European Journal of Sustainable Development Research
2025, 9(3), em0294
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Research Article

OPEN ACCESS

Evaluation of the tensile properties of additive manufactured acrylonitrile butadiene styrene plastic

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Citation: Orhorhoro, E. K., Omoyi, C. O., & Agbonko, E. B. (2025). Evaluation of the tensile properties of additive manufactured acrylonitrile butadiene styrene plastic. *European Journal of Sustainable Development Research, 9*(3), em0294. https://doi.org/10.29333/ejosdr/16336

ARTICLE INFO

Received: 30 Sep. 2024

Accepted: 04 Dec. 2024

ABSTRACT

Because it allows for material recycling and reusing, three-dimensional (3D) printing is more sustainable than traditional manufacturing techniques. Recycled metal or plastic can be used by many 3D printers, minimizing the environmental impact and lowering the requirement for new resources. Not only that, but additive manufacturing techniques may easily produce complexly shaped components. Fused deposition modeling (FDM) is one of the most popular 3D printing techniques due to its versatility in producing huge components. Several thermoplastic filaments are frequently used in the FDM technique, including polylactic acid, polyethylene terephthalate glycol, and acrylonitrile butadiene styrene (ABS). Before choosing such polymers for a purpose, one must be aware of their tensile properties. This paper examines the tensile behavior of ABS materials that are 3D printed in this regard. Using SolidWorks modeling software, the tensile specimens are modeled in compliance with ASTM guidelines. The specimens are put through a universal tensile testing machine test after being 3D printed using the FDM technique. Three printing orientations (0^0, 45^0, and 90^0), printing speeds of 32 mm/s, and layer thicknesses of 0.165 mm and 0.258 mm were the printing parameters. A universal testing machine equipped with an extensometer (634.12E-54) is used for the tensile testing, which complies with ASTM D-638. A tensile rate of 0.2 in/min (0.0847 mm/s) is applied. The load and elongation are measured while the ABS samples are tugged till they fracture. To calculate the average and deviation of the property values, the samples of each orientation and layer thickness were evaluated. The findings indicate that the 0° printing orientation has the highest Young's modulus, ultimate stress, yield stress, and superior elongation qualities in tensile tests. As a result, a raster angle of 0° and a layer thickness of 0.258 mm are recommended for 3D printing ABS material.

Keywords: additive manufacturing, tensile strength, layer thickness, printing angles, acrylonitrile butadiene styrene plastic

INTRODUCTION

Three-dimensional (3D) printing, also known as additive manufacturing (AM) or additive fabrication, is the broadest term used to describe techniques for manufacturing prototypes, tools, various pattern designs, and conceptual components, as well as the creation of functional components with desired properties for direct industrial services and applications (Geng et al., 2021). AM uses 3D modelling software like CAD for developing the design and hence the product within the least possible time (Aziz et al., 2020; Chadha et al., 2019; Haq et al., 2021). Besides, concern about how human activity is affecting the environment has grown over the last few decades. Manufacturing is one of the main areas of concern. It is well known that manufacturing processes use large amounts of natural resources and generate enormous amounts of trash. These environmental issues now have a workable answer thanks to 3D printing. Despite being around since the 1980s, technology has just lately been broadly accessible and reasonably priced. Applications for it could be found in consumer goods, medical implants, and aeronautical engineering. Conventional manufacturing techniques frequently use a lot of water for cleaning and cooling procedures and a lot of energy for product production, transportation, and assembly. However, 3D printing usually does not require the use of water and uses a lot less energy because it just needs electricity to run the printer and heat the material to print, which further lessens the manufacturing process's impact on the environment. It is standard procedure to produce a huge number of identical products even in the absence of market demand. This may result in waste and surplus inventory, increased energy use, and increased carbon emissions. 3D printing makes it possible to create one-of-a-kind, personalized goods that are catered to specific tastes without generating waste or extra inventory.

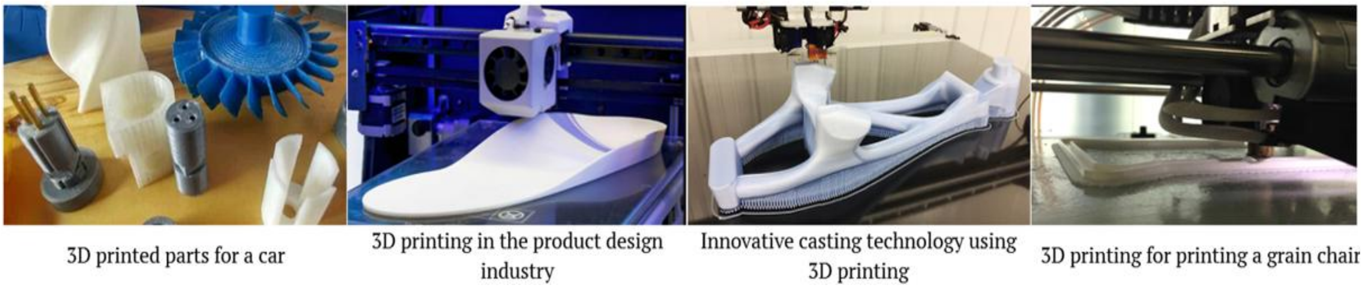

Figure 1. Applications of 3D printing (Haq et al., 2021)

Furthermore, the capacity of 3D printing to produce replacement components for already-existing products increases product lifespan, decreasing the need for new purchases and making a significant contribution to sustainability. It also includes a wide range of technologies that are united by the idea of constructing components layer by layer. **Figure 1** illustrates the many uses for 3D printing, which include biomedical, aerospace, automotive, and more industries. Over the past ten years, the 3D printing business has grown at an exponential rate. The global market for goods and services made via 3D printing is predicted to grow from $12 billion in 2020 to over $40 billion by 2024, according to Statista. This quick expansion can be linked to developments in 3D printing technology, a rise in the variety of printing materials available, and a decline in the price of 3D printers and materials.

For example, 3D printing has proved crucial to the aerospace industry's ability to produce durable, lightweight components that can resist harsh environments. For instance, Airbus claims that more than 1,000 3D-printed parts are used in their A350 XWB aircraft, which results in notable fuel savings. In a similar vein, the automotive sector has been using 3D printing to quickly produce prototypes and intricate parts. 3D printers are being used by Ford and BMW among other companies to streamline manufacturing and cut costs associated with development. 3D printing has created new opportunities in the healthcare industry, including the ability to create personalized prosthetics, dental implants, and even bio print organs and tissues for transplantation. This can be done by rapid prototyping technologies. Product is manufactured by adding successive layers of material on each other by using the data from the designing software (Ashrafi et al., 2019; Naveed, 2021a, 2021b). This wide-ranging application and growth of 3D printing have necessarily raised the attention on the quality of 3D printed parts, particularly their strength, given that these parts are now being utilized in crucial applications where failure is not an option. Reducing process time and processes is the primary goal of AM. Single-step and multistep manufacturing are the two basic categories into which AM falls (Kumar & Sathiya, 2021). In order to achieve the basic geometry, the single step requires the fusion of material (Ashrafi et al., 2019), but the multi-step approach completes the process in several steps by using the adhesion principle.

In order to acquire the desired clustering mechanical, optical, and physical qualities in the final product, researchers are mixing materials through interdisciplinary studies employing AM (Baba et al., 2019; Birozs et al., 2021; Citarella & Giannella, 2021). It is more effective in cutting the lead time for crucial replacement parts and streamlining the supply chain, as demonstrated by Citarella and Giannella (2021). From an economic perspective, it is anticipated that during the next several years, the AM sector will grow by 15.8 billion USD (Wohlers & Gornet, 2015). Large corporations like Siemens and General Electric Aviation are moving to AM these days to produce parts. However, because of the high initial costs and lack of operational expertise, several industries, such as MSME (micro, small, and medium enterprises), are reluctant to collaborate with AM. There has been recent research on improving supply chain management to boost AM efficiency. A modified supply chain, sometimes referred to as a hybrid chain, has been proposed in which the product's components are made by outside AM centers and assembled at the head center upon receipt of the product's order (Boothroyd, 1994; Ning et al., 2015). It has been noted that a number of factors, including printing pattern and infill %, affect both the mechanical and tribological properties. The material qualities of the product are affected not only by the printing parameters but also by the technique selected. The two most commonly utilized printing materials are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), both of which are thermoplastic polymers. One common thermoplastic used in 3D printing is ABS. The mechanical characteristics of 3D printed ABS components, such as orientation-dependent tensile strength and creep fatigue properties, have not, however, been thoroughly studied (Rayegani & Onwubolu, 2014). The primary disadvantages of using pure polymers are their low mechanical properties, which include hardness, Young's modulus, and tensile strength. In order to combine the advantages of the polymer matrix and fillers into a single material as a composite for wider applications, filler material mixing is therefore crucial (Li et al., 2021; Perez et al., 2021). Because of its many advantageous mechanical properties, ABS is a widely used engineered thermoplastic polymer material for industrial, commercial, and residential applications such vacuum liners, pipes, etc. The mechanical performance of composites is enhanced by the blending of filler materials with ABS polymer; this improvement may be attributed to fewer voids resulting from decreased chemical bond breaking and plastic deformation. Polymeric composites are frequently exploited because of their cheaper cost, high strength, and simplicity of manufacture. Reinforcements include glass, carbon, and aramid fiber in addition to various nanofiller materials such nano-silica, alumina, ZrO_2, and others. Polymer composites are becoming more and more common because of their improved mechanical properties.

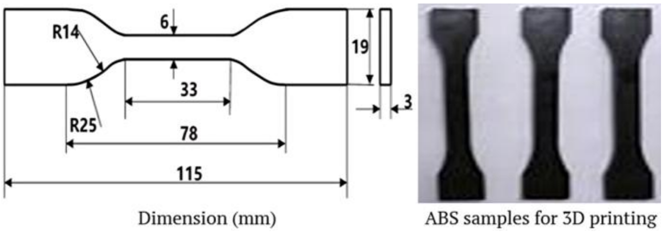

Figure 2. ABS samples preparation (Bardiya et al., 2021)

One of the most crucial mechanical characteristics of engineering materials is tensile strength. But in contrast to isotropic homogenous materials like metals, prior extensive research has shown that 3D printing polymers are anisotropic in terms of their strengths and fracture toughness's. This is because multiple tensile strengths can be measured in the various loading directions of a single 3D printing polymer (Saini et al., 2020; Torre & Brischetto, 2022; Yao et al., 2020; Ye et al., 2021). Thus, prior to the significant application of any 3D printing materials, an accurate determination of the minimum tensile strength is required. The use of several 3D printing materials in massive constructions has increased recently, thus it is now crucial to consider how their strengths are affected by scale (Sadiq et al., 2023; Zhao et al., 2019). One of the primary issues with using pure polymers is that they do not have good mechanical properties like tensile strength (Hsueh et al., 2021). In order to combine the advantages of the polymer matrix and fillers into a single material as a composite for wider applications, filler material mixing is therefore crucial. Because tensile strength is such an important feature for mechanical parts, researchers have documented how changes in part orientation and infill % of a PLA-based specimen affect its tensile strength (Bardiya et al., 2021). Modifying the aforementioned parameters in fused filament fabrication or fused deposition modeling (FDM) has been shown to result in a significant variation in the tensile strength (Bardiya et al., 2021). The layer thickness of 0.3 mm, the 0° orientation, and the 80% infill percentage had the maximum recorded tensile strength (Bardiya et al., 2021). Also, for construct orientation of 0^0, raster angle of 5^0, negative air gap of -0.0025, raster width of 0.2034 meters, and layer thickness of 0.127 meters, the greatest tensile strength was observed (Hsueh et al., 2021). Therefore, it is required to assess how various raster angles and layer thicknesses affect the tensile characteristics of ABS plastic material when using FDM. The results will aid in determining the impact of varying layer thicknesses and raster angle variations in both the horizontal and vertical directions on the tensile property of ABS plastic.

MATERIALS AND METHODS

Preparation of the of ABS Sample

In accordance with the ASTM D638 standard, the ABS plastic geometry was created using SolidWorks on a dog bone shape sample. The completed CAD model is then exported to an STL file format. Stereolithography, commonly known as standard tessellation language, is a crucial step in the 3D printing process and is represented by this file extension. With no representation of color, texture, or other model properties, this format solely translates a 3D object's surface geometry. **Figure 2** illustrates how the sample is ready.

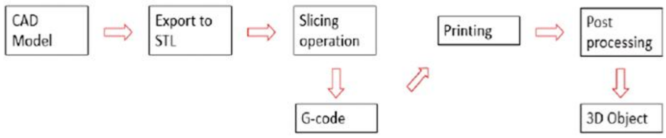

Figure 3. Process chart of the 3D printing process (Sadiq et al., 2023)

Table 1. Printing parameters

Printing orientations angles	Layer thickness (mm)	
0°	0.165	0.258
45°	0.165	0.258
90°	0.165	0.258

Printing of ABS Sample

The FDM printing process was chosen, and the Stratasys F170 3D printer was the one used. The following are the printing parameters: Variations in the melting temperature; 220-240 °C; 0.8 mm nozzle diameter; 32 mm/s printing speed; 0.165 mm and 0.258 mm layer thickness; 100% infill; and 100% dense packing accumulation mode. An application known as the slicer is used to load the STL file. Some slicers are open source and may be used on several platforms, while others are part of the 3D printer's interface and are tailored to a particular brand of 3D printer. To enable the printer to construct the model, the slicing program generates a set of instructions known as code. In this instance, the STL model is divided into multiple levels, with distinct cartesian coordinates assigned to each point on each layer. The 3D printer understands a set of instructions called G-code, which is created from all of the coordinates. The last phase is printing, when the printer receives the data from the model that has previously been cut (G-code). The printhead moves along various axes as indicated by the G-code as soon as the printer gets the command to print. Layer by layer, the model is being constructed. An example of the 3D printing process's flow chart is shown in **Figure 3**. Three printing orientations (0^0, 45^0, and 90^0) are chosen in order to examine how printing orientation affects the mechanical characteristics of the 3D printed ABS samples. The way a sample is printed on the platform determines its printing orientation, which ultimately has an impact on the sample's tensile strength and other characteristics. The interfaces between the various layers were referred to as the printing surfaces. An idealized, non-thick surface or line with interfacial strengths but no stiffness is what makes up an interface. The three distinct layer thicknesses were applied for each of the printing orientation angles, as indicated in **Table 1**.

Tensile Testing of 3D Printed ABS Samples

A universal testing machine equipped with an extensometer (634.12E-54) is used for the tensile testing, which complies with ASTM D-638. A tensile rate of 0.2 in/min (0.0847 mm/s) is applied. The load, elongations, yield stress, ultimate stress, and Young's modulus are recorded while the ABS samples are tugged till they shatter. To calculate the average and deviation of the property values, three samples of each orientation and layer thickness were evaluated.

Table 2. Results of tensile test evaluation for layer thickness of 0.258 mm for angle of orientation of 0°, 45°, and 90°

Load (N)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (mm)	Young's modulus (GPa)
0°				
0	0	0	0	0
20	160	226	0.026	1.56
40	172	246	0.028	1.68
60	188	266	0.029	1.78
80	198	276	0.030	1.89
100	210	280	0.033	1.99
45°				
0	0	0	0	0
20	156	205	0.012	1.35
40	168	214	0.016	1.43
60	172	227	0.019	1.57
80	183	234	0.020	1.60
100	190	256	0.029	1.69
90°				
0	0	0	0	0
20	146	195	0.009	1.28
40	158	206	0.010	1.35
60	162	219	0.012	1.47
80	173	226	0.018	1.51
100	142	239	0.021	1.58

Table 3. Results of tensile test evaluation for layer thickness of 0.165 mm for angle of orientation of 0°, 45°, and 90°

Load (N)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (mm)	Young's modulus (GPa)
0°				
0	0	0	0	0
20	147	209	0.021	1.37
40	153	228	0.024	1.49
60	169	249	0.027	1.48
80	177	258	0.029	1.67
100	195	261	0.030	1.75
45°				
0	0	0	0	0
20	136	193	0.009	1.15
40	148	206	0.011	1.23
60	152	217	0.018	1.39
80	163	229	0.019	1.41
100	171	246	0.021	1.59
90°				
0	0	0	0	0
20	126	175	0.008	1.09
40	139	186	0.009	1.17
60	142	198	0.010	1.23
80	153	215	0.011	1.32
100	121	223	0.019	1.39

RESULTS AND DISCUSSION

Table 2 and Table 3, respectively, display the results of the tensile test assessment for layer thicknesses of 0.258 mm and 0.165 mm for orientation angles of 0°, 45°, and 90°.

Figure 4, Figure 5, Figure 6, and Figure 7 shows the examination of the tensile properties of the printed ABS plastic at varied printing raster angles and thickness layers.

As can be seen from Figure 4, Figure 5, Figure 6, and Figure 7, with a printing layer thickness of 0.258 mm, a printing raster with a 0° exhibits superior yield qualities, ultimate stress properties, and Young's modulus in every printing.

Also, 45° printing raster angles displayed superior tensile qualities than 90° in yield stress, ultimate stress properties, and Young's modulus at a printing layer thickness of 0.258

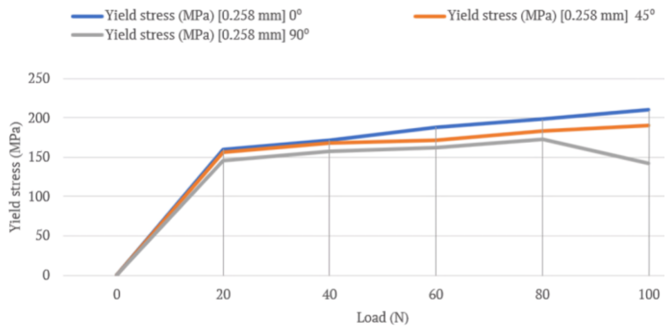

Figure 4. Comparative analysis of yield stress at 0.258 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

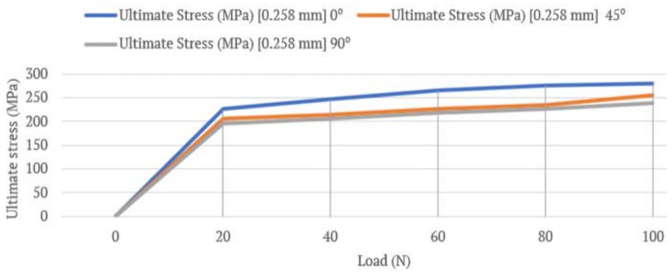

Figure 5. Comparative analysis of ultimate stress at 0.258 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

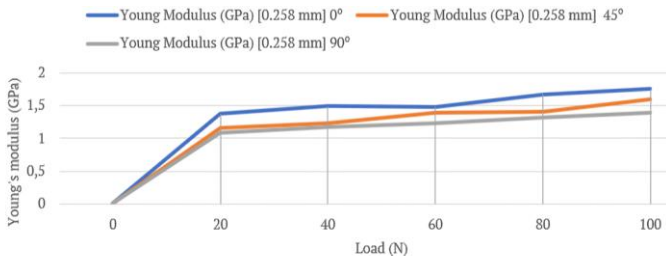

Figure 6. Comparative analysis of Young's modulus at 0.258 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

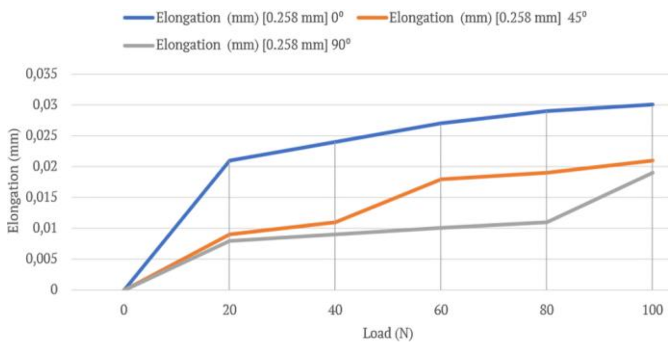

Figure 7. Comparative analysis of elongation at 0.258 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

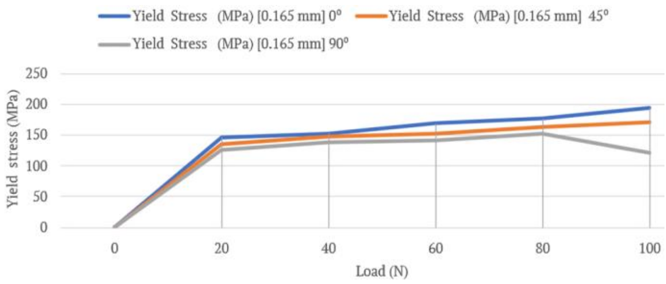

Figure 8. Comparative analysis of yield stress at 0.165 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

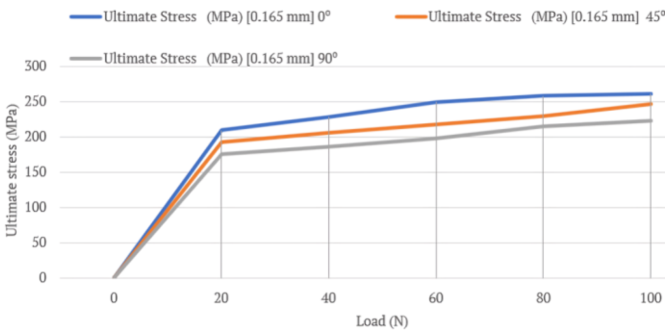

Figure 9. Comparative analysis of ultimate stress at 0.165 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

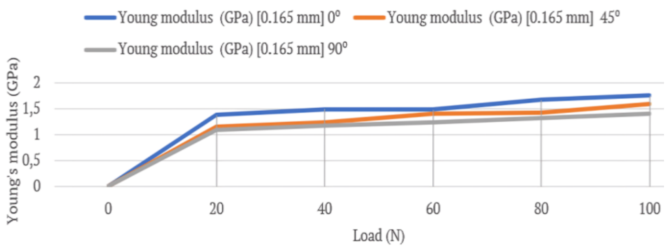

Figure 10. Comparative analysis of Young' modulus at 0.165 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

mm. However, in this experiment, printing at raster angle 90^0 for both 0.258 mm and 0.165 mm layer thickness was the least done.

According to a prior study, 0^0 specimens printed in flat, edge, and upright directions have better tensile properties (Brandl et al., 2012). Therefore, a 0° raster angle should be employed for the optimal design and printing of 3D ABS plastic.

Additionally, for best results, 0.258 mm should be utilized if the ABS plastic's layer thickness falls between 0.0 and 0.258 mm.

The yield stress, ultimate stress, and Young's modulus findings for the 0°, 45°, and 90° raster angles 3D printing at 0.258 mm and 0.165 mm layer thickness are displayed in **Figure 8**, **Figure 9**, **Figure 10**, and **Figure 11**.

Once more, with a printing thickness of 0.165 mm and 0.258 mm, the 0^0 raster angle outperforms the 45^0 and 90^0 raster angles orientation. The loading direction during the tensile test is in line with how the sample is printed during the

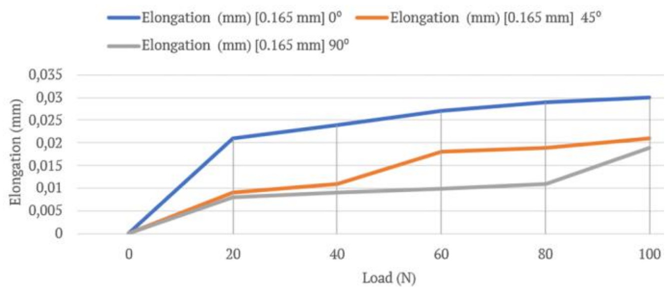

Figure 11. Comparative analysis of elongation at 0.165 mm layer thickness and printing angles of 0°, 45°, and 90° (Source: Authors' own elaboration)

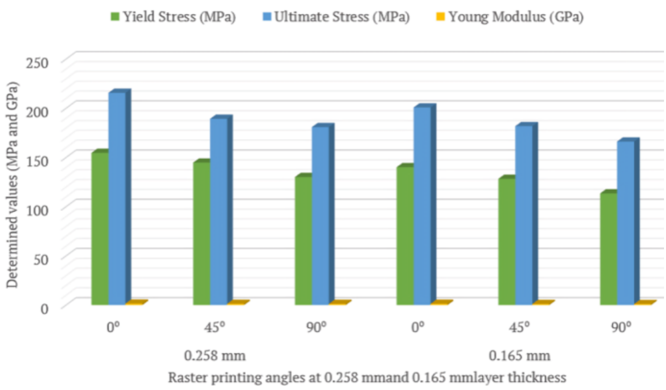

Figure 12. Comparative average tensile properties of the ABS plastic at different raster angles and layer thickness (Source: Authors' own elaboration)

process, which is the primary cause of the 0°'s comparatively higher ultimate strength. The results agreed with the findings of (Bagsik et al., 2010). According to this finding, while attempting to produce a higher ultimate strength in applications, the ideal printing orientation is 0°. Previous research has demonstrated that while a 3D printed specimen's tensile strength is comparable, its internal microstructure causes a variable time before fracture (Bagsik et al., 2010).

The average yield stress, ultimate stress, and Young's modulus of the 3D printed ABS plastic under the 0°, 45°, and 90° orientations is shown in **Figure 12**. At a thickness layer of 0.258 mm, 0° has the highest average ultimate strength of 215.67 MPa, followed by 45° with 189.33 MPa. Similarly, at a thickness layer of 0.258 mm, 0° has the highest average Young's modulus of 1.78GPa. However, printing an orientation angle of 90° had the lowest ultimate stress of 166.17 MPa. Our findings are quite similar to the study's by Tymrak et al. (2014) that reported average Young's modulus of a 3D-printed ASTM D638 bar is 1.8 GPa.

The ABS beam samples' stress behavior was impacted by variations in layer thickness. Better stress-strain behavior was found with a printed layer thickness of 0.258 mm (**Figure 13**).

In contrast to the 0.165 mm layer thickness, which results in an ultimate stress of 1.94 MN/m^2 (**Figure 14**), the 0.258 mm layer thickness provides an ultimate stress of 2.26 MN/m^2 prior to failure. Therefore, the tensile behavior of the ABS beam samples employed in this investigation increased in proportion to an increase in layer thickness from 0.165 to 0.258 mm.

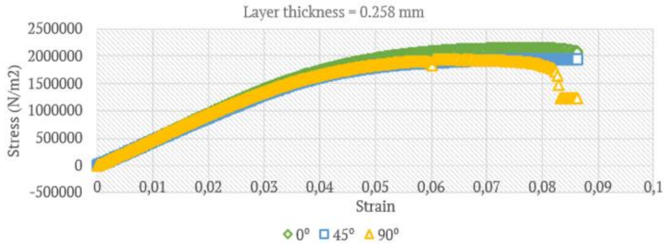

Figure 13. Graph of stress/strain curve for tensile properties of the ABS plastic at different raster angles and layer thickness of 0.258 mm (Source: Authors' own elaboration)

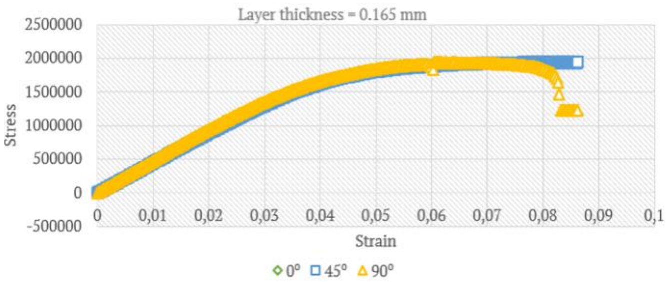

Figure 14. Graph of stress/strain curve for tensile properties of the ABS plastic at different raster angles and layer thickness of 0.165 mm (Source: Authors' own elaboration)

CONCLUSION

There is an expected growth and improvement in 3D printing technology, drops in prices, and advance sustainability more than ever as it becomes more widely used. Furthermore, a wide range of industries' sustainability initiatives highlight the enormous potential that 3D printing provides for next-generation ecologically friendly products. This study effectively evaluated the tensile characteristics of ABS plastic made by AM. The 3D printed ABS specimens at 0°, 45°, and 90° were subjected to tensile testing. The results showed that the 0° orientation had the best tensile qualities due to its biggest yield stress, ultimate strength and average Young's modulus. Consequently, it is recommended to print ABS materials at a printing raster angle orientation of 0^0.

Author contributions: Each author made an equal contribution to each of the following sections: introduction, materials and methods, laboratory work, results and discussion, and conclusion.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that ethical committee permission was not necessary in the study because neither human subjects nor animals were used in the investigation. Confidentiality and privacy were guaranteed by the ethical sourcing and responsible use of all data. In addition, the study was conducted in accordance with the strictest ethical guidelines for scientific publishing.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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