Tensile mechanical properties of composite materials with continuous fiber produced by additive manufacturing

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Abstract. Additive manufacturing of composites parts reinforced with continuous fibers is emerging as a versatile process, capable of producing complex computer-aided design models by fabricating parts adding material layer by layer. Fused deposition modelling using polymeric materials has been used to produce prototypes, with the constraint of the strength of the material. Recently, the use of continuous fiber reinforcement has provided an alternative for the production of load-bearing functional parts. Current international standards for the characterization of composite materials from mechanical tests are established for parts manufactured by conventional methods, such as, manual molding, injection or coatings. Moreover, the standards do not specify procedures for composite materials produced by additive manufacturing. The objective of this work is to evaluate the performance of the reinforced composite materials produced by additive manufacturing for tensile tests under ISO and ASTM standards, and compare the results in terms of the topology of the material configuration. Average values of the tensile strength for composite materials having a triangular nylon matrix reinforced with fiberglass were obtained within the range of 205 MPa to 234 MPa, with deformations no greater than 0.020 mm. These values are higher than the strength provided by additive manufacturing using materials such as polylactic acid and acrylonitrile butadiene styrene.

1. Introduction

The material technologies of additive manufacturing (AM) and composite materials seek to expand the development and use of new materials, as one of the current challenges of modern engineering [1–3]. Combining the properties of different materials allows for obtaining better specifications in terms of strength, tenacity, and hardness [4,5], together with the possibility of easily producing complex geometries [6].

In recent years, AM has been successfully used to produce composite materials in metallic [1] or polymeric [7] matrices, allowing to manufacture complex parts for sensitive industry sectors as, e.g., the aerospace industry. Design paradigms are changing and, today, we are not constrained by geometry limitations such as those inherited from the traditional processes to manufacture composite materials [8]. Recently, a fused deposition modelling (FDM) technique that allows the use of continuous fiber filament has been developed [9], and research on the mechanical characterization of the parts produced by this technology has been developed [10–13]. Early adoption of these type of
manufacturing technologies and fully understanding of new design capabilities could provide a competitive advantage to the local markets.

In this work, we compare two similar standards commonly used for conventional composites, i.e. ASTM and ISO standards, to provide insight on the mechanical response of the parts produced by these new manufacturing techniques [14]. The objective of this research is to investigate the stiffness and strength of the continuous fiber composite materials produce by AM, based on a comparison of standards, with the purpose of providing guidelines for the shift in the design paradigm.

2. Materials and methods
The research was divided into two stages, the phase of the validation of standards and the experimental tests.

2.1. Standard selection
We selected the norms based on two fundamental criteria. We consider the use of a composite material with a continuous fiber, and the type of test which is traction. Table 1 shows the standards that are closer to the model for this research.

Table 1. International standards for plastics and composites. Availability for continuous fiber materials and tensile tests.

| Standard | UNE-EN ISO 527-1 [15] | UNE-EN ISO 527-2 [16] | UNE-EN ISO 527-3 [17] | UNE-EN ISO 527-4 [18] | UNE-EN ISO 294-1 [19] | ASTM D3039M-17 [20] | ASTM D638 [21] |
|----------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Continuous fiber composite | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Tensile test | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Selection | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

We selected “Standard test method for tensile properties of polymer matrix composite materials” ASTM D3039M–17 [20] and the standard “Determination of tensile properties. Part 4: Test conditions for isotropic and orthotropic fiber-reinforced plastic composites” ISO 527–4 [15]. These standards fulfil the required characteristics and are suitable for research purposes.

2.2. Geometric dimensions
The geometric dimensions and the shape of the specimens were determined from the standards, considering possible imperfections in the 3D printing. These measures were used to evaluate the area that defines the strength of the material. Nominal measurements were chosen for each standard and are illustrated in Figure 1. The number of test specimens was also determined as a minimum for each standard. The dimensions recommended for each standard are reported in Table 2 and Table 3.

![Figure 1. Geometry of the test specimens, \(lt^a\): total length, \(w^b\): width of test specimens, \(t^c\): thickness of test specimens.](image)

Table 2. Measurements of the test specimen according to ASTM D3039M [20].

| Nominal measure (mm) | Average test specimen measure (mm) | Difference % |
|----------------------|-----------------------------------|-------------|
| Total length (lt)    | 250.00                            | 248.89      | 0.44         |
| Width (w)            | 25.00                             | 25.21       | 0.84         |
| Thickness (t)        | 2.00                              | 2.65        | 6.00         |
Table 3. Measurements of the test specimen according to ISO 527 [15].

| Nominal measure (mm) | Average test specimen measure (mm) | Difference % |
|----------------------|------------------------------------|--------------|
| Total length (lt)    | 240.9                              | 240.97       | 0.44         |
| Width (w)            | 12.70                              | 12.86        | 0.84         |
| Thickness (t)        | 2.00                               | 2.13         | 6.00         |

2.3. Design parameters
The test specimens were manufactured on a Markforged Mark Two 3D printer, a new generation of 3D printer that allows continuous fiber reinforcement. Table 4 reports the design parameters of the printed specimens, which have a nylon matrix reinforced with four layers of continuous fiberglass.

Table 4. Design parameters.

| Image | Observations |
|-------|--------------|
| Composition | A proportional composition was set for 33.3% in fiberglass reinforcement material with nylon matrix |
| Tensile test | A triangular type configuration was specified for the core of the nylon matrix to improve stiffness response. |
| Fiber settings | Both standards recommend the reinforcement fibers oriented at 0° |

2.4. Internal structure
The internal structure of the test specimen manufactured by AM with a nylon matrix and reinforced with fiberglass is shown in Figure 2. Notice the different regions that are defined in the cross-section of the specimens. The walls form the external nylon structure that acts protecting the part from abrasion. The solid regions are made of nylon, with raster orientation at 0° with respect to the longitudinal axis. The matrix regions are a honeycomb-like structure printed in nylon, in this case with a triangular internal pattern.2.
2.5. Test parameters

Figure 3 shows the specimens printed by AM to conduct the tensile tests. An MTS Bionix® tabletop test system with a load cell of 25KN was used. The longitudinal deformation and the contraction of the cross-section were measured using the linear variable displacement transducer (LVDT) of the machine and the laser extensometer LX500, respectively. Similarly, to relate the standards, it was specified a speed of 2 mm/min.

![Image](image_url)

**Figure 3.** Printed specimens.

3. Results

All results were evaluated to determine the strength and deformation of the specimens using the following equations taken from ASTM D3039M [20] and ISO 527-1 [15].

3.1. Stress

The tensile stress at each required data point was calculated using Equation (1):

$$
\sigma = \frac{F}{A}
$$

where $\sigma$ is the value of the stress (MPa), $F$ is the measured force (N), and $A$ is the area of the cross-section of the test part (mm$^2$).

3.2. Strain and deformation

Using the extensometer, the strain is evaluated using Equation (2):

$$
\varepsilon = \frac{\Delta L_o}{L_o}
$$

where $\varepsilon$ is the value of the uniaxial strain expressed as a dimensionless relation, $L_o$ is the reference length of the test specimen (mm), $\Delta L_o$ is the increment in the length of the specimen measured in the reference marks (mm).

3.3. Elastic modulus

The modulus of elasticity in traction was calculated using the Equation (3):

$$
E_t = \frac{\Delta \sigma}{\Delta \varepsilon}
$$

where $E_t$ is the modulus of elasticity in traction (MPa), $\Delta \sigma$ is the stress difference in (MPa), $\Delta \varepsilon$ is the difference of the value of strain for a nominal, dimensionless point.

3.4. Poisson's ratio

The Poisson’s ratio relates the change in the cross-section of the specimen with the change in the length of the reference longitudinal section, expressed in Equation (4):

$$
\nu = -\frac{\Delta \varepsilon_n}{\Delta \varepsilon_l}
$$
where \( \nu \) is the dimensionless Poisson’s ratio, \( \varepsilon_n \) denotes the strain in the cross-section direction, and \( \varepsilon_l \) is the strain in the longitudinal direction.

The results of each test are shown in Table 5, where \( F_u \) is the ultimate force average in the tensile test. The table shows the comparison of a continuous fiber composite material evaluated using two different types of standards. Based on the results reported by the Markforged Mark Two datasheet, it was found that the stress values of the specimens are similar to those indicated by the manufacturer.

| Standard            | \( A (\text{mm}^2) \) | \( F_u (\text{N}) \) | \( \sigma (\text{MPa}) \) | \( \varepsilon \) | \( E_t (\text{MPa}) \) | \( \nu \) |
|---------------------|------------------------|-----------------------|--------------------------|-----------------|------------------------|--------|
| ASTM D3039M [20]   | 66.80                  | 13715.19              | 205.31                   | 0.061           | 6494.51                | 0.22   |
| ISO 527-4 [18]     | 27.39                  | 6409.50               | 234.00                   | 0.029           | 8495.28                | 0.31   |

Figure 4 shows the difference in strength proposed by each standard, presenting different results for the stress-strain curve. Notice that the results for ISO 527-4 [18] present a linear response, proportional to the ratio of stress against deformation. This test showed a constant elastic modulus, considering that its cross-sectional area is smaller, the deformation response is corresponding to an elastic material.

The results for the specimen of the ASTM D3039M [20] standard presents a much more noticeable dispersion in the progressive part of the material. It is observed in the figure that the material presents an elastic deformation similar to the results for the other standard, almost in the same range of strain for a value of \( \varepsilon = 0.00435 \). After this point, the material presents a bilinear response until reaching the breaking point. For this reason, note that the modulus of elasticity does not differ in large comparative proportions between each standard but if we compare the final results, a more approximate model to characterize a continuous fiber composite material manufactured by AM is the one reported by ISO 527-1 [15] standard.

4. Conclusions
This research aimed to determine the mechanical properties of the composite materials printed by additive manufacturing, and reinforced with continuous fiber, based on a comparison of similar standards for these types of materials. This will allow establishing a baseline on the knowledge of these new materials, and their application in engineering design.

According to the results of the characterization of the material, the mechanical properties are lower than those of the plastic materials manufactured in a conventional manner, as a result of the fused deposition modelling of the thermoplastic filament. However, the reinforcement increases strength significantly. Having as reference the design parameters, notice the freedom of the user to manipulate, create and assemble elements by AM. The high number of process parameters defining the printing, such as, the density of the core, type of matrix, the configuration of continuous fibers, and the number of layers of the reinforcement affect the mechanical response of the printed parts.
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