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Research on Parts Manufacturing from Composite Materials with Short Carbon Fibers using FDM Process

SUMMARY

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Contents

Introduction

Currently, the principles of additive manufacturing technologies used in the design and manufacturing of industrial parts are the subjects of an extensive process of re-evaluation and reorganization of the traditional design and manufacturing processes, representing an important direction of research in industrial engineering. Considered to be a part of the fourth industrial revolution, additive manufacturing processes are a current topic of discussion, being used in various fields such as: automotive industry, the aerospace industry, medicine, civil construction or just as for hobby applications [BLA24A]. In addition to the used additive manufacturing processes, the present doctoral thesis entitled ***Research on Parts Manufacturing from Composite Materials with Short Carbon Fibers using FDM Process*** uses a very up-to-date technique - Reverse engineering, mainly for the case study developed in order to validate the research results [SRI16]. The study corresponds to the ***field of Industrial Engineering***.

The doctoral thesis focuses on performing research related to the thermoplastic extrusion of the material - FDM/FFF, with the aim of maximizing the mechanical characteristics of the parts which are resulted from the manufacturing process. The main reasons for the selection of this technology are the relatively low costs of equipment and of the used materials. In most of the research, the specified reasons are considered to be lower compared to other additive manufacturing processes. Also, the actuality of this research topic resulted from the increased interest of researchers in the development of this manufacturing process, considering the multiple advantages identified.

Among the advantages, the compatibility of the manufacturing process with a wide range of materials, from polymers to composite materials, with an increased capacity to expand the types of materials that can be used, should not be neglected. Considering the type of application, the used material is aimed to maximize various properties, such as thermal, chemical, optical, mechanical and rheological properties [WIC20], [KAF21].

Considering the approach of a method of manufacturing of the parts with structural functionality, a challenge for these applications is to maximize the values of the mechanical properties. In this regard, a great disadvantage of the parts manufactured by the FDM/FFF process is the anisotropic behavior of the material. In reality, in various applications, multidirectional loading appears. The improvement of the process imposes the knowledge of the influence of the elements with consequences over the final results, and the establishment of those with greater impact.

The research performed within the doctoral study program aims at several levels: the costs of the materials, the implementation time and the closeness to reality for the stated hypotheses.

The completed stages, which take into account the milestones previously mentioned, are also structured into chapters as follows.

In the first chapter, the technical literature is studied, highlighting the current state of the research for the FDM/FFF manufacturing process, the influence of the manufacturing parameters on the mechanical properties (various types of loadings) of the parts, but also the behavior of the materials, especially for composite filaments with carbon fibers.

Based on the conclusions stated at the end of the first chapter, the second chapter establishes the objectives of the research, and in the following chapters are presented the methods of solving them.

In the third chapter, the theoretical concepts are established. Also, the materials and equipment used in the research are identified and described. Considering the previously presented equipment, specimens made from short carbon fiber composite filament are fabricated. These are subsequently tested for tensile, compression, bending and shear loadings. After testing, they are analyzed macroscopically and microscopically. Also, failure criteria are documented.

In the fourth chapter, considering the results obtained in chapter 3 for the tensile specimens, after a statistical processing of the experimental data, a regression model is developed. This is used to determine values of the tensile strength for any value of the manufacturing parameters considered in experimental research.

In chapter five, as in the third chapter, the same analyzes and tests are performed for specimens made from the polymer of the studied material.

The sixth chapter presents the influence of the addition of carbon fibers in the polymer in terms of mechanical behavior, appearance and manufacturing defects.

The seventh chapter mathematically describes the studied material and shows how FEM analysis is performed in order to compare virtual simulations with experimental tensile tests.

In the eighth chapter, a case study is performed for two parts from a drone assembly, using the PET CF15 material. In order to perform the studies, the parts are selected, redesigned, remanufactured considering the studied material, and tested for a vertical loading.

Chapter nine is dedicated to the presentation of the final conclusions of the research, the personal contributions made in the field of the doctoral thesis, the methods in which the research is disseminated and future research directions.

As methodology, in order to determine the approach for obtaining better results that can be obtained, especially from the point of view of mechanical properties, initially a thorough study of the technical literature regarding the use in the FDM/FFF process of simple polymers, but also composite ones containing short and continuous fibers is performed. The aim is to identify and differentiate various types of materials, and to identify their advantages and disadvantages. During the research, the thesis considers theoretical research methods which are correlated with experimental research methods through experimental tests. These are sustained by simulations in a virtual environment, such as Finite Element Analysis (FEA) and experimental design methods (Design of Experiments - DoE). For these, working hypotheses are issued based on the conclusions obtained following the literature review, corroborated with theoretical concepts and similarities with materials which are already studied.

1. CURRENT STATE OF RESEARCH IN THE FIELD OF ADDITIVE MANUFACTURING USING FDM PROCESS

Thermoplastic material extrusion comes from the English translation and adaptation of the name of Filament Deposition Modeling, abbreviated as FDM. The FDM process is based on the principle of material extrusion. Thus, the material from the filament roll is melted and with a constant pressure it is uniformly distributed along the path followed by the extruder, with the help of a nozzle, as it is shown in Figure 1. The extruded material solidifies approximately to the shape generated by the nozzle and adheres to the previously deposited material to form the printed layer and subsequently the entire part. As long as the material is extruded, the machine controls the material deposition to generate the section of the part, which is parallel to the printing platform, thus allowing for additional layers of the part to be completed.

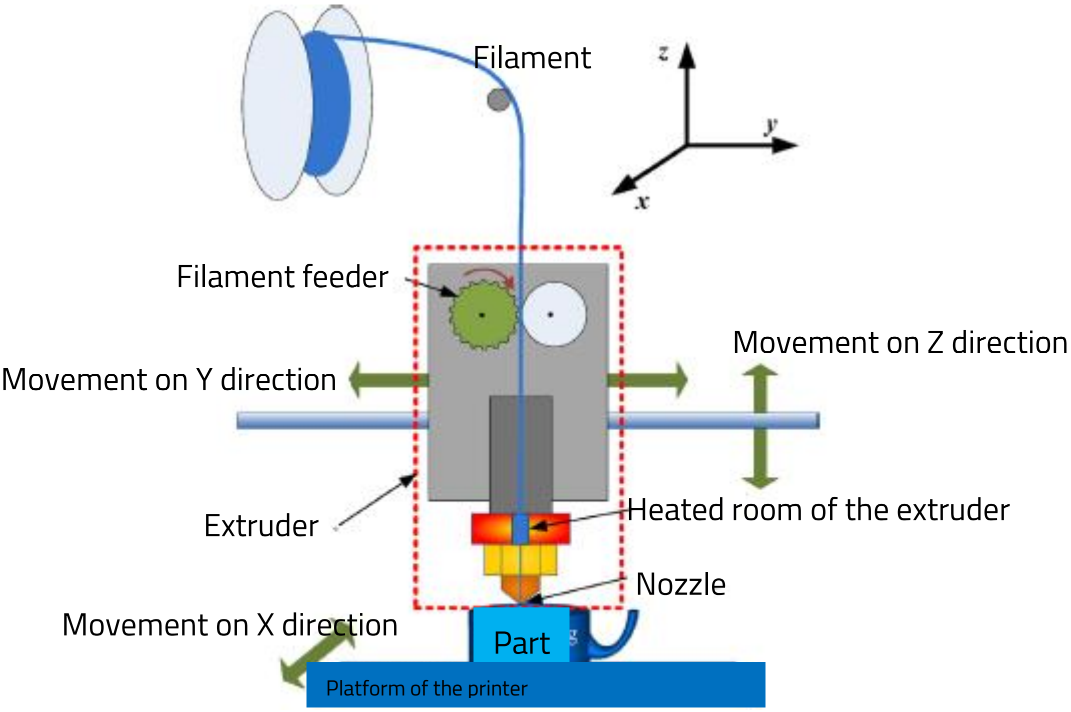


Figure 1 Basic chart of the extrusion system [JIN15], [BLA21]

The FDM additive manufacturing process is a manufacturing technology for which, depending on the used material and the manufacturing parameters, the final values of the mechanical properties of the part can be different. In the technical literature, it is highlighted that there are a number of manufacturing parameters that can significantly influence the mechanical properties of the parts, such as the layer thickness, infill, the orientation of the part on the printer table, the temperature used, etc. [MAZ19], [WIC20], [KAF21]. It is specified that by knowing the influence of the manufacturing parameters, the control of the manufacturing process can be performed. There is an increased correlation between the manufacturing parameters and the mechanical properties of the parts. In practice, it is recommended to know the purpose of the application in order to minimize the occurrence of manufacturing defects.

The highest influence over the mechanical properties is defined by the layer thickness, the part orientation on the printer table and the infill, these parameters being taken into account for the research carried out in the present thesis. The topic of geometric stability is also approached - it is noted that initially it is recommended to create the outer contour of the part, followed by the deposition of the material in order to complete the desired surface.

Considering the topic of the manufacturing defects, it is noted that their presence has a high impact on the mechanical characteristics of the parts, in the technical literature being highlighted the issue of material voids and a low adhesion of the carbon fibers into the matrix [BLA22B].

As a result of the literature review, it is found that the parts manufactured considering the FDM process have a similar behavior to composite materials. Due to the similarity with them and the fact that there are no test standards for the additive manufacturing, the standards defined for composite materials are used for testing the specimens made considering FDM process.

Regarding the manufacturing considering FDM/FFF process of parts from composite materials, after consulting the specialized literature, the following research directions can be defined:

- Determination of the optimal values of the manufacturing parameters;
- Determination of a similarity with already studied materials;
- Determination of the mechanical behavior under the action of various types of loading on the composite material, including on the polymer;
- The influence of fiber content on the polymer study;
- Development of mathematical models for the calculation of the mechanical properties according to the manufacturing parameters;
- Identification of manufacturing defects and methods to combat their occurrence;
- Identification of the failure modes and their causality;
- Determination of dimensional deviations of parts manufactured by FDM/FFF;
- Identification of methods for testing and validation for parts obtained considering FDM/FFF.

2. OBJECTIVES OF THE DOCTORAL THESIS

The study of manufacturing parameters is a major interest for researchers, because currently there is no standardized method or procedure which can be used as a reference in the design and manufacturing by the FDM/FFF process of parts that have the characteristics imposed by the final user.

Following the literature review (the first chapter of the thesis), eight objectives of the doctoral thesis are defined in order to perform the research regarding the parts manufacturing made from composite material with short carbon fibers using the FDM process. To fulfill the objectives, in certain situations, intermediate objectives are also proposed. These are the following:

1. Determination of a similarity in the behavior of the parts manufactured by the FDM/FFF process, with known materials;

2. The study of the main manufacturing parameters (layer thickness, infill and the part orientation on the printer table) in order to determine the optimal values – for usage of a composite filament produced by Innofil/Ultrafuse, with a composition of 15% short carbon fibers and a polymer of polyethylene terephthalate (PET):

    a. Development of a methodology for determining the values of manufacturing parameters;

    b. Identification of tensile, compression, bending and shear test methods;

    c. Manufacturing, testing, analysis and macroscopic and microscopic verification of tensile specimens;

    d. Manufacturing, testing, analysis and macroscopic and microscopic verification of compression specimens;

    e. Manufacturing, testing, analysis and macroscopic and microscopic verification of bending specimens;

    f. Manufacturing, testing, analysis and macroscopic and microscopic verification of shear specimens;

    g. Determination of manufacturing defects that influence mechanical characteristics;

    h. Determination of the main failure criteria of specimens tested in the laboratory.

3. The study of the mechanical behavior for the specimens made from the polymer (polyethylene terephthalate - PET), which is considered of the study for the main manufacturing parameters considered in objective 2:

    a. Manufacturing, testing, analysis and macroscopic and microscopic verification of tensile specimens;

    b. Manufacturing, testing, analysis and macroscopic and microscopic verification of compression specimens;

    c. Manufacturing, testing, analysis and macroscopic and microscopic verification of bending specimens;

    d. Manufacturing, testing, analysis and macroscopic and microscopic verification of shear specimens;
    e. Determination of manufacturing defects that influence mechanical characteristics;
    f. Determination of the main failure criteria of specimens tested in the laboratory.

4. The influence of the manufacturing parameters and the studied materials on the dimensions of the specimens;
5. Determination of the influence of short carbon fibers on the properties of the specimens;
6. Development of a mathematical model for the determination of tensile strength;
7. Statement for the calculation hypothesis for FEA simulation of the previously considered specimens:
    a. The statement of a calculation hypothesis by similarity with other materials and by theoretical calculation concepts;
    b. Defining the composite material based on the stated hypothesis;
    c. Virtual testing for tensile specimens;
    d. Viability of the hypothesis - Comparison with experimental tests results.
8. Verification and validation of the results obtained considering the case studies:
    a. The choice of two parts representative for the aerospace industry for the development of case studies for which the FDM/FFF manufacturing process is applied;
    b. Usage of the concept of Reverse Engineering for the two parts;
    c. Parts remanufacturing;
    d. Practical validation of the two parts by testing the entire assembly.

3. RESEARCH ON DETERMINATION OF MECHANICAL PROPERTIES OF PARTS MADE FROM COMPOSITE MATERIAL WITH SHORT CARBON FIBERS USING FDM PROCESS

3.1. Theoretical Concepts

To perform theoretical and experimental research regarding the determination of the values of the manufacturing parameters, the layer thickness and the infill, for the Fused Deposition Modeling process using Innofil/Ultrafuse filament with 15% short carbon fibers, with a polymer polyethylene terephthalate (PET), but also from PET filament, 3 values are chosen for each parameter [BLA22B], [BLA24A]:

- Layer thickness: 0.15 mm, 0.20 mm and 0.25 mm.
- Infill: 100%, 75% and 25%.

These parameters are chosen based on the literature review as those with a high influence on the mechanical properties of the parts that are manufactured considering the FDM process. According to those concluded in the literature review stage, the main orientation of the material deposition for the study is the longitudinal direction. Considering this direction, the initial tests and experiments are performed. For the most advantageous results from the point of view of mechanical properties, the related tests are performed in order to obtain details for the other orientation directions of the material deposition. For these values, a description of the material is made from the point of view of compression, bending and shear loadings on the 3 main orientation axes. In parallel, based on the same results of the manufacturing parameters, tensile, compression, bending and shear tests are performed for the 3 main orientation axes of the PET CF15 and PET materials, in order to observe the behavior of the polymer and the influence of the carbon fibers in the matrix.

In the research, to identify the specimens according to the type of loading, material, deposition and the value of the parameters chosen for the study, the following notation is used: *Material_ Solicitare_ Infill_ GrosimeStrat_ AxaOrientarePiesă*,

where: material can be PET CF15 or PET, *Solicitare* (Loading) can be T for tension, C for compression, I for bending, and F for shear.

For the density of deposited material (infill), the percentage value is used: 100, 75 or 25, and for *GrosimeStrat* (Layer Thickness), the 2 decimal places of the layer thickness are used, from the chosen parameters (such as 15, 20 or 25). *AxaOrientarePiesă* (Part Orientation) refers to the orientation of the part on the printer table, coded as longitudinal X, transverse Y or vertical Z [BLA22B], [BLA24A].

According to what is specified in the literature review, the parts made by the FDM process are similar to those made from composite materials, their material being considered anisotropic, due to the differences in the mechanical properties that appear in all orientation directions of the material [TUT13], [BLA22A]. In this case, the material is considered to be orthotropic, i.e. it has different physical and mechanical properties in 3 directions of a fixed orthogonal system, being a particular case of anisotropy [BLA22A]. Also, as a hypothesis it is considered that the material is considered to be homogeneous.

Due to the similarity with the composite materials, the following standards are used for testing:

- For tensile – ASTM D638 standard [AST14A];
- For compression – ASTM D695 standard [AST15];
- For bending – ASTM D790 standard [AST17];
- For shear – ASTM F606 standard [AST14B].

3.2. Equipment and materials used

Innofil/Ultrafuse filament with 15% short carbon fibers with a polyethylene terephthalate - PET matrix is used as a study material in this research. In order to highlight the influence of the carbon fibers on the PET polymer, an Innofil/Ultrafuse PET filament is also used in the research.

The manufacturing process uses the BCN3D Epsilon W50 machine, which is an industrial printer with large working platform dimensions (420mm x 300mm x 400mm).

For the tensile, compression and bending tests, the universal testing machine WDW-150S manufactured by IE Corporation, Jinan, China is used. For the shear stress, the MTS Criterion C43.504 testing machine manufactured by MTS System Corporation, USA is used.

For visual analysis of the specimens, the Nikon T1-SM microscope produced by Nikon Industrial Metrology in Japan, the Leica Emspira 3 microscope produced by Leica Microsystems in Germany are used. Hitachi S3400N type II microscope produced in Japan is used for SEM analysis.

3.3. Microscopic analysis of the PET CF15 filament

Since the quality of the filament is important to the final result of the obtained parts, a visual analysis is performed using the Nikon T1-SM microscope and the Hitachi S3400N Type II microscope.

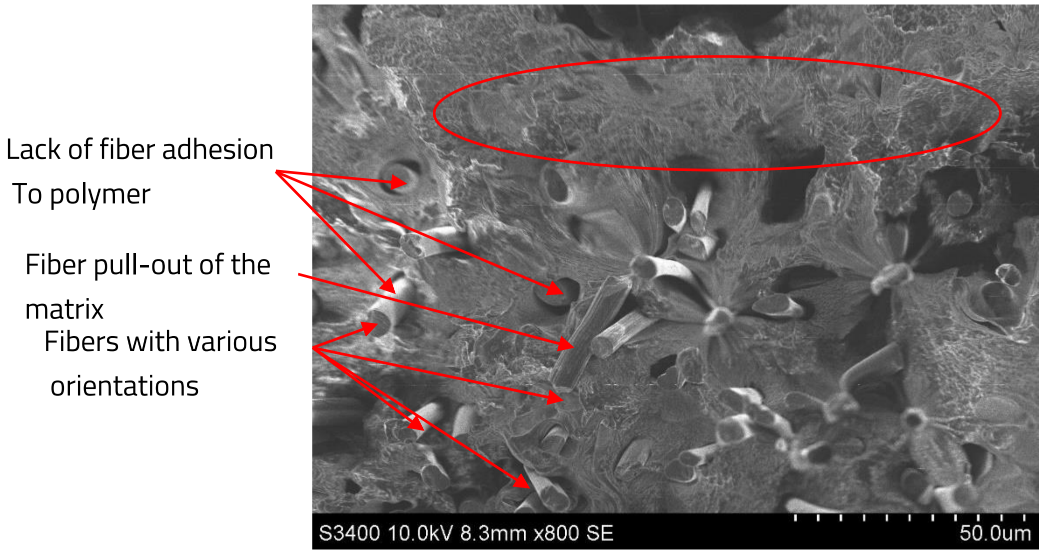


Figure 2 Cross-Section of PET CF15 Filament - Hitachi S3400N Type II Microscope [BLA24A]-Detail

For the areas considered for the visual inspection, it is found that the cross-sections considered show circularity deviations, material voids by variable sizes, short carbon fibers conglomerates or areas where carbon fibers are not present. The presence of carbon fibers that are not oriented perpendicular to the considered section or carbon fibers that are out of the matrix are also found, as in the example from Figure 2.

3.4. Manufacturing and tensile testing of PET CF15 specimens

Initially, it is referred to the manufacture and testing of tensile specimens in the longitudinal direction. A set of 5 specimens is printed for each combination of parameters. Following the manufacturing of the 9 sets of 5 specimens each, it was found that visually, the surfaces/parts made with the help of this printer are of good quality [BLA24A]. The fabrication time varied from 4 to 8 hours, with the specimens having the same position on the printer platform.

Figure 3 Tensile Specimens – Longitudinal direction – before and after testing [BLA24A]

Figure 3 shows the tensile specimens manufactured with the orientation of the deposited material in the longitudinal direction, before and after testing, for each set considered – based on the related coding. Following the tensile loading, it is found that for the set in which the material density is 100% and the thickness of the material layer is 0.15 mm, the most homogeneous results are obtained, the breaking section being relatively similar and in approximately the same location. The influence of the infill is visible with the decrease of the value up to 25%, where the weakest characteristics are observed from a visual point of view: there are areas with more pronounced delaminations compared to the other specimens (with other values of the infill), but also areas in which the break occurs at random points of the specimens, there being no similarity between them.

Visually, for the variation parameter of the thickness layer, no conclusions can be assumed after a macroscopic analysis, due to the similar results regarding the fracture and the generated sections. The influence of this parameter is analyzed using the microscope [BLA24A].

Also, for each set of specimens the material curves are defined, but Figure 4 shows the material curves for the set with the best results, for the set where the material density is 100% and the layer thickness is 0.15 mm.

Analyzing Figure 4, a similar behavior can be observed for all 5 specimens. In the linear area of the curve, an almost identical overlap of them is observed, the area where Hooke's Law is applicable. Starting with the area where the transition from elastic to plastic regime takes place, i.e. the area where the strains values increase more suddenly, the specimens begin to differentiate, but the differences are not major, having a similar behavior. After passing the point where detrimental deformations appear, the part begins to have plastic deformations, which lead to the continuation of the curve differentiation regime, the material behaving differently, registering different points for the tensile strength, recorded at different values of the strains.

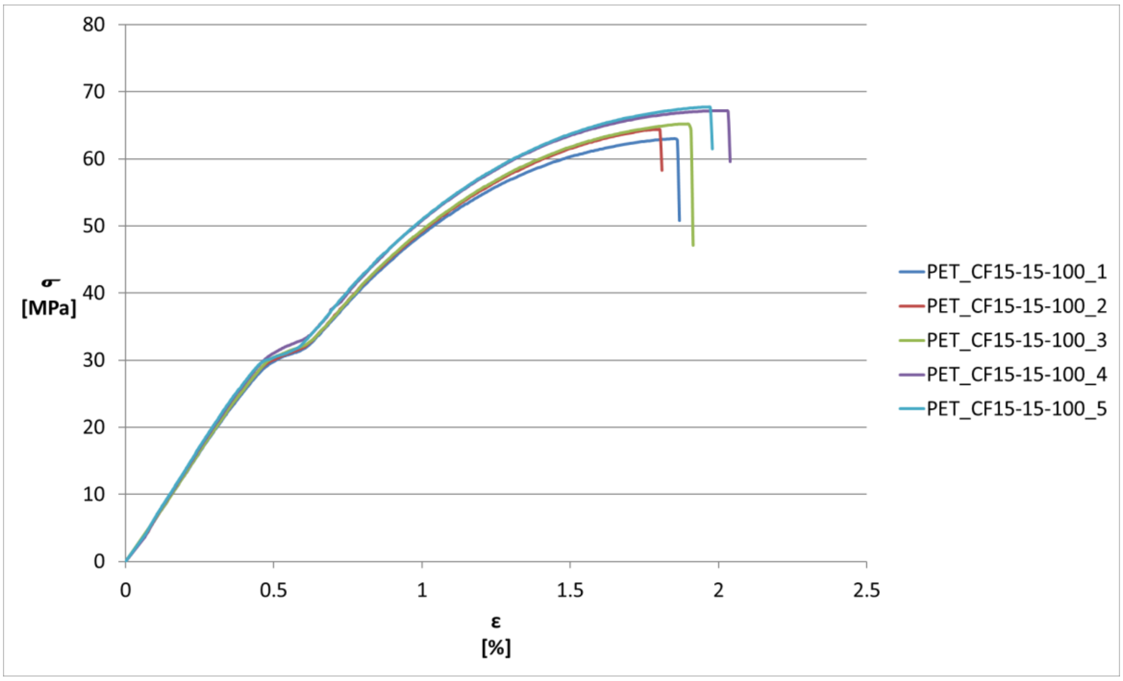


Figure 4 Tensile material curve for PET CF15_15_100 – longitudinal [BLA24A]

The representative values that will be used to mathematically describe the PET CF15 material in the longitudinal direction are shown in Table 1. From the values mentioned in the previous table, an identical stiffness is recorded for all the specimens, and the average values of the whole set of specimens are calculated, which are further used for comparisons and analyses. For the tensile strength, the maximum recorded value is 68 MPa and the minimum value is 63 MPa. The yield strength has a maximum value of 55 MPa and a minimum value of 49 MPa. The maximum value of strain at break is 2.05%, and the minimum value is 1.82%. The maximum value for stresses is recorded at specimen number 5, the minimum value at specimen number 1. The maximum value for strains is recorded at specimen number 4 and the minimum at specimen number 2.

These are the values of the manufacturing parameters that will be used further in the description of the material, as well as for other comparisons, but also for the case study. Moreover, the manufacturing parameters are used to continue the tensile study for the other directions, as well as to determine the behavior of the material in compression, bending and shear.

Table 1. Tensile test results for the longitudinal direction of the specimens PET_CF15_15_100 [BLA24A]

Specimen	Parameter					
	Fm [kN]	Rm [MPa]	Fp [kN]	Rp[kN]	E [GPa]	ε [%]
PET_CF15_15_100_1	2.661	63	2.066	49	9	1.88
PET_CF15_15_100_2	2.718	64	2.133	50	9	1.82
PET_CF15_15_100_3	2.753	65	2.146	51	9	1.91
PET_CF15_15_100_4	2.837	67	2.228	53	9	2.05
PET_CF15_15_100_5	2.86	68	2.326	55	9	1.99
Average value	2.77	65.40	2.18	51.60	9	1.93

The paper similarly performs detailed analyzes for each set of specimens. The most disadvantageous results are obtained for the set where the infill is 25% and the thickness layer is 0.25 mm. Their average values are: Rm of 36.40 MPa, Rp of 29 MPa, Young's modulus of 7 GPa and ε at break of 1.44%.

A dimensional analysis of the specimens is also performed. The deviations are calculated for the nominal thickness of the specimen of 3.2 mm and at its nominal width of 13 mm. Through the prism of the obtained results, it is found that the most dimensionally stable parts are the parts with the lowest infill value, and the thickness of the material layer does not have a major impact in this analysis. There are specimens that, due to manufacturing defects, have dimensional deviations with extreme values, generally these are larger than the nominal dimensions proposed by the standard. The largest deviations are recorded in the width of the specimens.

Similar to the method of manufacturing and testing longitudinal specimens, the same steps are followed to obtain results for the specimens with transversely deposited material. In this case it is found that this set of specimens has a more brittle behavior compared to the sets with material deposited in the X direction. Thus, for the transverse direction, Rm is 41 MPa, Rp is 9 MPa, E is 7 GPa and the elongation at breakage is 1.00% [BLA24A]. From the point of view of dimensional deviations, in this case there are no specimens that record dimensional deviations with extreme values, in general they are larger than the nominal dimensions proposed by the standard.

The same steps are followed for the tensile specimens with material deposited in the vertical direction, where the values of the mechanical properties are: Rm is 3 MPa, Rp is 1 MPa, E is 1 GPa and the strain at break is 0.23%. Specimens with material deposited in this direction have the most unpredictable behavior, in practical applications it is necessary to avoid manufacturing parts with material deposited in this manner. From the point of view of the dimensional analysis, it is found that the specimens are not compact, and extreme values are recorded, even if they are manufactured in the same set and conditions.

Thus, Table 2 shows the results of the tensile tests for the PET CF15 specimens, values that will be used further in the research.

Table 2. Tensile test results of PET CF15 specimens [BLA24A]

Tensile Specimen	Parameter			
	Rm [Mpa]	Rp [Mpa]	E [Gpa]	ε [%]
PET_CF15_X	65.4	51.6	9	1.93
PET_CF15_Y	41	9	7	1.00
PET_CF15_Z	3	1	1	0.23

After the tensile tests are completed, each specimen is visually inspected to identify manufacturing defects and to determine failure criteria. For a good visual inspection, for the analysis are used the previously presented microscopes.

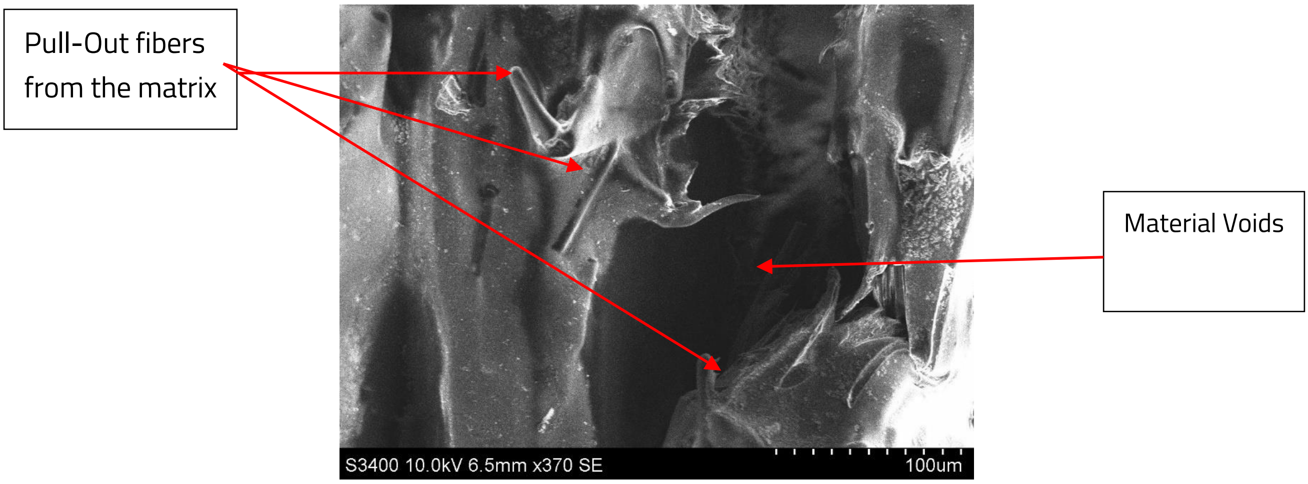


Figure 5 Manufacturing defects – Tensile X- PET CF15 – Material defects (370X) – Microscope Hitachi S3400N Type II

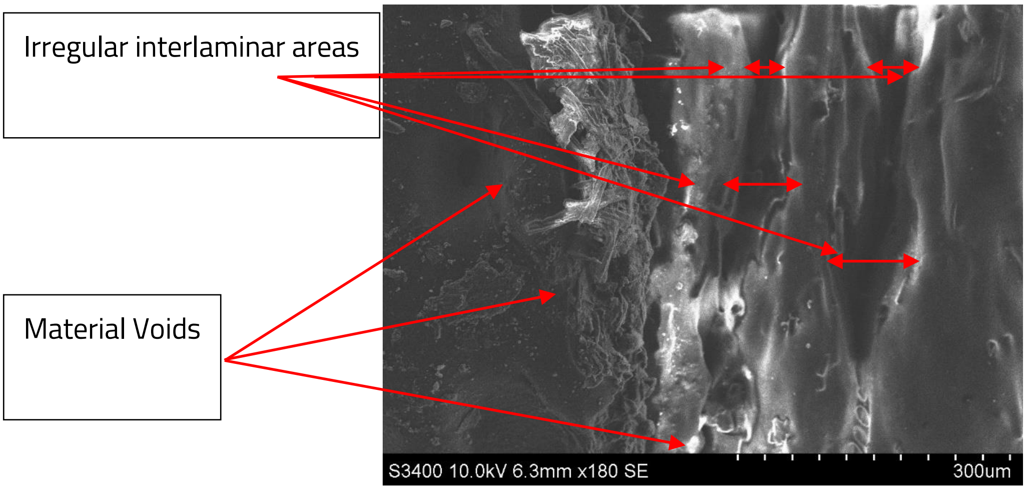


Figure 6 Manufacturing defects – Tensile X - PET CF15 – Material Defects(180X) – Microscope Hitachi S3400N Type II [BLA24A]

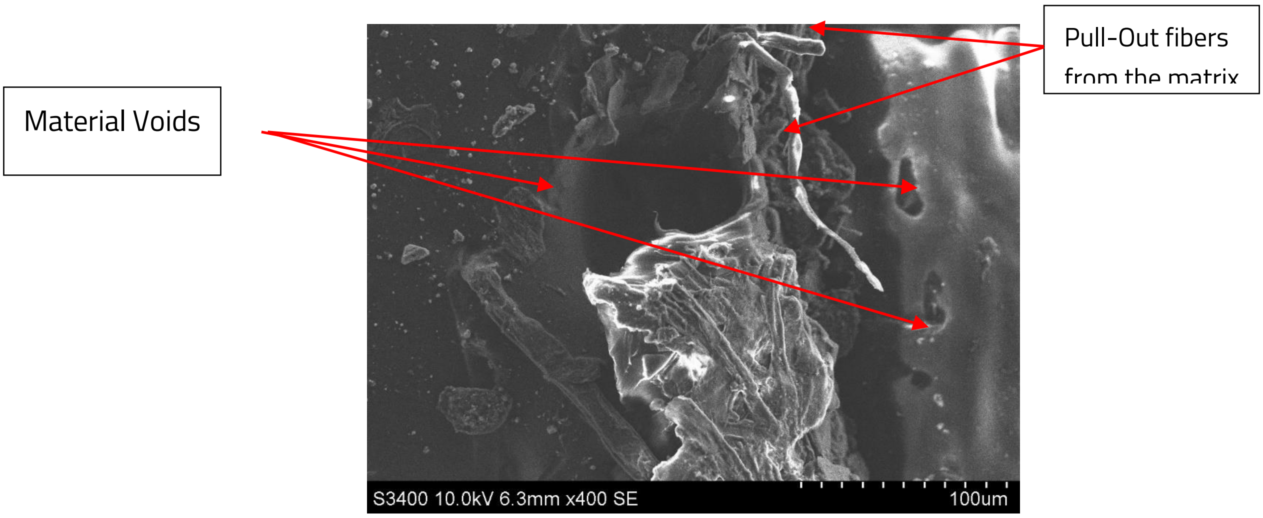


Figure 7 Manufacturing defects – Tensile X - PET CF15 – Material Defects (400X) – Microscope Hitachi S3400N Type II [BLA24A]

After processing the information from the images obtained under the microscope, it is found that there are manufacturing defects in all the specimens, in all of them material voids have been identified, the size and occurrence of which differ, and cannot be predicted. There are also manufacturing defects in specimens that have a much lower recurrence, depending on both the quality of the filament and the additive manufacturing process. These include areas with missing material between deposited layers, areas with layers by different sizes from their nominal dimensions, fibers protruding from the matrix, areas with lack of adhesion between layers, short randomly oriented carbon fibers, the presence of some conglomerates of material affecting the dimensions of the neighboring layers, areas with non-conforming material deposits, areas with overlapping and defective solidification of material or irregular interlaminar areas. Figure 5, Figure 6 and Figure 7 show some examples of defects encountered in the analyzed specimens.

From all the defects presented, not all of them can be anticipated and mitigated. For this reason, for each new material used, manual or automatic monitorization is recommended in order to identify common material defects, but also to determine its behavior for defects that cannot be estimated. For various applications, a validation of the quality of the parts with tests is recommended [BLA24A].

Failure modes are influenced by the presence of previously identified manufacturing defects. These include carbon fibers coming out of the matrix after material yielding under tensile loading, which occurs as a result of poor adhesion between polymer fibers, delamination, cracking or breaking in non-uniform sections of the material.

3.5. Manufacturing and compression testing of PET CF15 specimens

The study for the compression loading is performed for the specimens manufactured with a layer thickness of 0.15 mm and infill of 100%. As a result of the tests, a behavior of the specimens is found: depending on the material deposition direction, both a brittle behavior is obtained for the material orientation directions in X and Y, and a more flexible behavior for the Z deposition direction. Table 3 shows the compression test results for PET CF15 specimens.

Table 3. The results of the compression tests of the PET CF15 specimens

Compression Specimens	Parameter			
	Rcu [MPa]	Rcy[MPa]	E [GPa]	ε [%]
PET_CF15_C_X	70.6	62	2.22	1.47
PET_CF15_C_Y	70.6	62	2.22	1.47
PET_CF15_C_Z	108.8	56.8	1.41	9.81

All parts have dimensional deviations from the nominal dimensions of the specimen, but in this case, the values of the deviations are reduced.

As manufacturing defects, the studied specimens show material voids that may be caused by a poor adhesion of the fibers to the PET matrix, leading to delamination and settling of the material layers in the internal structure. There are also defects that cannot be estimated, these being influenced by the quality of the filament, but also by the manufacturing process. These include: the presence of areas with a lack of material, the lack of adhesion of carbon fibers to the PET matrix, but also the lack of adhesion of layers of material with different widths after deposition.

As failure criteria, in the case of orientation of material deposition in the X and Y direction, delamination and buckling occur, on the other hand, for the vertical direction of material deposition, it is found that not all specimens have failed, the recording of values being limited by the software system of the universal testing machine.

3.6. Manufacturing and bending testing of PET CF15 specimens

Research for bending loading is performed for specimens manufactured with 0.15 mm layer thickness and 100% infill, for all 3 specified orientation directions. For the bending loading of the specimens made of PET CF15, a brittle behavior of the specimens is observed. The weakest result is obtained for the specimens with the material deposited in the Z direction, where a weak adhesion of the material layers is found.

Table 4 shows the values recorded for the PET CF15 specimens that will be used in the research. It is noted that the best results were obtained in the Y direction in this case.

Table 4. The results of the bending tests of the PET CF15 specimens

Bending specimen	Parameter		
	Rbru [MPa]	Rbry [MPa]	Eb [GPa]
PET_CF15_I_X	105	98.8	4.1
PET_CF15_I_Y	122.4	120.8	6.5
PET_CF15_I_Z	35	28	3.5

All parts show reduced dimensional deviations from the nominal dimensions of the specimen.

As manufacturing defects, the studied specimens show material voids that may be caused by a poor adhesion of the fibers to the PET matrix leading to failure of the specimens. There are also defects that cannot be estimated, these being influenced by the quality of the filament, but also by the manufacturing process, these being similar to those presented for tensile and compression loadings.

As failure criteria, in the case of orientation of the material deposition along the X and Y directions, the occurrence of material failures is observed in approximately the same place, which highlights a stability and a relative homogeneity of the parts in this specific batch. In contrast, for the specimens with material deposited in the Z direction, it is found that the fracture occurs in different areas.

3.7. Manufacturing and shear testing of PET CF15 specimens

For the shear loading of the specimens made of PET CF15, a similar behavior is observed for all specimens, the deviations being small. The results are obtained for the manufacturing parameters: layer thickness of 0.15 mm and infill of 100%.

As failure modes, a break is found in an uneven section of the specimens. Compared to the specimen's characteristic of other types of loadings in the case of the deposition of the material in the Z direction, it is found that failure does not occur in the interlaminar zone. Table 5 shows the shear loading tests results values for CF15 PET specimens, which can be used in research.

Table 5. The results of the shear tests of the PET CF15 specimens

Shear specimens	Parameter			
	Rsu [MPa]	Rsy[MPa]	G [GPa]	γ [%]
PET_CF15_F_X	70.5	38.8	2.71	1.83
PET_CF15_F_Y	70.5	38.8	2.71	1.83
PET_CF15_F_Z	47.2	37.3	2.95	1.65

All parts show dimensional deviations from the nominal dimensions of the specimen, but in this case, the values of the deviations are relatively small.

4. STATISTICAL ANALYSING OF EXPERIMENTAL DATA FOR TENSILE LOADING

For a fast determination of the value of the tensile strength according to the values of the manufacturing parameters, the design of experiments is assumed to develop a mathematical model. The aim is to describe the influence of the variables considered in the experiments mentioned in chapter 3 (layer thickness and infill) on the tensile strength. In the definition of the mathematical model, the results obtained for the tensile specimens for the longitudinal direction are considered to identify, from a mathematical point of view, the importance of the manufacturing parameters.

In this study, 2 parameters are considered, each having 3 levels, each with 5 iterations. In this case, a mathematical regression model is built, because by designing experiments, information about one variable can be predicted depending on the other. With the help of the MiniTab software system, the established order for conducting experimental research is determined.

In this case, the determination of the regression model is an iterative process, in which the tensile strength – Rm is considered as the dependent variable. The independent values considered for each determination are the density of the material (Infill) [%] and the thickness of the deposited material layer [mm].

By filling in Minitab the values obtained from tests of all the specimens, these defining the sampling area, in this case Y=Rm, and X1=Infill [%] and X2= layer thickness [mm]. After an iterative selection process, the following polynomial equation is obtained, where I is the material density (the Infill) and t is the layer thickness [BLA24A]:

$$R_m = 67.7 + 0.2739 \cdot I - 3.15 \cdot t + 0.0653 \cdot t^2 \tag{1}$$

In Minitab, a summary of the regression model is obtained, and it can be found in Table 6. The values of the R^2 coefficients being over 90%, the mathematical model presents a high functionality, and it can also be used to obtain values outside the reference ranges of the independent parameters used [BLA24A].

Table 6. Summary of the regression model for the prediction of Rm [BLA24A]

S	R-sq	R-sq [adj]	R-sq [pred]
2.3268	94.08%	93.65%	92.85%

The terms of the equation are correlated with the Pareto chart of the regression model. In this case, the highest influence of Infill is observed compared to the other terms of the relationship.

The coefficient of determination of over 90% recommends the use of the obtained mathematical model for the calculation of the tensile mechanical characteristics (tensile strength) for samples made of PET CF15 material depending on the input parameters considered: the thickness layer and the Infill [BLA24A].

5. RESEARCH ON DETERMINATION OF MECHANICAL PROPERTIES OF PARTS MANUFACTURED FROM THE POLYMER OF COMPOSITE MATERIAL WITH SHORT CARBON FIBERS, USING FDM PROCESS

The specimens made of PET are produced with a layer thickness of 0.15 mm and infill of 100% and tested under the same conditions as the specimens made of PET CF15, to highlight the influence of the addition of carbon fibers in the PET polymer.

5.1. Manufacturing and tensile testing of PET specimens

For the tensile loading of specimens made of PET, the best results are recorded for the specimens positioned in the longitudinal direction (X). Based on these results, the analysis of the material is continued for the other directions, namely Y and Z.

As the orientation of the part on the printer table changes, it is found that the yield zones are positioned differently, the samples becoming more brittle, especially for parts with material deposited in the Z direction.

Table 7 shows the recorded tensile loading values for the PET specimens.

Table 7. Tensile test results of PET specimens

Tensile Specimen	Parameter			
	Rm [MPa]	Rp [MPa]	E [GPa]	ε [%]
PET_X	32.6	26.8	2.2	2.03
PET_Y	31	7	2	0.94
PET_Z	7	3	1.5	0.35

As manufacturing defects, the studied specimens show voids of material which may be caused by a poor adhesion of the fibers to the PET matrix. There are also defects that cannot be estimated, as these are influenced by both the quality of the filament and the manufacturing process. In the specimens with the material deposited in the Z direction, the weakest adhesion between the material layers is found.

The observable failure modes of the material under tensile stress are mainly determined by delamination.

All samples show dimensional deviations from nominal dimensions, but these are influenced by how the part is oriented on the printer table. In some cases, high values are also found, with major differences compared to the rest of the specimens, but these are the result of the manufacturing defects.

5.2. Manufacturing and compression testing of PET specimens

For the compressive loading of PET specimens, a different behavior is observed. Depending on the material deposition direction, both a brittle behavior is obtained for the material orientation directions in the X and Y directions and a more flexible behavior for the Z deposition direction.

As a mode of failure, in the case of orientation of the material deposition in the X and Y direction, the appearance of delamination is found on the other hand, for the vertical direction of material deposition, it is found that not all specimens have failed, the recording of values being limited by the software system of the universal machine to be tested. Table 8 shows the values recorded for the PET specimens that will be used in the research.

Table 8. The results of the compression tests of the PET specimens

Compression Specimens	Parameter			
	Rcu [MPa]	Rcy [MPa]	E [GPa]	ε [%]
PET_C_X	48.2	44.2	1.09	1.41
PET_C_Y	48.2	44.2	1.09	1.41
PET_C_Z	71.2	64.6	2.17	4.62

As manufacturing defects, all the studied specimens show material voids, delamination and subsidence of the material layers in the internal structure. The parts register dimensional deviations from the nominal dimensions of the specimen, but in this case, the values of the deviations are relatively small for the studied manufacturing process.

5.3. Manufacturing and bending testing of PET specimens

For the bending loading of the specimens made of PET, a brittle behavior of the material is observed. The weakest result is obtained for the specimens with the material deposited in the Z direction, where a weak adhesion of the material layers is found. Table 9 shows the values recorded for the PET specimens that will be used further in the research, it can be seen that in the Y direction in this case better results were obtained.

Table 9. The results of the bending tests of the PET specimens

Bending specimen	Parameter		
	Rbru [MPa]	Rbry [MPa]	Eb [GPa]
PET_I_X	85	83	4.3
PET_I_Y	96	85	4.5
PET_I_Z	50	31	4

As a method of failure, in the case of the orientation of the material deposition in the 3 directions, it is found that the breaking occurs in different places, in some specimens there are also multiple breaking zones.

As manufacturing defects, the studied specimens show material voids that can be influenced by a poor adhesion of the fibers to the PET matrix, leading to failure of the specimens. There are also defects that cannot be estimated, these being caused by the quality of the filament, but also by the manufacturing process.

All parts have dimensional deviations from the nominal dimensions of the specimen, but in this case, the values of the deviations are small.

5.4. Manufacturing and shear testing of PET specimens

For the shear loading of specimens made of PET, a similar behavior is observed for all specimens, the deviations being relatively small. Table 10 shows the recorded values for PET specimens that can be used in research.

Table 10. The results of the shear tests of the PET specimens

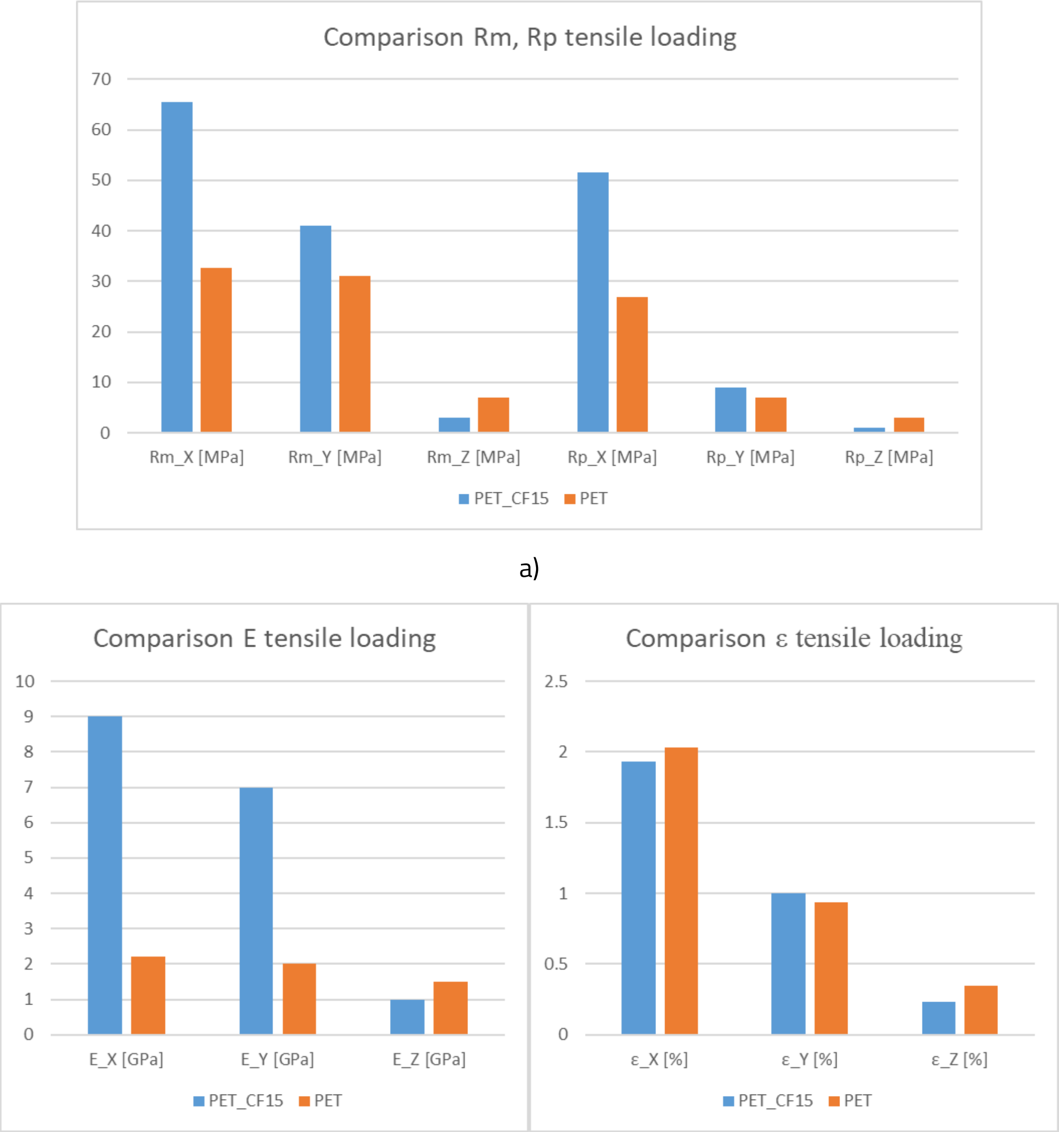
Shear specimen	Parameter			
	Rsu [MPa]	Rsy[MPa]	G [GPa]	γ [%]
PET_F_X	52.3	47.2	2.36	2.03
PET_F_Y	52.3	47.2	2.36	2.03
PET_F_Z	49.9	39.6	1.83	2.25

As failure mode, the fracture is found to occur in a non-uniform section of the specimens. Compared to the specimens of other types of loading, in the case of the specimens with the material deposited in the Z direction, it is highlighted that failure does not occur in the interlaminar zone.

All parts show dimensional deviations from the nominal dimensions of the specimen, but in this case, the values of the deviations are small.

6. INFLUENCE OF CARBON FIBERS ON MECHANICAL BEHAVIOR OF PET MATERIAL

In this chapter, a comparison of the results obtained in chapters 3 and 5 is made to highlight the influence of short carbon fibers on the PET material that constitutes the polymer of the PET CF15 composite material, from the point of view of mechanical properties, but also of manufacturing defects and the failure criteria following the various demands of the studied specimens. From the point of view of the results obtained for the mechanical properties, a comparison is made of the values obtained and presented in Table 1-Table 5 and Table 7-Table 10. Thus, analyzing the results from the previous tables, it is found that the addition of 15% of short carbon fibers in the PET material has a beneficial effect on the mechanical properties, which are, as a rule, improved, regardless of the material's deposition direction.



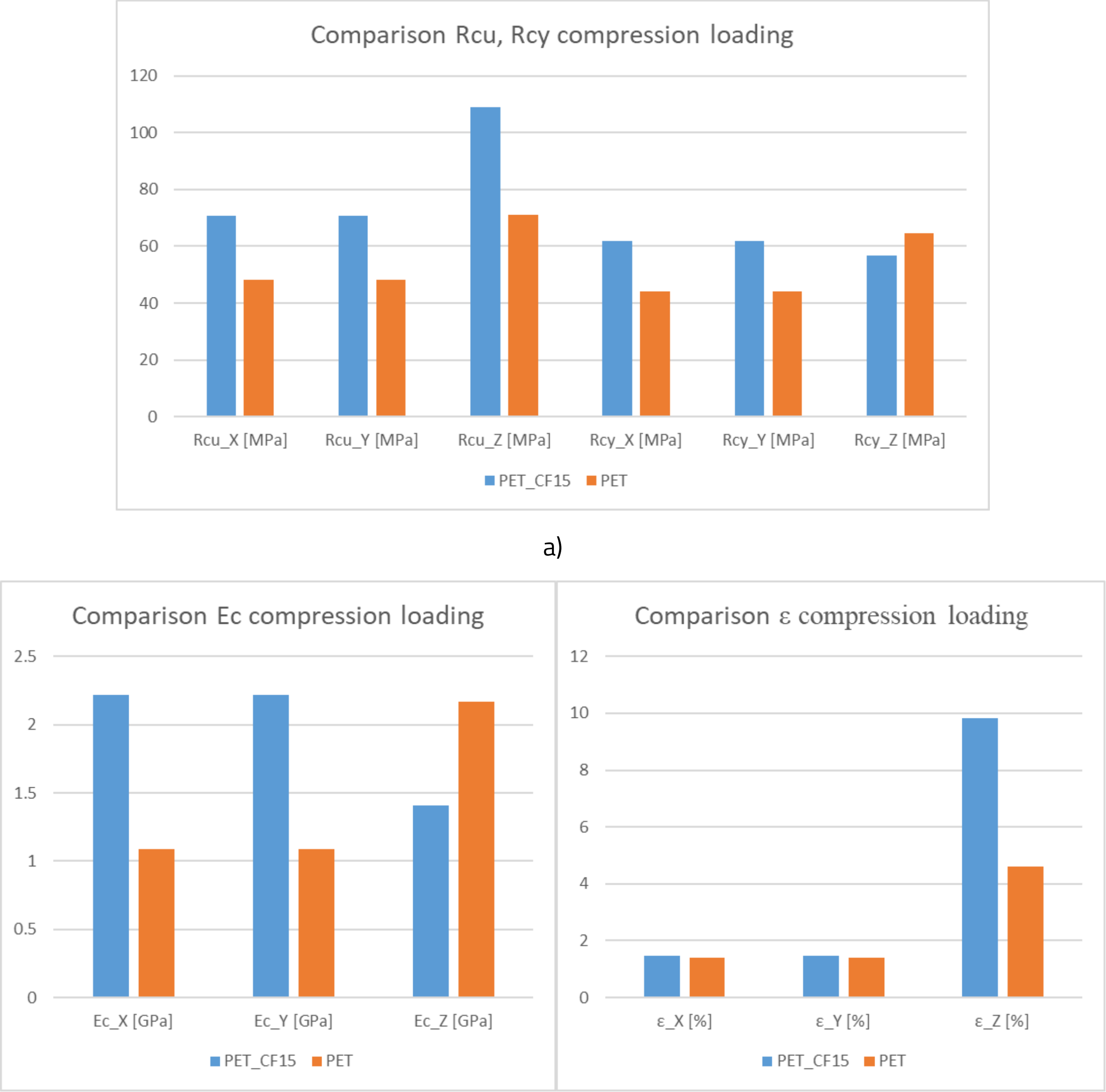
a)

b)

c)

Figure 8 Comparison of mechanical properties values for tensile loading – PET CF15 vs PET: a) Comparison Rm [MPa], Rp [MPa]; b) Comparison E [GPa]; c) Comparison ε [%].

When the tensile loading is in the X direction (longitudinal direction), a substantial increase on the mechanical properties is found (a doubling of the values for Rm, Rp and approximately 4 times the longitudinal modulus of elasticity E). In the Y direction (transverse direction) there is an increase of around 30% in the sizes Rm, Rp and 3.5 times the longitudinal modulus of elasticity (E). For both materials, the worst results are recorded for specimens with material deposited in the Z direction, these being not 100% relevant. In this case, the explanation lies in the fact that the layers of material deposited do not show a high adhesion between them, compared to the other directions of deposition, mostly voids of material are recorded, resulting in some specimens with a brittle character, which do not have recorded values for related tests. Based on the centralized data in Table 2 and Table 7, a graphical comparison is made to highlight the influence of short carbon fibers in PET - Figure 8.



a)

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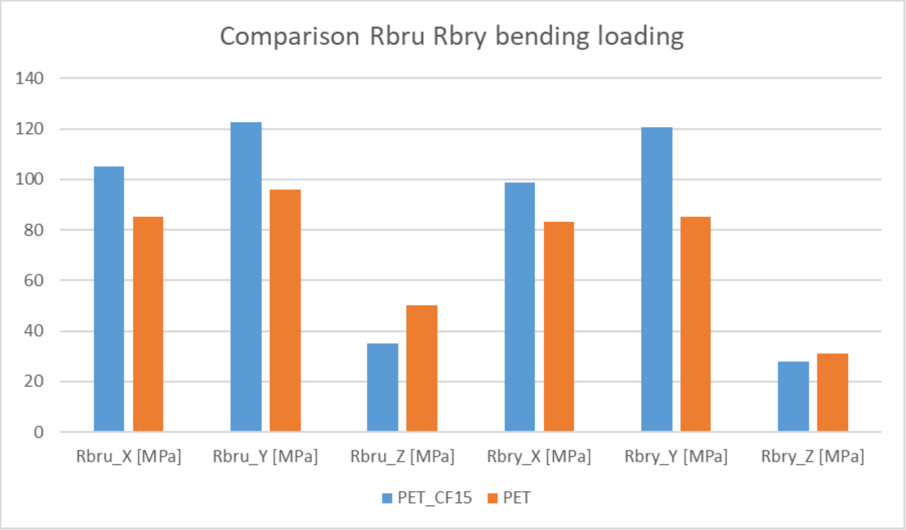
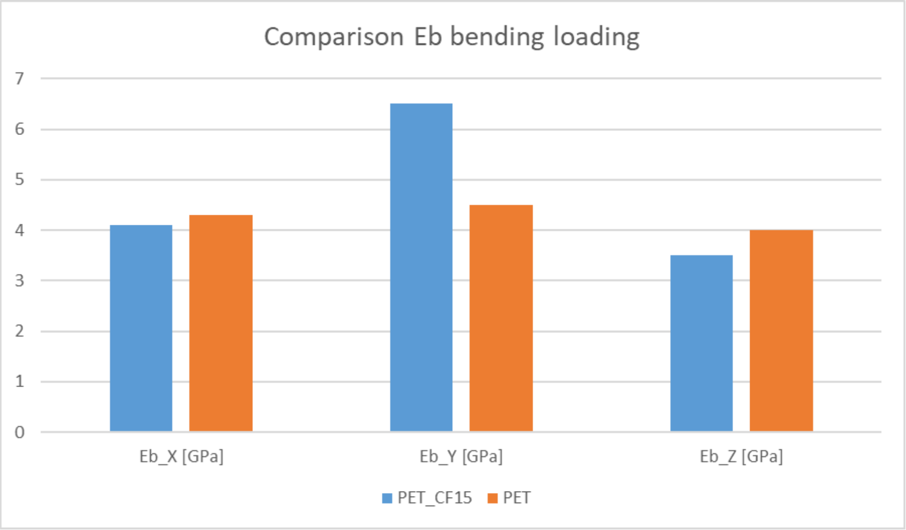
Figure 9 Comparison of mechanical properties values for compression loading – PET CF15 vs PET: a) Comparison Rcu [MPa], Rcy [MPa]; b) Comparison Ec [GPa]; c) Comparison ε [%].

For compression, the most advantageous results are obtained for the Z direction. In this case, a different behavior of the materials is observed: PET CF15 has a brittle character, while PET has a more flexible character. This behavior is highlighted both in the final result of the visual inspection after testing, but also in the way the material curves are made. For the PET specimens, the appearance of the barrel effect is observed (in the specimens manufactured with the material deposited in the Z direction), having a high deformation capacity compared to the CF15 PET specimens. Thus, for the Z direction there is an increase of approximately 1.5 times the value for Rcu and approximately 2.1 times for the elongation, but for Rcy and E, the addition of short fibers has a negative influence, the values of these quantities decreasing to approximately 0.87 times for Rcy and 0.64 times for E. However, for the longitudinal/transverse direction, the addition of short carbon fibers represents a 1.5 times improvement in the Rcu and Rcy values and a doubling of the stiffness value. The strain value is similar. The values presented in Table 3 and Table 8 are materialized in graphic format (Figure 9), in this way the influence of short carbon fibers on the PET material is comparatively visualized.



a)

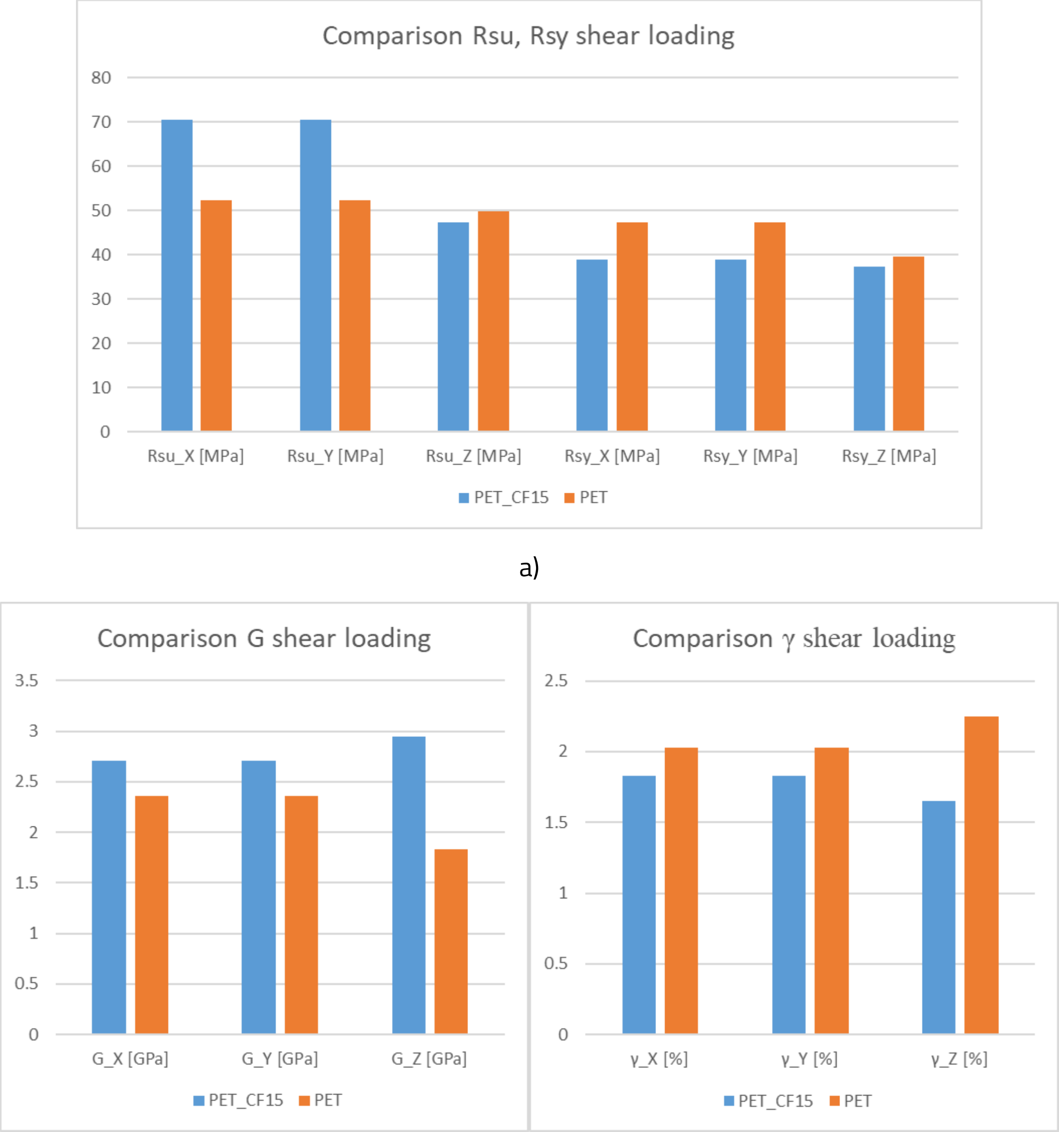


b)

Figure 10 Comparison of mechanical properties values for bending loading – PET CF15 vs PET: a) Comparison Rbru [MPa], Rbry [MPa]; b) Comparison Eb [GPa].

For bending, the most advantageous results are those obtained for the Y direction, and the weakest for the Z direction. In this case, similar manufacturing defects are present as in the case of the tensile specimens. The flexible character of the material is highlighted especially for the specimens with material deposited in the Z direction, where for Rbru a value of 0.7 times lower is recorded following the addition of carbon fibers. Rbry and E decrease by about 0.9 times. For the other directions (X and

Y), improvements in values between approximately 1.2-1.4 times are recorded. For bending loading the values from Table 4 and Table 9 are plotted and shown in Figure 10.



a)

b)

c)

Figure 11 Comparison of mechanical properties values for shear loading – PET CF15 vs PET: a) Comparison Rsu [MPa], Rsy [MPa]; b) Comparison G [GPa]; c) Comparison γ [%].

For the shear loading, the most advantageous results are obtained for the specimens with the direction of the deposited material in the X, Y direction. In this case, for the Z direction it is found that the interlaminar failure did not exist, but only the existence of irregular sections. The addition of carbon fibers in PET has a positive effect for the situation where the material is deposited in the longitudinal/transverse direction – an increase of approximately 1.3 times in the Rsu size value and 1.14 times in the stiffness is recorded. Otherwise, the addition of carbon fibers represents a disadvantage, the values of the results decrease up to approximately 0.7 times for γ, when the material is deposited in the Z direction. For the same result, in the case of the material being deposited in the X, Y direction, the values decrease by approximately 0.9 times. Considering the values presented in Table 5 and Table 10, the graphic comparison is made (Figure 11) in which the influence of short carbon fibers in the PET material, in shear, is highlighted.

Material voids are recorded for the studied specimens. These are more frequent and larger for specimens with carbon fiber addition, a result supported by other research and explained by the fact that the matrix does not adhere 100% to short carbon fibers. This aspect is also reflected by a poor adhesion of the layers of PET CF15 material to those of PET.

Compared to the specimens made only of PET, other defects and failure criteria are recorded, i.e. following various loadings, cases are recorded where the short carbon fibers have come out of the matrix or failed by breaking.

7. FEM SIMULATION OF SPECIMENS USED FOR TENSILE LOADING

Based on the hypothesis that the material is an orthotropic, homogeneous material, it results in its definition through the engineering constants that are also defined in the previous chapter [BLA22A]. These values are also used in finite element analysis software system.

The PET CF15 material is defined with the values previously presented in the form from MSC Patran 2008 [MSC12]. Considered to be a linear elastic and homogeneous material, material properties are assigned to elements of type HEX [BLA22A].

In the pre-analysis step, the tensile design case is created with the average force value of 2770 N taken from Table 1 by embedding the specimen at one end and applying the tensile force at the other end using a RBE3. This type of element has a central node where the force is applied and by setting it to a displacement of 0, it is applied uniformly distributed over the entire width of the specimen, as in Figure 12 [MSC12].

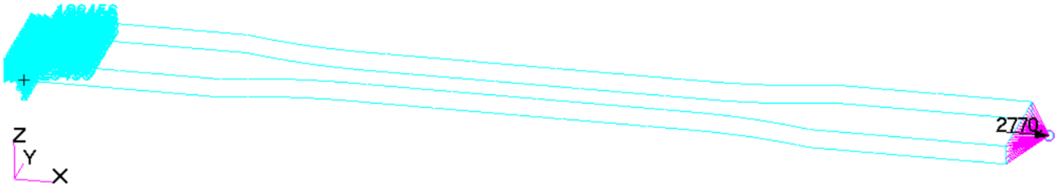


Figure 12 Tensile Specimen – Tensile calculation case in MSC Patran 2008

The calculation solution chosen is SOL 101, which represents a Linear Static calculation. Figure 13 shows the result, assuming that the material is modeled homogeneously and orthotropic [BLA22A]. If the average Rm of 65.4 MPa is obtained in the tests, in the FEM a result of 70 MPa is obtained, 7.03% more than in the tests. This difference is explained by the presence of manufacturing defects that cannot be captured in the mathematical modeling in the FEM. In this situation, the material voids remaining between the layers of material, which appear in the case of parts obtained by additive manufacturing, the FDM/FFF process, are not caught either.

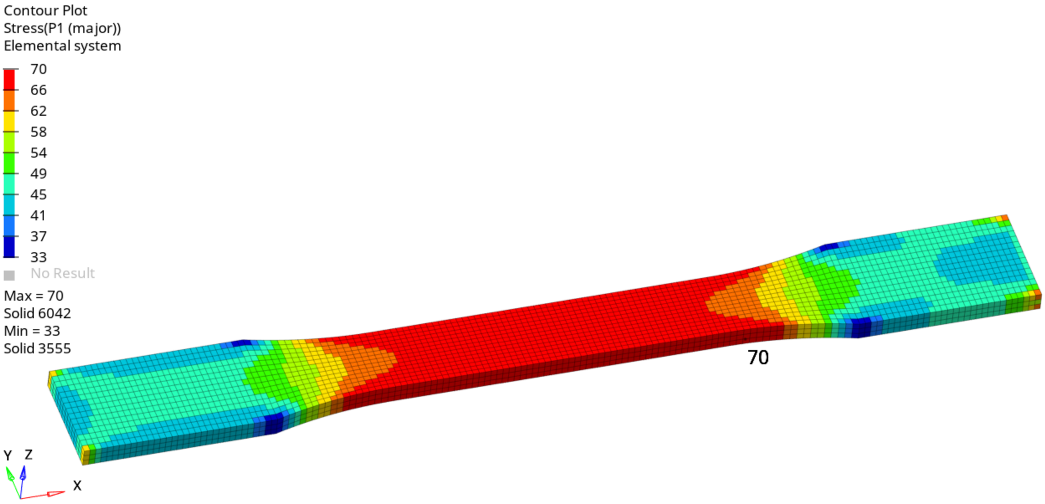


Figure 13 Tensile specimen – Tensile calculation case in MSC Patran 2008

8. RESEARCH ON REMANUFACTURING OF PARTS FROM DJI PHANTOM 3 PRO DRONE

In the case of research that practically validates the use of PET CF15 material, the DJI Phantom 3 Pro drone [WWW12], shown in Figure 14, was chosen. The DJI Phantom 3 Pro drone is proposed for study following the intention to remanufacture parts through the manufacturing process FDM/FFF, parts that are damaged following an incident. This occurred due to the drone colliding with a tree, resulting in an unrecoverable dive accident as the drone's battery was lost. After the accident, detrimental deformations of the landing gear and gimbal breakage were identified. Due to the impact, the gimbal support plate showed cracks.

Figure 14 Drone DJI Phantom 3 Pro [WWW12]

Thus, for the case studies, 2 parts are identified: the landing gear (two identical parts) - Figure 15 and the gimbal support plate - Figure 16.

Figure 15 Landing Gear DJI Phantom 3 Pro– view from inside and outside (relative to mounting mode) [BLA24B]

Figure 16 Gimbal Support Plate DJI Phantom 3 Pro– v view from inside and outside (relative to mounting mode) [BLA24B]

Considering the role of the parts in the structure of the drone, a redesign of them is necessary, taking into account the design rules for additive manufacturing, but also the results obtained from the study of the PET CF15 material.

As a calculation case considered for these parts, a Z-axis load case is considered.

To redesign the parts, the reverse engineering technique is used, which involves, in the first phase, the 3D scanning of the parts (Figure 17 and Figure 18).

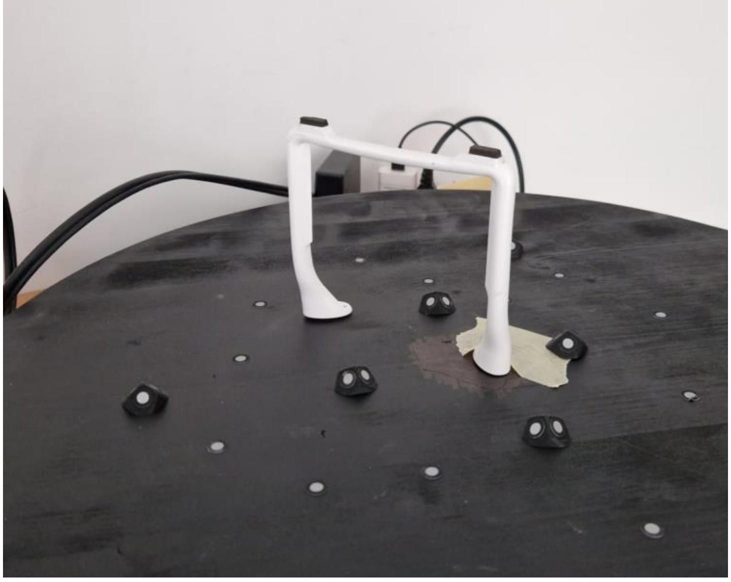


Figure 17 DJI Phantom 3 Pro – landing gear – Part position for 3D scanning [BLA24B]

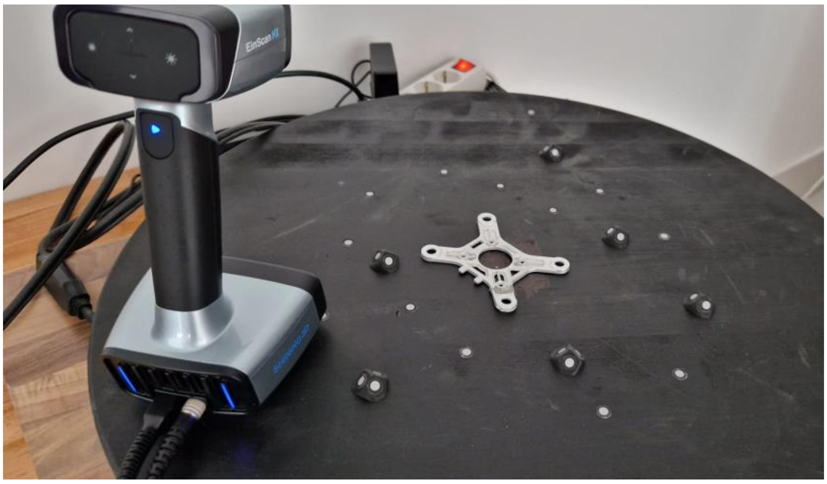


Figure 18 DJI Phantom 3 Pro – gimbal support plate – Part position for 3D scanning [BLA24B]

As working steps, after scanning the parts with the EinScan HX scanner, a processing of the obtained point clouds (Figure 19) takes place in a CAD environment (Catia) (Figure 20), with the aim of reshaping the parts to obtain solid objects that will later be manufactured considering the FDM/FFF process.

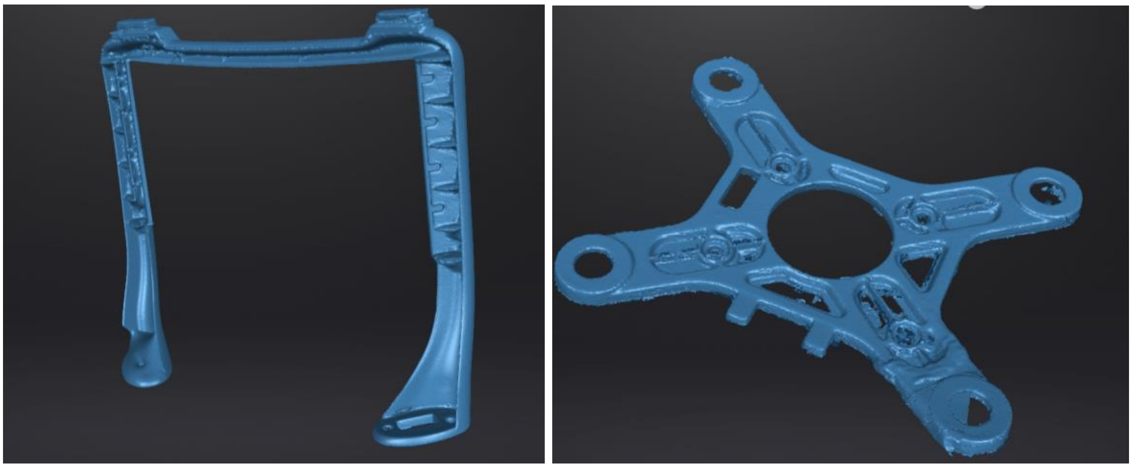


Figure 19 DJI Phantom 3 Pro – landing gear & gimbal support plate – 3D Scanning result with EX Scan HX [BLA24B]

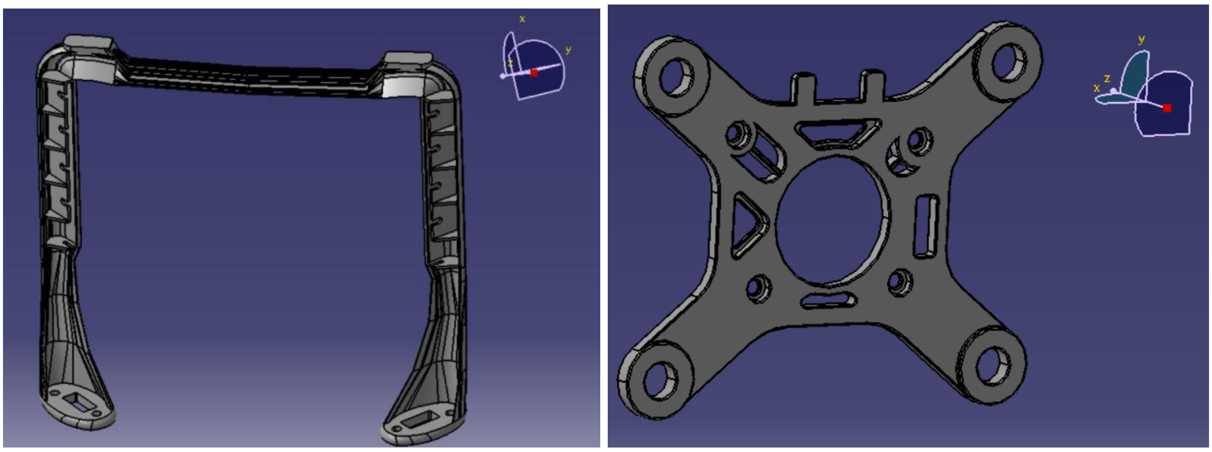
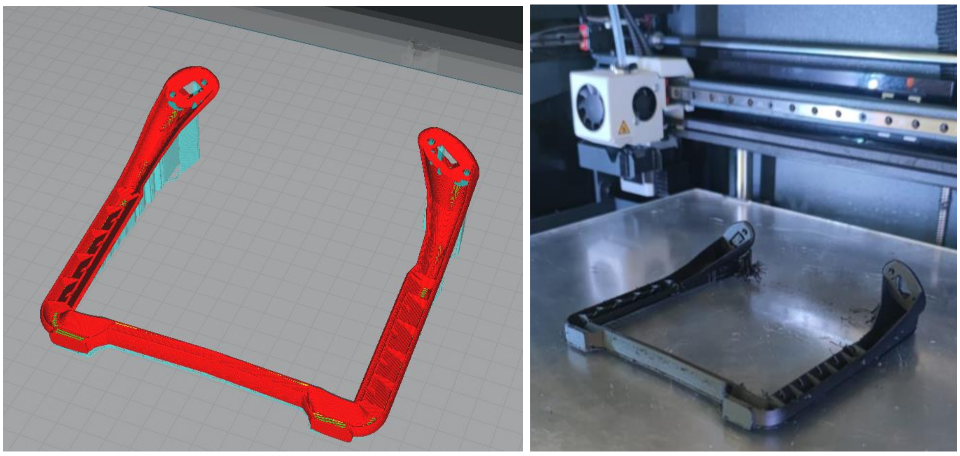


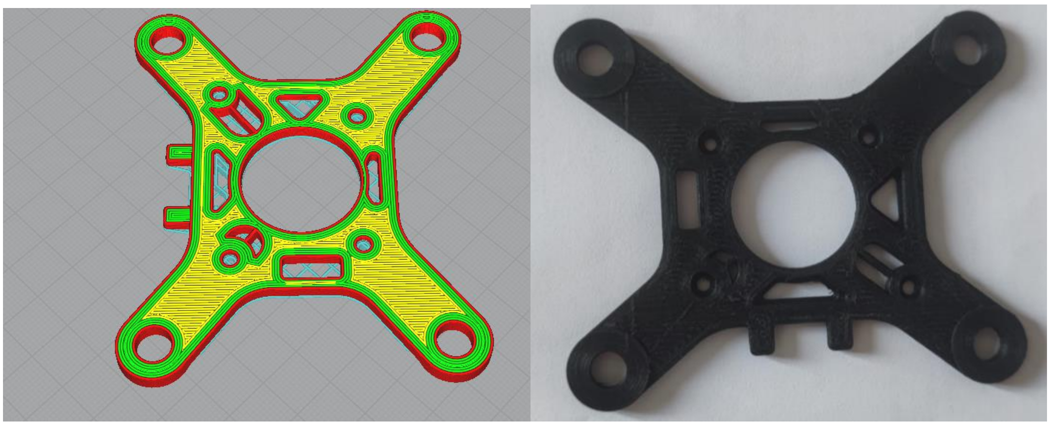
Figure 20 DJI Phantom 3 Pro – landing gear & gimbal support plate – CAD model in Catia [BLA24B]

Taking into account the information from the current stage, but also the results of the tests carried out for the PET CF15 material for the manufacturing parameters with the best results (layer thickness of 0.15 mm and infill of 100%) the two parts considered in the study are being prepared to be remanufactured (Figure 21 and Figure 22).



a) b)

Figure 21 DJI Phantom 3 Pro – landing gear– Representation in BCN3D Stratos and on the printing platform of BCN3D Epsilon [BLA24B]



a) b)

Figure 22 DJI Phantom 3 Pro – gimbal support plate– Representation in BCN3D Stratos and after remanufacturing [BLA24B]

Figure 23 DJI Phantom 3 Pro – drone after the mounting of the redesigned and remanufactured parts [BLA24B]

The remanufactured parts are mounted on the drone to be tested in the assembled state (Figure 23). In order to make a comparison between the drone with original parts and the one with the remanufactured parts by the FDM/FFF additive manufacturing process, the WDW 150S test machine is used, testing a drone with the remanufactured parts as well as a drone with the original parts. Each drone is tested for the proposed calculation case.

Since the materials of the other components of the drone are not known, the behavior of the entire system is analyzed to observe the movements of the parts of interest, of the entire structure, but also the appearance of detrimental deformations and failure of the parts.

For the drone with the original parts, the detrimental deformations occur at 710 N, with a displacement of about 9 mm. The structure breaks to a loading of approximately 1690 N. Similarly, the test for the drone is performed with the redesigned and remanufactured parts considering the FDM/FFF additive manufacturing process. The behavior is relatively similar, in this case the force at which the detrimental deformations appear is 960 N with a maximum displacement of almost 6 mm, and the failure occurs at 1440 N. From the period of the test, a much stiffer behavior can be observed for the drone with the remanufactured parts, and the deformations in the lateral directions not being so great.

The fact that the detrimental deformations occur at 960 N compared to 710 N for the original part, leads to the idea that PET CF15 material can be used successfully for this application. Considering the chosen redesign method, the protection area of the gimbal is ensured, thus preserving the important elements of the drone.

Figure 24 DJI Phantom 3 Pro – drone test with original parts – visual inspection of the structure after tests [BLA24B]

Figure 25 DJI Phantom 3 Pro – drone test with remanufactured parts – visual inspection of the structure after tests [BLA24B]

After analyzing the results, it can be highlighted that, in the first case, the drone shows detrimental deformations in the area of the landing gear and the failure of the lower casing, as shown in Figure 24. In the second case shown in Figure 25, the drone shows the failure of the landing gear landing. In this case, an irregular break appears which can be caused by possible manufacturing defects. The appearance of delamination in some areas is also observed, which are shown in the same figure. It is also worth mentioning that for this drone the casings do not show detrimental deformations.

For the support plate of the gimbal, not being a part with a structural role, no structural changes are found for any tested case. This is protected by casings that have a high degree of deformation.

In this chapter, both the redesigned and remanufactured parts and the material used in the application, PET CF15, are validated practically, the drone structure fails, in this case, to higher values of the action force in the Z direction.

9. FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. DISSEMINATION OF RESULTS. FUTURE DIRECTIONS OF RESEARCH

9.1. Final conclusions

The general conclusions regarding the research conducted and presented in the doctoral thesis can be summarized as follows:

a) Conclusions from the current state of research:

- The FDM/FFF manufacturing process is rapidly developing and has the potential to replace some traditional processes due to its advantages, such as the ability to produce complex geometries at low costs with various materials, ranging from simple polymers to composite filaments that can contain short or continuous fibers.
- The manufacturing process is influenced by several parameters, each having a different impact on the final results. These range from the quality of the filament used, to environmental factors and printer functionality settings. Among the manufacturing parameters with the highest degree of influence are: the thickness layer, the orientation of the part on the printing table, the infill, the temperature used. Furthermore, dimensional stability is sought. In this case, it is recommended that the outer contour of the part is made initially, followed by deposition of the material to complete the desired surface.
- It is pointed out the need to highlight the manufacturing defects that are present in parts manufactured using this technique - in particular, material gaps appear, and low adhesion of the fibers to the matrix is observed in composite filaments. These are found to have a high impact on the mechanical properties of the parts.
- In order to design parts that are fabricated by this manufacturing process it is recommended to know the application (e.g. method and the environment of usage) to minimize manufacturing defects. In this way, by directly influencing the mechanical properties, the behavior of the components in practice can be considerably improved.

b) Conclusions drawn from the research:

- In the research presented in the paper the following manufacturing parameters were considered: thickness layer, orientation of the part on the printing table and infill. For each parameter 3 values are considered, and following the tests performed on specimens manufactured by combining them, the best variant is chosen.
- The examination of the studied material (PET CF15) shows that it exhibits defects, the most common being deviation from circularity and an uneven distribution of short carbon fibers: there are conglomerates with fibers or there are areas where only the polymer is noticeable. There are also carbon fibers protruding from the polymer matrix and carbon fibers that are not oriented in the direction of the filament.
- Knowing the behavior of the material is a necessary step in approaching various practical applications - its behavior cannot be predicted given its anisotropic nature. For this reason, on the based of the conclusions drawn from the specialized literature, the hypotheses for the definition of the material, that is considered orthotropic and homogeneous, are formulated.

- The manufacturing and testing of specimens made of PET CF15 starts with the tensile loading. Five specimens are made for each set of parameters. Following the analysis of the experimental results, it is found that the best results are obtained for specimens manufactured with a thickness of the deposited material layer of 0.15 mm and 100% infill, these being oriented in the longitudinal direction of the printing platform: Rm is 65.4 MPa, modulus of elasticity is 9 GPa and ε is 1.93%. For the whole set of specimens analyzed there are small variations between the results, which proves the degree of homogeneity of the material in the longitudinal direction.
- Considering the set of parameters and values presented above, samples are also made for the other loadings: compression, bending and shear. The tests show that for the compression, a maximum strength (in the Z direction) of 108.8 MPa is obtained, with a modulus of elasticity of 1.41 GPa and ε of 9.81%. For bending the results are: the strength for the bending stress is 105 MPa, with a modulus of elasticity of 4.1 GPa. For shear the maximum strength is 70.5 MPa, with a modulus of elasticity for shear of 2.71 GPa and γ of 1.83%.
- For the specimens analyzed, the occurrence of manufacturing defects is observed, mainly material gaps. There is also a lack of adhesion of short carbon fibers to the PET polymer, sometimes a random distribution of fibers in the matrix (conglomerates of short carbon fibers or areas where only polymer is present). There are also areas where the thickness of the layer is not respected - it is smaller (under-extrusion) or larger (more material is deposited). These types of defects cannot be anticipated and have a negative influence on the mechanical properties of the parts.
- Due to the multitude of factors influencing this manufacturing process it is recommended to develop mathematical models based on material analysis to save time and costs in particular. In the present research, a mathematical model was developed taking into account the results obtained for the tensile loading in the longitudinal direction, and following the statistical analysis of the input parameters, it is found that the greatest influence is given by the infill parameter, followed by the thickness layer.
- Similar to the manufacturing and testing of PET CF15 specimens, the same experimental analyses are also performed for specimens made from the composite filament matrix, PET. Thus, the value for tensile strength of 32.6 MPa, modulus of elasticity of 2.2 GPa and ε of 2.03% are recorded. For compression, in this case too, a maximum strength of 71.2 MPa, modulus of elasticity of 2.17 and ε of 4.62% is recorded in the Z direction. For bending the maximum strength is 85 MPa, with a modulus of elasticity of 4.3 GPa, and for shear the maximum strength is 52.3 MPa, with a modulus of elasticity for shear of 2.36 GPa and γ of 2.03 GPa.
- As a parallel to the recorded manufacturing defects, material gaps are also present in the studied samples, but material adhesion is higher in PET parts. It is also found that the addition of carbon fibers transforms the material from one with some flexibility into a breakable material - due to filament and manufacturing flaws in the PET CF15 specimens.

- The FEM simulation is not 100% relevant due to the large number of factors that cannot be mathematically traced in the model. A good knowledge of the material and its behavior is obtained through experimental tests. In the case of the FEM analysis performed, a deviation on the values obtained is observed - this is explained by the fact that manufacturing defects cannot be captured in the FEM model [BLA19], even if a test for a planar stress state was performed.
- To perform the case study, the parameters with the best experimentally determined values are used: material layer thickness of 0.15 mm, with 100% infill, and for orientation the stress patterns for each part and calculation instance are analyzed and consequently the positioning on the printer bench is chosen. As parts 2 components from the DJI Phantom 3 Pro drone are chosen which are redesigned, remanufactured and then tested. Tests are also performed for the original parts in order to compare the influence of the material modification on the whole rigidity system. As results, the occurrence of detrimental deformations at a higher value of the applied actuating force in the Z-direction is determined for the drone with parts made of PET CF15.

9.2. Personal contributions

As a result of the research performed in the individual study program presented in the PhD thesis, a significant number of personal contributions have been made in the field of additive manufacturing of short carbon fiber composite components using the FDM/FFF process. These are as follows:

1. Elaboration, following a literature review, of a review of the current state of research in the field of additive manufacturing in general, and the FDM/FFF process in particular, highlighting the main aspects and trends in the advancement of further research (Chapter 1);

2. Conduct in-depth research on the mechanical behavior (tensile, compression, bending and shear loadings), according to industry standards, of specimens manufactured by the FDM/FFF process, from Innofil/Ultrafused 15% short carbon fiber filament with a polymer of polyethylene terephthalate - PET CF 15 (Chapter 3);

3. Determination of the main manufacturing parameters and respective recommended values to be used in practice in order to obtain the best mechanical behavior. The parameters are: layer thickness, infill and orientation of the part on the printing platform, and the recommended values: layer thickness - 0.15 mm, infill - 100%, part orientation - longitudinal, X direction (Chapter 3);

4. Macro- and microscopic highlighting of both the major failure criteria of specimens made of the composite material under analysis, experimentally tested in the laboratory, and the manufacturing defects that influence the mechanical characteristics of the composite material under analysis (Chapter 3);

5. Using the Design of Experiments technique and the Minitab software system, a mathematical model was developed expressing the dependence between the tensile strength and the studied parameters, infill and layer size (Chapter 4);

6. Performing research on the mechanical behavior (tensile, compression, bending and shear loadings), according to the standards in effect, of the samples manufactured with the parameters

previously established for the composite material studied, by the FDM/FFF process, from the polymer of the composite material, polyethylene terephthalate - PET (Chapter 5);

7. Highlighting the influence of short carbon fibers on the properties of specimens fabricated from the chosen composite material and polyethylene terephthalate (PET) polymer (Chapter 6);

8. The use of experimentally obtained data in the description of the studied material in a FEM environment (MSC Patran/MSC Nastran, Altair HyperWorks 2021) and simulation of the tensile behavior of the manufactured and tested specimens (Chapter 7);

9. Elaboration of two case studies allowing the validation of theoretical and practical results, for two parts of a partially destroyed drone, for which the Reverse Engineering technique and the FDM/FFF process have been used in order to redesign and remanufacture them from PET CF15 material (Chapter 8);

10. Practical validation of the components by assembly and then experimental testing, with determination of the values related to the mechanical properties (Chapter 8).

9.3. Results dissemination

The results of the research performed during the period of doctoral studies and included in the doctoral thesis have been promoted through the publication of 5 scientific papers, all as first author, distributed as follows: two in Clarivate-WoS indexed journals and three in conference proceedings (one indexed Clarivate WoS - CPCI, one SCOPUS and one BDI). In addition, the three articles published in conference proceedings were presented by the PhD candidate through participation in the conference.

The published papers are the following:

1. Mădălina-Ioana Blaj, Sebastian Marian Zaharia, Cristin Olimpiu Morariu, Alin Pop, Gheorghe Oancea, *Tensile Behavior of Parts Manufactured Using a Material Extrusion Process from a Filament with Short Carbon Fibers and PET Matrix*, Processes (https://www.mdpi.com/2227-9717/12/2/334, indexată Clarivate Analytics WoS-Article, jurnal Q2) Impact Factor 3.5 (2024).

2. Mădălina-Ioana Blaj, Sebastian Marian Zaharia, Alin Pop, Gheorghe Oancea, *Tensile Properties and Manufacturing Defectives of Short Carbon Fiber Specimens Made with the FDM Process*, Materiale plastice (https://revmaterialeplastice.ro/pdf/4%20BLAJ%201%2022.pdf, indexed Clarivate Analytics WoS-Article) Impact Factor 0.782(2021), Presented at Conference PPE21;

3. Mădălina-Ioana Blaj, Gheorghe Oancea, *Parametric design of a complex part in a FEM environment* MATEC Web of Conferences (https://www.matec-conferences.org/articles/matecconf/abs/2019/48/matecconf_mtem2019_03005/matecconf_mtem2019_03005.html , indexed Clarivate Analytics WoS-CPCI),presented at conference indexed Clarivate ISI MTeM2019 (https://mtem.utcluj.ro/);

4. Mădălina-Ioana Blaj, Gheorghe Oancea, *Fused deposition modelling process: A literature review*, - IOP Conference Series Materials Science and Engineering (https://iopscience.iop.org/article/10.1088/1757-899X/1009/1/012006/pdf), presented at CoSME Conference (indexed SCOPUS);

5. Mădălina-Ioana Blaj, Gheorghe Oancea, *FEM hypothesis which can be applied for FDM Applications*, (https://www.afahc.ro/ro/afases/2022/lucrari/22-M%C4%83d%C4%83linaIoanaBLAJ,GheorgheOANCEA.pdf) presented at conference AFASES – Air Force Academy "Henri Coandă" (indexare BDI)

9.4. Future research directions

Future research directions that could be addressed in the PhD thesis area are:

- Identification of methods to mitigate manufacturing flaws;
- Identification of complex methods to capture material behavior in mathematical models;
- Development of computational hypotheses and identification of an enhanced simulation method;
- Developing hypotheses that help identify manufacturing patterns based on resulting defects and their recurrence;
- Extending the research by analogy to composite filaments with other short carbon fiber composition or other polymers;
- Creating software tools for automatic CAD model creation based on GCODE files to highlight interlaminar zones and material gaps.
- Investigating the impact of thermal variations on the studied material.

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