Original Article

Comparative evaluation of mechanical properties and finite element simulation of transparent boat materials: exploring PLA, PETG, and Tritan fabricated via FDM additive manufacturing

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Abstract

Additive manufacturing, commonly known as 3D printing, has been widely adopted across various industries; however, its application in the naval sector remains limited, particularly in the fabrication of transparent vessels. In this context, this study evaluates the feasibility of using PETG, PLA, and Tritan for constructing such vessels, with a focus on their mechanical and optical properties. Samples were fabricated via 3D printing and subjected to mechanical strength, impact resistance, and transparency tests, supplemented by scanning electron microscopy (SEM) and finite element simulations. The results indicate that PLA exhibits superior stiffness, while PETG demonstrates exceptional transparency and mechanical properties comparable to PLA and superior to Tritan. Variations in printing speed significantly affected dimensional accuracy and yield strength. Despite some limitations, PETG emerged as the most promising material, offering an optimal balance between robustness and optical clarity, making it suitable for prototyping in naval applications. However, further research is necessary to validate its applicability in full-scale vessel construction, particularly concerning structural integrity and long-term reliability. This study highlights new opportunities for integrating advanced materials into naval engineering, fostering innovation, sustainability, and operational efficiency.

Keywords: Fused deposition modelling; Mechanical properties; Additive manufacturing.

1 Introduction

In recent years, the naval sector for small vessels has experienced great growth, especially in vessels designed for recreational activities. This expansion has been accompanied by increasing demand for environmentally sustainable designs [1-3]. A notable development in this field has been the introduction of transparent vessels, commonly referred to as "clear boats," which offer enhanced interaction with marine environments.

Current research has focused on polymer-based materials, including thermoplastics such as polyethylene terephthalate (PET), PLA (Polylactic Acid), and Polyvinyl Chloride (PVC) [4]. Some of these materials are widely used in additive manufacturing processes like fused filament fabrication (FFF), thanks to their ease of processing, low cost, and diverse mechanical properties. Among these, a PET´s variant, the Polyethylene Terephthalate Glycol (PETG), demonstrates superior transparency and impact resistance, making it particularly promising for applications requiring structural clarity [5-7]. However, research indicates that 3D printing parameters, including infill density, print speed, and layer thickness, significantly influence these materials' mechanical and optical properties [8-10].

Despite advances in computational modeling and experimental analysis, the potential of 3D printing for producing high-performance transparent vessels remains underexplored. The relationship between processing parameters and resulting properties - including tensile strength, impact resistance, and light transmittance - requires further investigation.

FFF additive manufacturing offers distinct advantages for prototyping and producing transparent vessel components. This technology provides precise control over geometric features, enabling optimization of mechanical and optical properties beyond traditional manufacturing capabilities. Additionally, 3D printing facilitates rapid design iteration, offering a cost-effective approach for material and configuration testing [11].

Recent studies have emphasized the role of infill density and layer thickness in determining the structural and optical behavior of 3D-printed polymers. For example,

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denser infills generally enhance tensile strength and impact resistance, but may compromise transparency due to increased light scattering at the layer interfaces [12,13]. Similarly, variations in printing speed and nozzle temperature directly influence the crystallinity of the material, influencing both the clarity and mechanical performance [14]. These trade-offs emphasize the need for comprehensive parameter optimization in transparent vessel manufacturing.

The concept of clear boats, first patented in the United States during the 1990s. This is a vessel made entirely of transparent material, providing the vessel's crew with better viewing and interaction with marine systems. Tourism activity has grown abruptly in natural areas in recent years, which can lead to numerous environmental impacts. The study of the relationship between tourism development and environmental sustainability aims to understand the evolutionary process of tourism and the environmental issues arising from this practice. Thus, the use of transparent vessels could improve numerous issues related to ecotourism, since it allows greater interaction between tourists and marine species in an interactive and less aggressive way [15].

Despite their advantages, transparent vessels remain predominantly used in Mexico, presenting opportunities for expanded application in other regions with significant coastal tourism, such as Brazil. Conventional clear boats typically employ polycarbonate or acrylic materials, valued for their high transparency and impact resistance. However, the availability of alternative polymers, including PETG, PLA, and Tritan - a bisphenol A-free polyester developed as a polycarbonate alternative - warrants investigation.

This study examines PETG, PLA, and Tritan as potential materials for transparent vessel construction, with particular focus on how printing speed variations affect their material properties.

2 Materials and methods

The specimens were fabricated using fused filament fabrication (FFF), technology, as illustrated in Figure 1, employing a GTMax H5 3D printer. In this process, PETG, Tritan, and PLA filaments were heated to their respective melting temperatures and subsequently extruded in a layer-by-layer deposition to construct the test specimens.

Tests were conducted under a wide range of printing conditions with printing speeds varying from 60 to 100mm/s. The infill density was of 20% and extrusion temperature of 270 °C were maintained throughout the fabrication process.

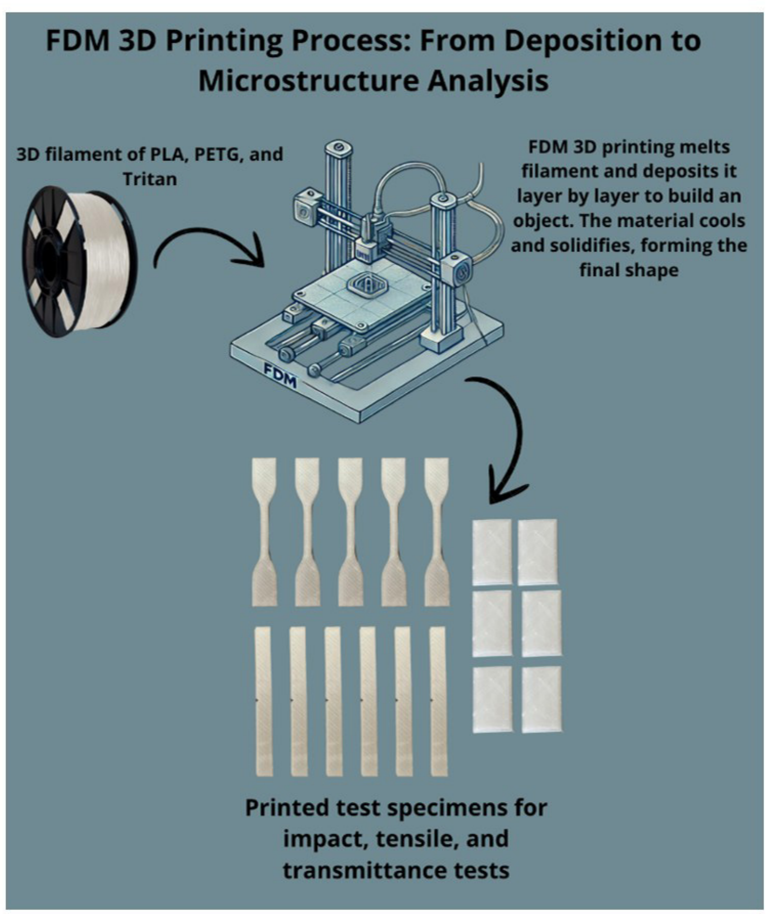

Figure 1. The image shows the scheme used to obtain the samples.

Moreover, the study varied the printing speed to examine its influence on the rheological and mechanical properties of the polymers. This systematic approach provided insights into how the interaction between printing parameters affects material performance in demanding applications, such as use in naval applications. All parameters were rigorously controlled during the fabrication process, and the resulting specimens underwent preliminary inspections to ensure the quality and uniformity required before mechanical testing.

2.1 Mechanical characterization

The specimens were subjected to comprehensive mechanical and optical characterization, including tensile testing, Charpy impact testing, and transmittance analysis. Tensile tests were performed in compliance with ASTM D638 standards using a calibrated universal testing machine (Instron 3367) with a 5 mm/min strain rate. Key mechanical properties - including ultimate tensile strength, elongation at break, and Young's modulus - were recorded to assess structural performance under axial loading conditions, particularly relevant for naval applications.

Charpy impact resistance was evaluated according to ASTM D256 specifications, with specimens machined to precise dimensions of 10 mm × 4 mm × 80 mm. Standardized notches were introduced to create consistent stress concentrations, enabling accurate measurement of fracture energy absorption.

2.2 Optical characterization

For optical characterization, transmittance measurements were performed using a high-precision spectrophotometer (e.g., Shimadzu UV-2600). Flat samples (1mm thick) were prepared and polished to ensure uniform surface conditions, and measurements were conducted over a wavelength range of 400–700 nm. This range was chosen to assess visible light transparency, a key property for applications requiring optical clarity, such as transparent observation panels or fluid reservoirs.

The combination of these tests (tension and transmittance) offered a detailed understanding of the interplay between mechanical performance and optical properties, providing a robust foundation for selecting materials suitable for demanding naval applications. Each test was carefully controlled to minimize variability and ensure the reliability of the results, contributing to the overall evaluation of the materials' potential for innovative engineering solutions.

2.3 Scanning electron microscopy analysis (SEM)

In addition to those tests, scanning electron microscopy (SEM) analyses of the fracture surface of the samples were performed. This analysis was performed to assess the uniformity of the impressions and the presence of other defects. These analyses were performed using a SEM model Quanta FEG 250, FEI brand, available at the laboratory of the Military Engineering Institute (IME), using 140x magnification.

2.4 Computational simulation

To complement experimental characterization, finite element analysis was performed using FEMAP software. High-fidelity 3D models were developed to precisely replicate specimen geometries and incorporate experimentally determined material properties. This computational approach facilitated comprehensive evaluation of PETG, Tritan, and PLA structural performance under diverse loading conditions, providing critical insights for transparent naval applications.

Experimental data, such as elastic modulus and yield strength, were used as inputs for the models, applying the Finite Element Method (FEM). This technique allowed for predicting the structural behavior of the materials and validating the experimental results. Specific boundary conditions and different loading scenarios were simulated, resulting in a detailed analysis and a robust foundation for interpreting the results and exploring the potential of these polymers in the maritime sector. Regarding the forces acting on this system, a weight of 3430 N was used, which would correspond to the weight of 5 crew members on the vessel, each weighing 70 kg, in addition to the engine, weighing 490 N. Finally, the static analysis was realized in software.

3 Results and discussion

Figure 2 shows the SEM images for each material sample. The PLA and TRITAN samples present layers with uniform thickness and excellent structural continuity. In contrast, the PETG samples exhibit less uniform layer deposition along with visible interlayer displacement (delamination). Additionally, particulate matter is observed in the PETG samples, likely resulting from extrusion process irregularities that may be temperature-related.

3.1 Mechanical properties

The results of the tensile test for the samples are shown in Tables 1, 2 and 3 (PLA, PETG and TRITAN, respectively). Analysis of the Elastic Modulus values reveals no significant variation with increasing printing speed.

However, examination of the Yield Stress and Maximum Stress data demonstrates a clear correlation between these properties and printing speed. This relationship is less evident in the TRITAN samples (Table 3), where reducing the printing speed from 80 mm/s to 60 mm/s showed negligible effect. Nevertheless, decreasing the speed from 90 mm/s to lower values resulted in increased yield stress, suggesting that further reductions would prolong printing time without substantially improving this property.

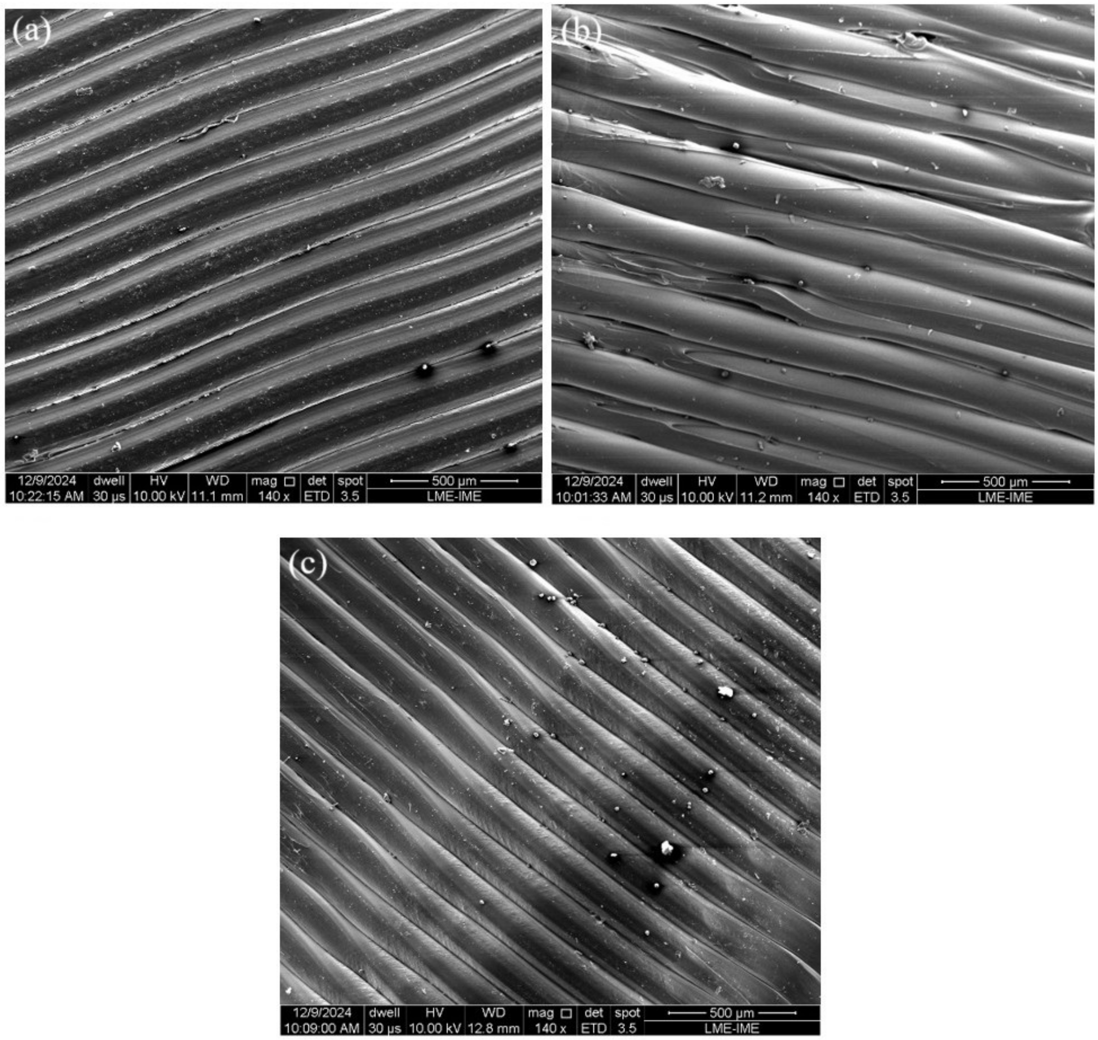

Figure 2. SEM images (140x) showing the printed layers of the samples in the following order: (a) PLA; (b) PETG; (c) TRITAN.

Table 1. Values for different printing speeds for PLA samples

Property	70 mm/s	80 mm/s	90 mm/s	100 mm/s
Maximum Tensile Strength (MPa)	30.54 ± 1.53	27.86 ± 1.29	27.98 ± 0.14	26.19 ± 1.54
Elastic Modulus (GPa)	7.96 ± 0.69	7.48 ± 0.52	6.60 ± 0.55	7.23 ± 0.69
Yield Strength (MPa)	30.9 ± 1.65	28.08 ± 1.38	27.83 ± 0.12	26.53 ± 0.95

Table 2. Results for different PETG samples

Property	60 mm/s	75 mm/s	90 mm/s
Maximum Tensile Strength (MPa)	41.68 ± 0.88	44.70 ± 0.71	44.06 ± 2.89
Elastic Modulus (GPa)	2.30 ± 0.05	2.31 ± 0.29	2.27 ± 0.28
Yield Strength (MPa)	30.46 ± 0.86	26.10 ± 3.79	21.01 ± 2.95

Table 3. Summary of maximum tensile strength, elastic modulus, and yield strength for different printing TRITAN speeds

Property	60 mm/s	80 mm/s	90 mm/s
Maximum Tensile Strength (MPa)	24.66 ± 2.01	25.80 ± 1.05	19.92 ± 1.23
Elastic Modulus (GPa)	3.38 ± 0.58	3.05 ± 0.74	3.82 ± 0.61
Yield Strength (MPa)	24.12 ± 1.52	25.16 ± 1.54	18.82 ± 1.89

A reduction in these properties is observed with increasing printing speed. This phenomenon has been previously reported in the literature, indicating that in materials with relatively low yield stress, increasing speed can result in unwanted deformations, layer defects or even structural failures. This occurs because the material may not have enough time to solidify properly between layers or during rapid movements, compromising the integrity of the printed object [16,17]. Similar results were found by other authors [18], who associated the reduction in material resistance with the increase in printing speed with the increase in internal porosity.

This behavior stems from the interdependence between printing speed and extrusion temperature. Higher speeds necessitate elevated temperatures to maintain proper material flow, which may adversely affect mechanical performance.

Additionally, it is important to note that higher printing speeds negatively affect the dimensional accuracy and surface quality of the printed parts. Conversely, very low printing speeds significantly increase production times, making them potentially impractical for industrial environments that demand high efficiency and rapid output. Furthermore, slower printing speeds lead to increased operational costs due to greater machine time and labor requirements per part. Therefore, finding an optimal balance between part quality, production time, and operational cost is essential for manufacturing process optimization.

Furthermore, it is worth noting that the mechanical property values obtained in this study exceed those reported in the literature for similar deposition parameters [19,20].

3.2 Transmittance´s analysis

The graphs in Figures 3a-c show the transmittance results for PLA, PETG, and TRITAN samples printed at different speeds. Transmittance measures the percentage of light that passes through a material and is commonly used to evaluate transparency.

By analyzing transmittance versus printing speed, we can understand how printing parameters influence the material's light transmission capability.

The results demonstrate a clear relationship between printing speed and print quality, showing that lower speeds produce higher quality prints for all materials. Printing speed refers to the movement rate of the extruder nozzle during filament deposition and varies according to the object's characteristics, material type, and printer capabilities. However, for optimal print quality, lower printing speeds are generally recommended as they improve precision and surface finish of the final part [21]. This speed-quality relationship is evident in the transmittance measurements (Figure 3), where lower printing speeds consistently yielded better optical properties, consistent with literature reports on deposition parameters' effects.

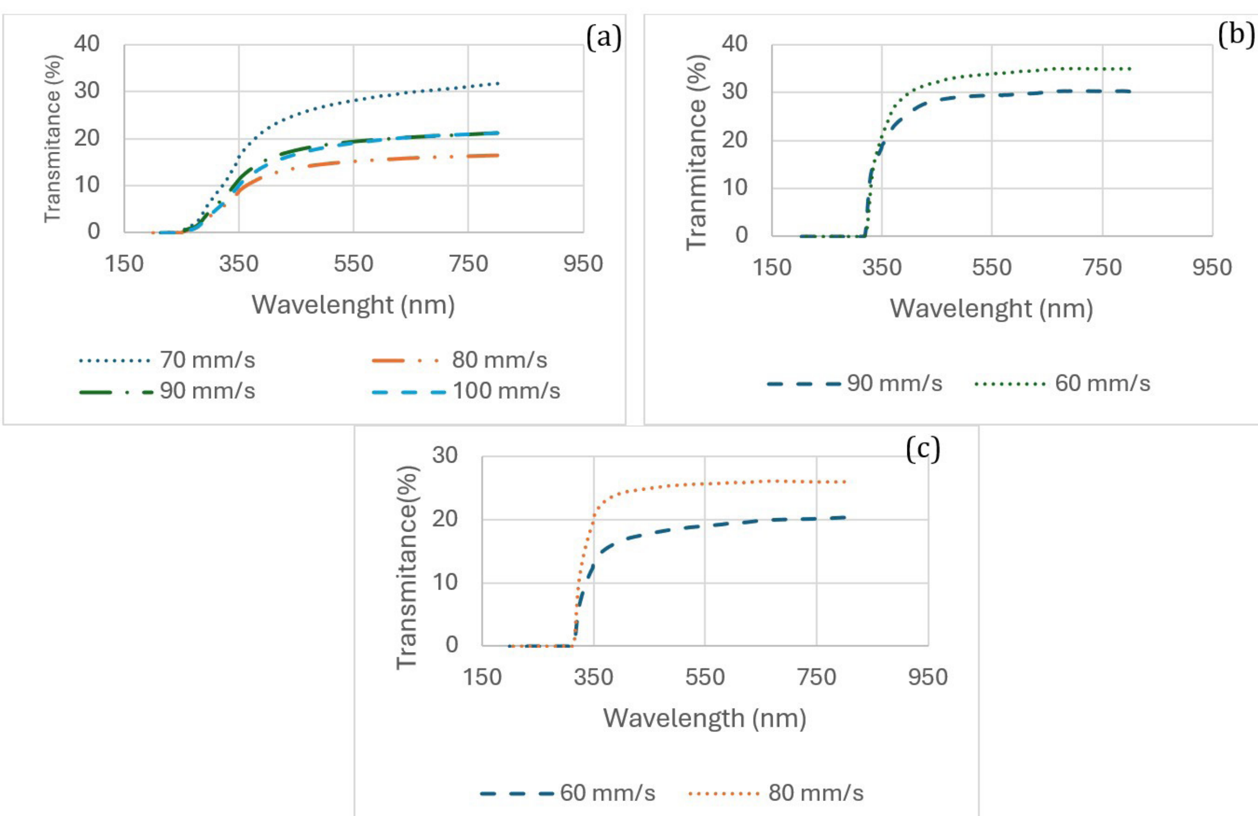

Figure 3. Transmittance test for samples of (a) PLA; (b) PETG; (c) TRITAN.

The optical characterization reveals distinct spectral behaviors among the materials. PETG and TRITAN exhibit sharp absorption cutoffs near 310 nm, while PLA demonstrates a more gradual absorption profile with superior transparency in the 250-300 nm range. Comparative analysis shows PLA and PETG achieve slightly higher transmittance values than TRITAN, with PLA samples printed at 70 mm/s showing optimal overall performance.

Furthermore, it is important to highlight that the values found for the transmittance of the samples are below those expected, since the literature reports that these materials have transparency greater than 80% in the visible region. This reduction in optical performance can be attributed to the 20% infill density employed in this study, as previously noted by [22]. The infill percentage presents a critical trade-off - low infill leads to incomplete material deposition and void formation, while high infill results in wall thickening and dimensional inaccuracies. These voids act as light scattering centers, disrupting material homogeneity and consequently reducing overall transparency [23]. The findings emphasize the need for careful optimization of infill parameters to achieve the desired optical properties while maintaining structural integrity in 3D printed transparent components.

3.3 Computational simulations

Figure 4 shows the computational simulation of the vessels designed with the materials proposed in this work.

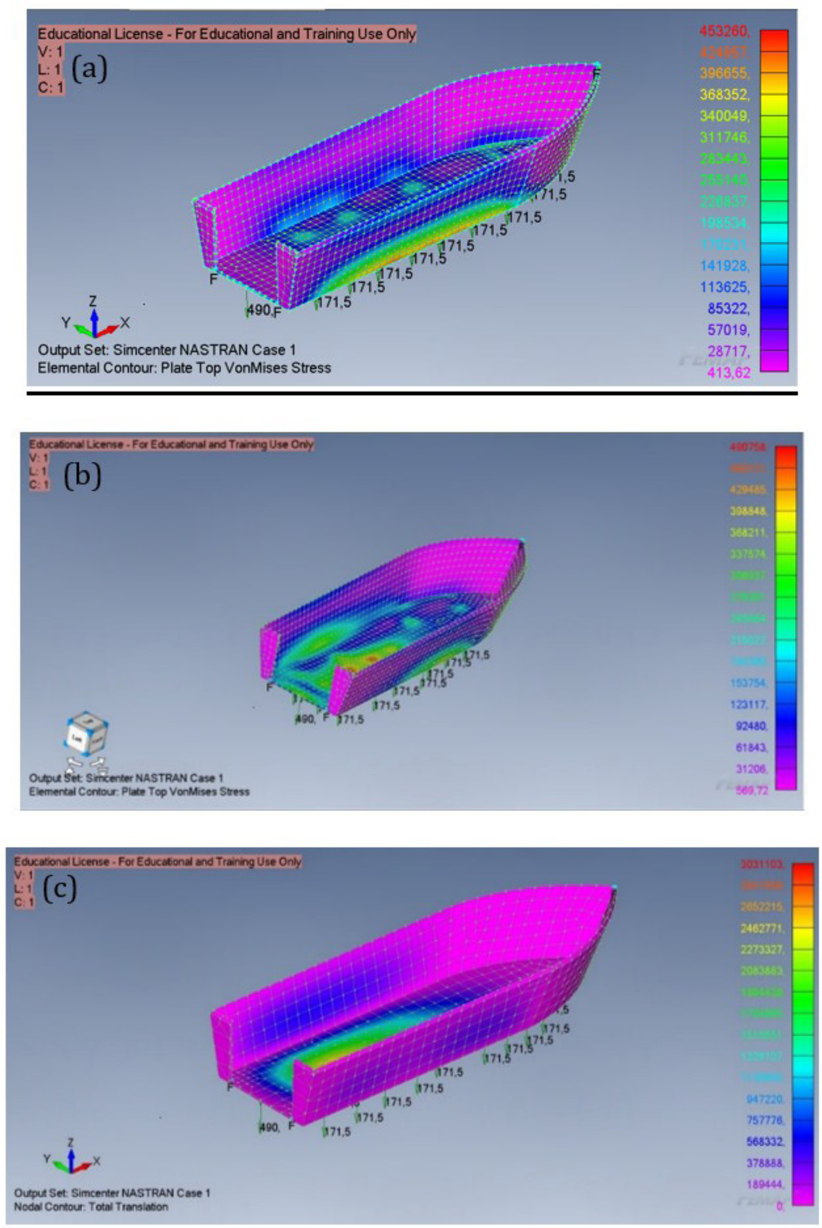

Figure 4. Tensile strength results for (a) PLA; (b) PTEG; (c) TRITAN.

The material subject to the highest level of stress in its structure is the vessel designed with TRITAN, while in the PLA and PTEG vessels stress levels are up to 10x lower than in this material. This may be associated with the lower values of mechanical properties indicated in Table 3, compared to the values observed in Tables 1 and 2. However, all tested materials remain viable options for this application. The simulation results confirm the design's safety across all materials, as the maximum von Mises stress values remain below each material's yield stress (as established in Section 2.1).

The stress analysis reveals consistent concentration patterns, with peak stresses occurring in the vessel's lower section - likely due to passenger loading. Notably, the substantial margin between operational stresses (10-100× below yield limits) suggests significant potential for design optimization. Among the materials, PETG demonstrates the most favorable ratio of yield strength to operational stress, indicating particularly robust performance margins. These findings confirm adequate safety factors while highlighting opportunities for material-efficient design improvements.

The first proposed structural optimization involves reducing the vessel wall thickness, while the second approach focuses on decreasing the layer infill density during 3D printing - a unique capability of additive manufacturing that conventional processes cannot achieve. Both strategies would effectively reduce manufacturing costs while maintaining structural integrity.

The simulation results present the von Mises stress distribution (in Pa) using a color gradient scale, where pink represents the lowest stress values and red indicates the maximum stress concentrations. This visualization clearly identifies the areas most susceptible to potential failure, allowing for targeted design improvements while preserving the established safety margins from previous analyses. The stress patterns confirm that both optimization approaches could be implemented without compromising the vessel's structural performance.

4 Conclusions

The results indicate strong potential for these materials in shipbuilding applications, offering advantages such as good strength and transparency, as evidenced by the obtained results. Although the preliminary results are positive, further in-depth studies are essential, as the integrity and reliability of the vessels are crucial aspects that cannot be compromised.

It was observed that the material's elastic modulus is insensitive to changes in printing speed, while the yield strength decreases with higher printing speeds. Printing speed also affects the extrusion temperature, requiring higher temperatures for faster speeds, which may compromise print precision.

The comparative analysis reveals that while PETG demonstrates mechanical properties comparable to or exceeding those of TRITAN and PLA, PLA maintains superior optical clarity. When evaluating both the strength-to-transparency ratio and computational simulation outcomes - which consistently showed PETG's enhanced structural performance - PETG emerges as the most viable candidate for transparent naval applications. However, comprehensive prototype development and testing under operational conditions remain essential to conclusively determine its suitability for full-scale vessel production, particularly regarding long-term durability and performance in marine environments.

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