IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

THE EFFECT OF FIBER REINFORCEMENT ON THE INTEGRITY OF COMPONENTS OBTAINED THROUGH ADDITIVE MANUFACTURING

Cumulative Doctoral Thesis – Abstract

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The doctoral thesis analyzes the effect of short carbon fiber reinforcement on the integrity and durability of components made from the thermoplastic material PLA (polylactic acid) and manufactured by 3D printing technology, specifically FDM (Fused Deposition Modeling). The aim of this work is to investigate the impact of fiber addition to the polymer filament, including a comparison between reinforced and unreinforced materials, and to provide a detailed characterization of mechanical properties (tensile, bending, impact, toughness, and fatigue). Additionally, the thesis presents aspects of fracture mechanics combined with finite element analysis.

Additive manufacturing (AM) is an advanced production technique widely used in modern manufacturing. Unlike traditional methods that remove material, AM builds components layer by layer starting from a 3D model. Initially used for rapid prototyping in the 1980s, it has evolved into a viable production method for various applications. As technology has advanced, its uses have expanded significantly, being adopted for the manufacture of rapid tooling and molds for end-use products. Major companies such as Boeing and Ford now integrate this technology into their processes. The most popular 3D printing technology is Fused Deposition Modeling (FDM), which extrudes thermoplastic filaments layer by layer to construct an object. AM offers competitive advantages by enabling the creation of customized goods with complex shapes, efficiently and cost-effectively. A representative process diagram for 3D printing can be seen in Figure 1.

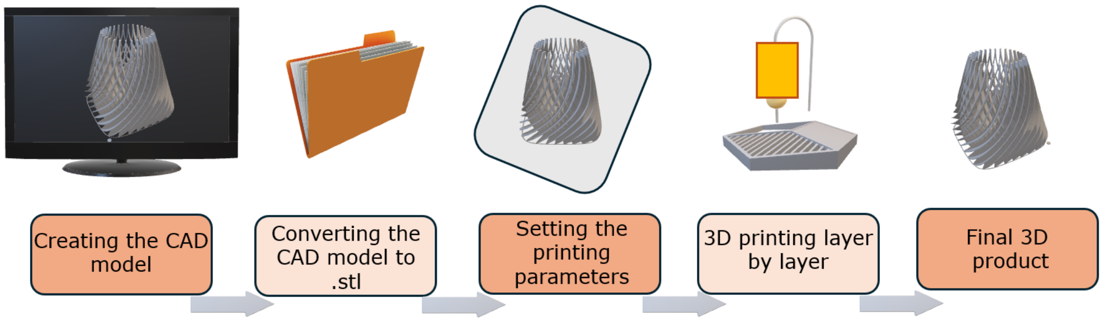

Fig. 1. Process diagram of the 3D printing method

This thesis is cumulative and is structured into 7 chapters: an introduction chapter, followed by 5 chapters containing scientific papers, and finally, a chapter with conclusions, personal contributions, and future objectives.

Chapter 1, entitled *"Introduction",* explores general concepts related to additive manufacturing for composite materials, providing an overview of various methods and techniques used in this field. As the chapter progresses, special emphasis is placed on Fused Deposition Modeling (FDM) printing technology, explaining the principles and advantages of this method. FDM is the main technology used for all experiments and studies presented in this thesis, demonstrating its applicability and efficiency in various scenarios involving thermoplastics reinforced or not reinforced with fiber.

The 3D printing process by Fused Deposition Modeling (FDM) begins with feeding the thermoplastic filament from a spool to the extruder via drive rollers. In the extruder, the material is heated above its melting point and pushed through the nozzle onto the build platform, layer by layer, to create three-dimensional objects. The build platform can be heated to improve interlayer adhesion, preventing defects. After each layer is completed, the extruder and platform move to allow deposition of the next layer. The process requires at least three axes for extruder movement, ensuring complete fabrication of the object.

The FDM method, developed in the 1980s and popularized in the 1990s by Stratasys Inc., is valued for its accuracy, low cost, and ability to create detailed 3D objects. By using solid thermoplastics, FDM enables material recycling and the processing of a wide range of polymers. Among its advantages are ease of operation and design flexibility, although there are limitations such as slower print speeds and inferior surface finish.

Printing speed, print orientation, raster angle, raster width, air gaps, layer thickness, and extrusion temperature are some of the most important parameters described in this chapter that influence the mechanical, thermal, and physical strength of the parts. Tensile strength is the main property analyzed, and FDM parts made from fiber-reinforced thermoplastics are studied in detail.

Figure 2 shows the process of forming the short fiber filament used as the base material for FDM technology.

Fig. 2. Processing of FDM filament with short fibers by mixing and extrusion

Although FDM has disadvantages and compromised mechanical properties, it finds applications in many fields due to its innovative potential. In medicine, FDM is used for creating training models and prototypes for surgical planning, as well as for producing masks and prosthetics. In the pharmaceutical industry, FDM is valued for its cost-effectiveness and versatility in creating dosage forms. It is also used in the textile industry for producing braided structures and shoe heels, and in the automotive and aerospace industries for complex and lightweight parts.

Chapter 2, entitled *"Static and fatigue behavior of 3D printed PLA and PLA reinforced with short carbon fibers"*, is based on the first scientific paper and investigates the differences in the tensile and fatigue mechanical properties of components made by FDM for two materials.

Two types of filaments were selected to compare their mechanical behavior: PLA (Silver, Prusa Polymers) and PLA-CF (Sunlu), which contains short carbon fibers (CF) (<20%) infused into the base PLA material to enhance its mechanical properties.

The geometry of the tensile specimens was designed according to the specifications set out in ISO 527-1 for type 1A tensile specimens (Figure 3a), and the geometry of the fatigue specimens was designed according to Mortazavian et al. (Figure 3b). The 3D printing parameters used were the same throughout the entire study presented in this thesis.

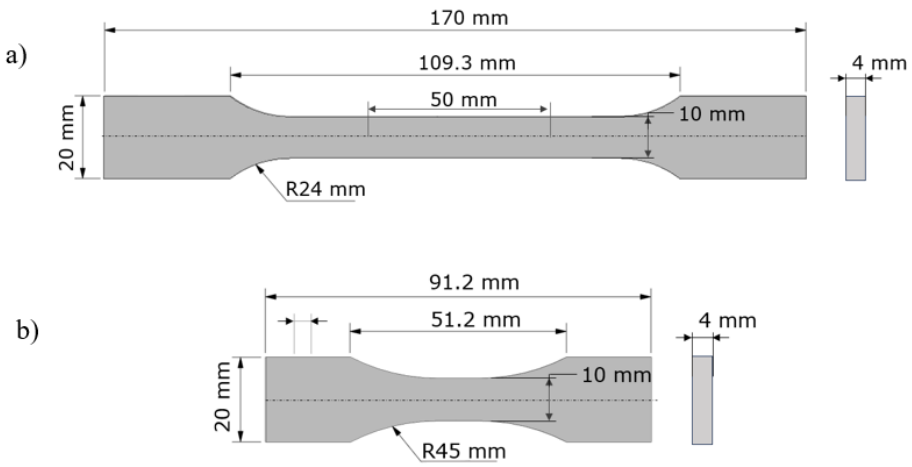

Fig.3. Geometry and dimensions of: a) tensile specimens and b) fatigue specimens

As a result of the tests, good correlations were obtained between the fatigue strength and tensile strength for each type of material. It was also observed that the samples reinforced with carbon fibers showed inferior properties in both tensile and fatigue tests. The weaker properties of the PLA-CF specimens could be attributed to several factors, such as higher porosity and weaker adhesion between filament layers compared to PLA.

Chapter 3 is represented by the second scientific paper, titled *"Effect of the notch opening angle on the quasi-static behavior of PLA and carbon fibers reinforced PLA realized through Fused Deposition Modelling"*. This paper investigates the fracture behavior of notched specimens, produced by FDM, from PLA and PLA reinforced with carbon fibers, using a local energy-based approach *(Strain Energy Density – SED)*. The specimens considered have smooth or double-notched geometries, and the notch opening angles vary between 30 and 120 degrees.

The Strain Energy Density (SED) method is a local, energy-based approach used to evaluate fracture behavior and fatigue life of materials. It is based on the idea that brittle fracture occurs when the total elastic energy, averaged over a given control volume, reaches a critical value. The SED method is widely validated for evaluating fracture under both static and dynamic conditions and is a useful tool for investigating fracture behavior and fatigue failure in materials.

The critical value of SED was obtained from the stress-strain curve of the smooth specimens for the two materials studied. After determining the characteristic length of the control volume, R_0, the data were summarized in terms of average SED values. The critical loads for the different geometries and materials considered were predicted by the method with a mean error of ±7%.

Chapter 4, entitled *"Static and fatigue behavior of 3D printed smooth and notched PLA and short carbon fibers reinforced",* represents an extended work of the previous one presented in Chapter 2, including the evaluation of static and fatigue behavior influenced by the geometry of the components, using the average strain energy density (SED) method. The materials used in this study are the same as those used in the previous chapters.

Samples with the same printing parameters were prepared for tensile, fatigue, and V-notch experiments. For the notch, the opening angles considered were 2α = 30°, 60°, 90°, 120° for the static tests and 2α = 90° for the fatigue tests.

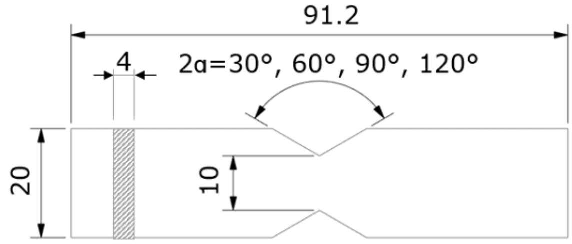

Fig. 4. Geometry and dimensions of the V-notched specimen

Quasi-static tensile tests were carried out on a Zwick Roell 005 machine with a 5 kN load cell, according to ISO 527-1. Both smooth and V-notched specimens were tested at 25°C, with a loading rate of 2 mm/min until failure. For each material and geometry, five specimens were tested.

For the fatigue tests, the Step Lab electrodynamic testing machine (UD/HUD series) was used with a load ratio of R = 0.1 and a frequency of 5 Hz. Both smooth and V-notched specimens with a notch opening angle of 2α = 90° were tested at 75% of the ultimate tensile stress, reducing the load five times down to 2 million cycles without failure. Three specimens were tested at each stress level to ensure repeatability of the results.

After data processing and FEA analyses, both materials exhibited ductile behavior, requiring the establishment of an equivalent elastic model for the correct application of the SED method. The critical value of SED was evaluated using the true stress-strain curve of the materials obtained from smooth specimens. For PLA, the critical SED value was 0.48 Nmm/mm^3 and R_0 was 0.81 mm, while for PLA-CF, the critical SED value was 0.41 Nmm/mm^3 and R_0 was 0.30 mm. The SED method was applied under both quasi-static and fatigue conditions, assuming that the influence of the outer layer characteristics would affect the general behavior of the material, regardless of geometry. The procedure resulted in a mean error of ±7% between the estimated and experimental critical loads for the different geometries and materials. Literature studies show that the critical angles for failure can vary between 0° and 180°, depending on the behavior of the material, and these trends are also common for materials produced using conventional manufacturing techniques.

Greater accuracy is reported for the application of the SED method under fatigue conditions when the characteristic length of the control volume is evaluated by considering raw fatigue test data from different geometries; moreover, such a procedure releases the application of the method from any consideration regarding the number of cycles at which to determine the mechanical properties for the calculation of R_0.

Chapter 5, represented by the fourth scientific paper entitled: " *Effect of notches on static and dynamic bending of 3D printed PLA and PLA reinforced with short carbon fibre",* focuses on the impact and bending behavior of notched specimens made from PLA and fiber-reinforced PLA and printed using FDM technology.

Impact and bending tests of the specimens were performed according to ISO 179-1 for Charpy tests and ISO 178 for bending. The bending tests were carried out on a Zwick Roell machine with a 5 kN load cell, at a loading rate of 2 mm/min, under displacement control, at room temperature. The dynamic tests were performed on an instrumented Instron CEAST 9050 pendulum, with a hammer weighing 0.9225 kg impacting the specimens at a velocity of 2.9 m/s. The specimens were tested in the edge direction, with a distance of 60 mm between anvils. For each material type and specimen type, 6 specimens were made, totaling 24 specimens tested for each type of static and dynamic test. Figure 5 shows the geometry of the specimens used for the static and dynamic bending tests. Figure 5a represents the smooth specimens, and Figure 5b represents the notched specimens.

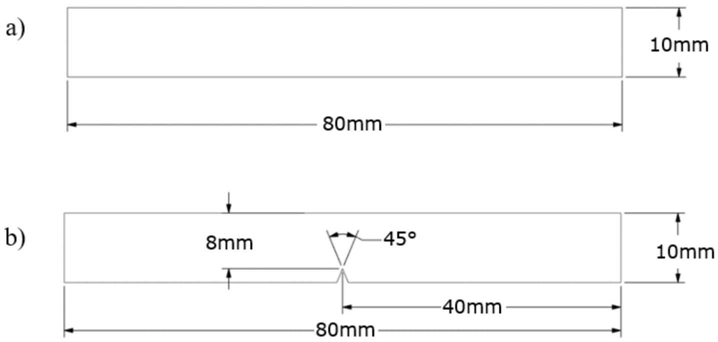

Fig.5. Geometry of impact and bending specimens: a) smooth and b) notched. Both types of specimens have a thickness of 4 mm.

After data processing and analysis, it was observed that PLA reinforced with carbon fibers has weaker mechanical properties than the virgin material, except for the total energy absorption under static loading. The notch reduces the maximum bending strength by 22% for PLA and by 25% for PLA-CF. The notch affects the maximum impact strength by 85% for PLA and by 93% for PLA-CF. The maximum energy absorption under static loading is seen in the smooth PLA-CF material, while under dynamic loading it is observed in PLA.

Chapter 6, entitled *"Are carbon fibres beneficial to improve mechanical and fracture properties of FDM printed composites?",* is represented by the fifth scientific paper and aims to assess the effect of short carbon fibers on the static and dynamic behavior of polymeric materials. The study includes a comparative analysis between PLA components with and without notches and the PETG material, to provide a more comprehensive overview of the effects of carbon fiber reinforcement on mechanical properties. Additionally, a morphological analysis is performed on the fiber-reinforced filaments before and after tensile tests, to better understand the observed mechanical behavior.

Increasing the fiber content in polymeric materials leads to greater strength and stiffness, but fiber orientation and printing strategy influence the resulting mechanical properties. Studies have shown that adding carbon fibers to PLA, ABS, and PETG improves modulus of elasticity and tensile strength, with PETG showing the highest strength. However, poor adhesion between fibers and matrix can result in reduced mechanical performance. Recent research indicates negative effects of adding fibers on mechanical properties due to increased viscosity and porosity. Special attention is needed when selecting matrix-fiber combinations to ensure the best results.

An important aspect is filament morphology, which can influence the final behavior of the components. Figures 6a and 6b show the voids in PLA-CF and PETG-CF filaments before tensile tests, which can lead to stress concentration and brittle fracture. After tensile testing, PLA-CF samples exhibited the phenomenon of "crazing," indicating more ductile behavior, while PETG-CF showed brittle fracture. Crazing, observed as whitening of the PLA matrix, produces more ductile behavior due to deformation of the fibrous and porous network. PETG appears to have longer fibers than PLA, which affects the material's behavior.

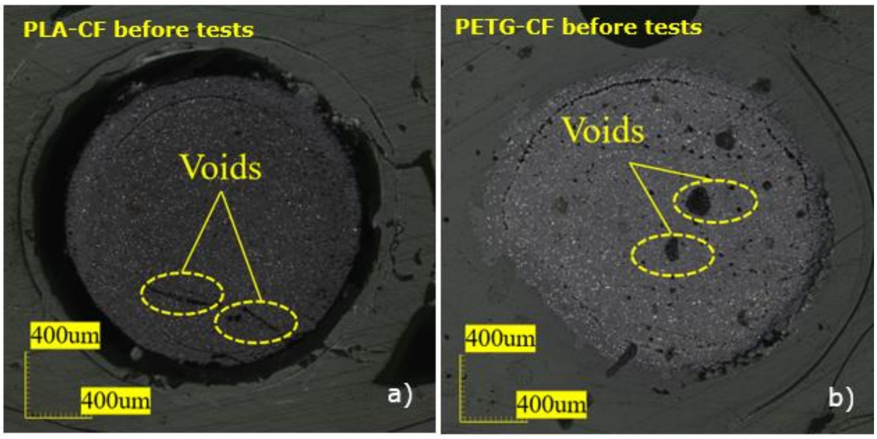

Fig. 6. Voids in the filament of: a) PLA-CF and b) PETG-CF before testing

The results of the impact tests confirm the trends observed in the other experimental tests. carbon fiber (CF) reinforcement had opposite effects on the studied materials: for PLA, the impact force decreased by 21.59% for unnotched specimens and by 45.89% for notched specimens. In contrast, for PETG, adding CF increased the impact force by 9.77% for unnotched specimens and by 48.62% for notched specimens. The printing parameters significantly influenced the experimental results.

Chapter 7, entitled *"Conclusions, Personal Contributions, and Future Research Directions",* provides a detailed and organized presentation of all the results obtained from the investigations carried out in this doctoral thesis.

The main conclusions are as follows:

- The two investigated materials have almost the same stiffness (Young's modulus), but unreinforced PLA has a maximum tensile strength that is 20% higher (41.86 MPa) compared to PLA reinforced with carbon fibers (33.43 MPa).
- The fatigue strength at 2 million cycles for PLA and PLA-CF was 12.6 MPa and 7.87 MPa, respectively.
- The lower mechanical strength (tensile and fatigue) of the PLA-CF samples could be associated with the process parameters used for specimen fabrication, which may result in weaker adhesion between the filaments or weak adhesion between the PLA matrix and the carbon fibers.
- The SED method was applied under static conditions, resulting in a mean error of ±7% in estimating the critical load of notched specimens. The method proved to be suitable for application to these complex components, and it is worth noting that, in accordance with the experimental results, a minimum critical breaking load is predicted at a notch opening angle of 60°.
- According to the observed results, a quick and inexpensive evaluation of filament

behavior can reveal important characteristics that help anticipate the influence of fiber reinforcement in printed materials, facilitating the selection of promising polymer matrix and fiber combinations.

This chapter also highlights the author's personal contributions, including significant achievements in the field of research. Chapter 7 concludes with a detailed presentation of the main research directions the author intends to explore in the future, including innovative aspects and potential practical applications of these studies.

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