and the material of the abrasive paper itself;
- the grit of the abrasive paper;
- the pressure exerted by the test sample on the active surface of the abrasive paper;
- the test duration;
- the speed of the rotational movement performed by the mandrel on which the abrasive paper is placed;
- the speed of the rectilinear movement of the test sample along a generatrix of the cylindrical surface materialized by the abrasive paper, movement corresponding to the feed movement of the lathe carriage.

Conditions for carrying out and results of the experimental tests

The experimental tests aimed to identify empirical mathematical models that would allow highlighting the influence exerted by some input factors in the abrasive erosion resistance testing process on the value of an output parameter from this process.

These experimental tests were carried out using the device whose schematic representations can be seen in Figs. 1 and 2.

The use of a full orthogonal factorial experiment of type *L*8 was considered, with three independent variables taking values on two levels of variation. As input factors in the process of evaluating the resistance to abrasive erosion, the nature of the material of the test sample (two composite polymer materials were used), the size g of the granulation corresponding to the abrasive papers used (abrasive papers with granulations g_1=320 and g_2=1000 were used) and respectively two values of the force of pressing the test sample on the abrasive paper (F_1=2.94 N and F_2=4.41 N). The selection of these input factors was carried out taking into account the significant influence they can exert on the value of the output parameters from the testing process and the possibilities of using the equipment on which the abrasive erosion testing was performed.

As an output parameter, the mass loss Δm of the test sample after a one-minute abrasive erosion process was used. The mass of the test samples before and after the abrasive erosion resistance evaluation test was determined using a RADWAG Partner AS 60/220/C/2 analytical balance.

As materials for the test samples, a ceramic–polymer composite materials-type material named Granite (manufactured by FormFutura - The Netherlands), and PolyMide (manufactured by the PolyMaker – U.S.A. and containing polyamide with 10% carbon fiber reinforcement elements) were used. Both PolyMide (PA12 + 10 wt% carbon fiber) and Granite (PLA + 50 wt% granite powder) are semi-crystalline thermoplastics. However, these materials exhibit significant differences due to their distinct molecular structures. PA12 features strong intermolecular hydrogen bonding facilitated by the presence of amide (-CONH-) groups, which enhances its mechanical integrity. In contrast, PLA contains ester (-COO-) linkages between its lactic acid monomers, resulting in moderate-strength polar interactions that define its polyester-based molecular structure.

The incorporation of carbon fibers in PA12 enhances tensile strength and stiffness while also improving dimensional stability, reducing warping, and increasing fatigue and wear resistance. Conversely, the addition of granite powder to the PLA matrix significantly increases the material's mass due to its high filler content. Additionally, it enhances compressive strength and provides a rough, textured surface finish to the resulting parts.

The peripheral speed of the cylindrical mandrel on which the abrasive paper was wound was 3.51 m/min and it corresponds to a constant rotation speed of 16 rev/min. The feed speed of the lathe carriage, which determines the movement of the test sample along a spiral trajectory on the surface of the abrasive paper was 5 mm/min, i.e., equal to the diameter of the test sample. This situation determined the permanent use of a surface unaffected by the wear of the abrasive paper. The test duration was 1 minute. The values of the three input factors mentioned (rotation speed, feed speed, and test duration) were kept constant during the experimental tests.

Table 1 – Conditions for carrying out and results of experimental tests

Exp. no.	Input factors						Reducing the mass Δm of the test sample, g		
	Material, m		Granulation, g		Normal force, F, N		The initial mass of the test sample, m_i, g	The final mass of the test sample, m_f, g	Mass loss, Δm, g
	Coded value	Real name	Coded value	Real value	Coded value	Real value			
Column no. 1	2	3	4	5	6	7	8	9	10
1	1	PolyMide	1	320	1	2.94	0.4306	0.4206	0.0144
2	1	PolyMide	1	320	2	4.41	0.4285	0.4272	0.213
3	1	PolyMide	2	1000	1	2.94	0.4493	0.4467	0.026
4	1	PolyMide	2	1000	2	4.41	0.4487	0.4450	0.0037
5	2	Granite	1	320	1	2.94	0.7535	0.7323	0.0202
6	2	Granite	1	320	2	4.41	0.7522	0.7018	0.0304
7	2	Granite	2	1000	1	2.94	0.7552	0.7456	0.0096
8	2	Granite	2	1000	2	4.41	0.7550	0.7297	0.0253

The values of the input factors in the testing process were entered in columns 3, 5, and 7 of Table 1, while in columns 2, 4, and 6 the coded values of the independent variables were mentioned, following the requirements of a full orthogonal factorial experiment of type $L8$.

In columns 8 and 9 the masses of the test samples were entered, before and after the tests, and in column 10, the mass loss Δm by the test samples was determined as a difference of the values entered in columns 8 and 9.

For processing the experimental results, specialized software [5] was used, which is based on the least squares method. This software provides conditions for determining the specific constants for 5 categories of empirical mathematical models (first-degree polynomial, second-degree polynomial, power-type function, exponential function, hyperbolic function). The selection of the most convenient variant of the empirical mathematical model from the 5 variants considered is carried out using the Gauss criterion. The most appropriate empirical mathematical model is considered to be the one for which the value of the Gauss criterion has the lowest value.

By using the specialized software, it was found that the most appropriate empirical mathematical model for the experimental results included in Table 1 is a mathematical function of the second-degree polynomial type (Eq. 1):

$$\Delta m = 0.0133 - 0.0121m + 0.00768m^2 - 0.000000141g - 0.0000000126g^2 - 0.00141F + 0.000376F^2, \quad (1)$$

case in which Gauss's criterion has a value S_G=1.324748·10^{-5}.

For many situations encountered in machine manufacturing, it is preferred to use empirical mathematical models of the power function type (for example, to highlight the influence of cutting conditions on the value of the roughness parameter Ra, on the size of the cutting tool life, on the sizes of the cutting force components, etc.). Examining the exponents attached to the independent variables in an empirical mathematical model of the power function type allows direct obtaining of information regarding the direction of action and the intensity of the influence exerted on the value of the output parameter by the input factor taken into account. However, it should be noted that power-type functions can be used only when it is considered that the evolution of the output parameter to the variation of the size of an input factor is monotonic or almost monotonic.

Taking into account the experimental results included in Table 1, the following empirical mathematical model of the power-type function type was determined by mathematical processing (Eq. 2):

$$\Delta m=0.617m1.414g{-}0.963F1.308. \quad (2)$$

As expected, since the empirical mathematical model of the power-type function is not the most appropriate for the experimental results included in Table 1, the value of the Gauss criterion corresponding to this model (S_G=6.454768·10-5) is higher than that in the case of the mathematical model of the second-degree polynomial type.

Experimental results and discussion

By taking into account the empirical mathematical model of the power function type (of equation (2)), the graphical representations in Figs. 4 and 5 were developed. Examination of the empirical mathematical model of the power function type and the diagrams in Figs. 3 and 4 allowed the formulation of the following observation.

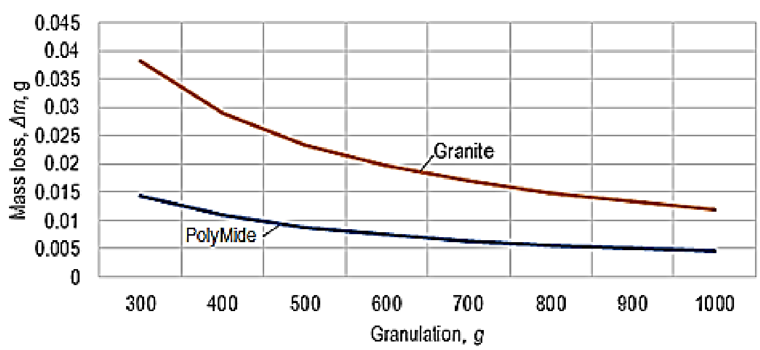

Figure 3 – Influence of granulation g on material loss Δm for the two materials of the test samples (F=3.75 N)

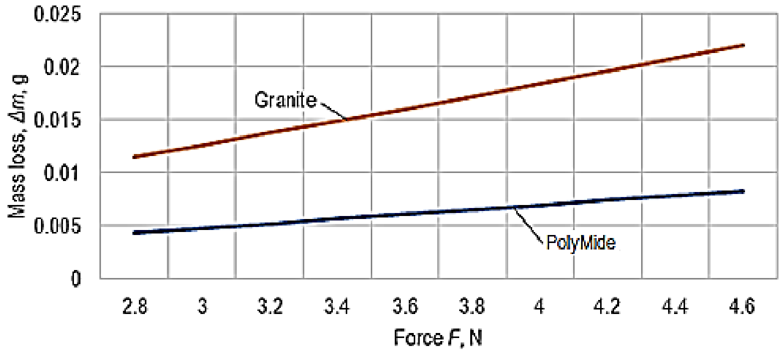

Figure 4 – Influence of the magnitude of the pressing force F on the material loss Δm for the two materials of the test samples (g=660)

It was thus found that the highest value of the exponent attached to an independent variable corresponds to the nature *m* of the test sample material, in this case, the exponent has a value of 1.414. This means that among the three input factors in the abrasive erosion testing process, the strongest influence is exerted by the nature *m* of the test sample material, this being followed by the magnitude of the force *F* of pressing the test sample on the working surface of the abrasive paper and, respectively, by the granulation *g* of the abrasive material. On the other hand, it is found that the value of the exponent attached to the variable *F* is positive, while the exponent attached to the grain size *g* has a negative value. As expected, when the force *F* of pressing the test sample increases, there will be an increase in the size corresponding to the loss of material *Δm* by the test sample, while increasing the variable *g* corresponding to the granulation, there will be a decrease in the size *Δm*. Let it emphasize that the number corresponding to the granulation *g* corresponds to the number of meshes per square inch of the sieve with which the abrasive grains were sieved. Among the two materials of the test samples, a higher resistance to abrasive erosion corresponds to the carbon fiber-reinforced polyamide. This may be due to the higher mechanical strength of the carbon fibers.

Conclusions

The use of parts made of composite polymer materials in conditions characterized by the possibility of wear through abrasive erosion led to the design of solutions for testing test samples made of composite polymer materials to abrasive erosion. For this purpose, a device was designed that uses the pin-on-cylinder testing method and that can be adapted to a universal lathe. A granite-type material and a carbon fiber-reinforced polyamide-type material were used as the materials of the test samples. The grain size of the abrasive paper and the pressing force of the test sample on the active surface of the abrasive paper were also used as independent variables. Mathematical processing of the experimental results allowed the determination of empirical mathematical models. These empirical mathematical models are capable of highlighting the direction and the intensity of the influence exerted by the input factors in the abrasive erosion testing process on the amount of material loss by the test sample for a test duration of 1 minute. It was found that the strongest influence on the loss of material by the test sample as a result of the abrasive erosion process is exerted by the nature of the test sample material, followed by the magnitude of pressing force on the test sample and, respectively, by the grain size of the abrasive material on the active surface of the abrasive paper. It was found that the carbon fiber-reinforced polyamide test samples demonstrated greater resistance to abrasive erosion, compared to the abrasive erosion resistance of the granite-type polymer composite material. In the future, it is intended to carry out experimental tests taking into account other input factors in the abrasive erosion testing process.

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