STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 3, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Investigating the Surface Defects and Structural Integrity of 3D Printed Hydrogen Storage Cylinders in UAV Applications

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Abstract

This research explores the processing and manufacturing challenges of 3D printed polymer composites for high-pressure hydrogen storage in UAVs. The study focuses on addressing surface integrity and structural robustness issues inherent in additive manufacturing. Finite Element Analysis (FEA) was conducted on four thermoplastic polymer ABS, PET-G, HDPE, and Nylon to assess their mechanical performance under 35 MPa of pressure. Results revealed that PET-G and ABS provided better stress distribution and deformation behaviour, identifying them as optimal candidates for further testing. Despite promising FEA results, the manufacturing process faced challenges in achieving adequate surface finish, with issues such as inherent roughness, visible layer lines, and microscopic voids in the printed cylinders. These surface defects are problematic as they serve as stress concentrators, reducing the structural integrity and safety of the cylinders under operational pressures. To evaluate the extent of these defects, non-destructive testing (NDT) techniques were applied, including multi-spectral imaging for assessing surface roughness, ultrasonic testing for detecting internal flaws, and dye penetrant testing for surface-level imperfections like micro-cracks. Experimental findings revealed significant manufacturing flaws: multi-spectral imaging highlighted surface roughness inconsistencies, ultrasonic testing uncovered internal voids and uneven material distribution, and dye penetrant testing exposed surface defects due to poor inter-layer bonding. These results underscore the limitations of current additive manufacturing processes in producing high-quality polymer composites suitable for high-pressure applications. In conclusion, PET-G and ABS show potential as materials for hydrogen storage in UAVs, but challenges related to surface finish and internal structure remain critical. The study emphasizes the need for improved 3D printing and post-processing techniques to create smoother, defect-free surfaces and consistent internal structures. Advancing these methods is essential to enhance the safety, reliability, and longevity of polymer-based hydrogen storage systems, offering valuable insights for aerospace and high-stakes industrial applications.

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Received Date: October 21, 2024
Accepted Date: November 30, 2024
Published Date: April 09, 2025

Citation: Kirubadurai. B, Jaganraj R, Jegadeeswari. G, Vinoth Kumar. M. Investigating the Surface Defects and Structural Integrity of 3D Printed Hydrogen Storage Cylinders in UAV Applications. Journal of Polymer & Composites. 2025; 13(Special Issue 3): S161–S191p.

Keywords: 3D printed polymer composites, thermoplastic polymers, deformation behaviour, non-destructive testing (NDT), multi-spectral imaging

INTRODUCTION

Recent developments in the study of 3D printed parts for use in UAV and aircraft applications have illuminated important parameters influencing the structural soundness and functionality of these parts, especially hydrogen storage systems [1]. Carried out an extensive investigation to examine the structural strength of 3D printed hydrogen reservoirs for UAVs using sophisticated finite element methods. Their research made clear how crucial it is to comprehend how stress is distributed and spot possible weak places in these tanks. The study's conclusion, which is consistent with that of [8], who similarly employed finite element analysis to investigate deformation and stress under operating loads—is that material selection is crucial to guaranteeing the safety and dependability of hydrogen reservoirs under operational conditions. These studies provide important information for choosing the right materials and optimizing tank design, which helps to create hydrogen storage systems that are more dependable and safer. Investigated the crucial element of material optimization and selection for compact hydrogen storage devices in unmanned aerial vehicles (UAVs) [3].

Their study used a multi-criteria decision-making technique to strike a compromise between important elements like durability, strength, and weight. The usage of advanced composites, which provide improved performance characteristics necessary for the challenging operating environments of UAVs, was strongly supported by the study's findings. According to Singh et al., combining these materials with optimized design techniques opens the door to creating high-performance hydrogen reservoirs that satisfy the demanding needs of contemporary aircraft applications. Surface imperfections in components made using additive manufacturing pose a serious problem, especially in aerospace applications where longevity and mechanical performance are crucial. An extensive study of the surface flaws that frequently appear in aeronautical components made using additive manufacturing was carried out [2]. Their investigation emphasized how these flaws negatively affect components' mechanical performance and how even small surface imperfections can result in considerable losses in durability and strength. Further emphasize the significance of resolving these surface imperfections by concentrating on the surface and structural characteristics of hydrogen storage cylinders that are additively built [11]. They noted that surface flaws can seriously impair the dependability of important aerospace components over time, making them a significant long-term performance problem.

Investigated a range of surface finishing methods that can be used on 3D printed components to lessen the detrimental effects of surface imperfections [4]. Their study showed that some post-processing techniques, such coating and polishing, can greatly improve the strength and surface quality of materials. For additively made parts to function mechanically and last in aerospace applications, surface integrity must be improved. Tackled this problem as well, putting forth sophisticated post-processing methods intended to enhance the mechanical characteristics and surface quality of 3D printed parts [12]. Allen's research highlights the necessity of utilizing innovative post-processing techniques to surmount surface flaws and ultimately improve the overall dependability of items produced by additive manufacturing. Additional information about the connection between surface roughness and mechanical characteristics of UAV components made using additive manufacturing was supplied [9]. The relationship between surface roughness and mechanical problems like stress concentration and crack initiation was clearly demonstrated by their research. They came to the conclusion that enhancing the longevity and dependability of UAV components requires addressing surface roughness with suitable surface treatments. Effective surface treatment techniques are essential because they can stop failure mechanisms—which are frequently brought on by surface imperfections—before they start. The significance of continuous attempts to improve surface treatment procedures in the additive manufacturing sector is brought to light by this study. The use of non-destructive testing (NDT) techniques has grown in significance when it comes to guaranteeing the integrity of aerospace parts made by additive manufacturing. Provide a thorough analysis of nondestructive testing (NDT) methods, with a focus on radiography and ultrasonic techniques, for determining the structural integrity of objects made using additive manufacturing [5]. The analysis shown how well these methods work to find intrinsic flaws that can jeopardize the dependability of aircraft parts. The study stressed that nondestructive testing (NDT) techniques are critical for finding hidden defects in additive manufacturing that might not be visible with a mere visual inspection.

Concentrated on using ultrasonic testing to find internal flaws in hydrogen storage cylinders made using additive manufacturing [6]. Their study showed that ultrasonic testing is a very useful technique for finding defects that could cause catastrophic failure in high-pressure environments, like those seen in UAV hydrogen storage systems. The significance of early defect identification in preserving the safety and dependability of crucial components is highlighted by this study, especially in high-stakes aerospace applications where failure is not an option. The results of Ahmed and Khan's study lend credence to the aerospace industry's wider adoption of ultrasonic testing. Added to the discourse on nondestructive testing (NDT) methodologies by contrasting the efficacy of various approaches, such as dye penetrant testing and ultrasonic testing [23,14]. The study conducted by Zhang and colleagues Centre on ultrasonic flaw detection and emphasized its capacity to detect interior faults that may jeopardize the structural strength of aeronautical constituents. In contrast, Wilson and Cooper conducted a comparison of dye penetrant and ultrasonic testing and came to the conclusion that while both techniques are useful, they should be utilized in tandem to provide a thorough fault detection.

According to their research, a multi-method approach to NDT yields the greatest results when it comes to guaranteeing the dependability and safety of parts made using additive manufacturing. The detection of surface flaws in 3D printed materials has also demonstrated potential when using sophisticated inspection techniques like multi-spectral imaging. Multi-spectral analysis has been applied for this purpose; This methodology can identify surface flaws that are not visible by typical inspection methods [7,15]. According to their research, multi-spectral imaging can be extremely helpful in enhancing additive manufacturing quality control procedures by offering a more thorough evaluation of surface integrity. This technology is a useful tool for guaranteeing the high quality of simultaneously made components, especially in aerospace applications, because it can identify flaws that would otherwise go undetected.

Ultimately, it has been determined that improving the parameters of 3D printing is a critical element in improving the material reliability and effectiveness of aeronautical components. How important it is to precisely regulate printing parameters, like temperature and print speed, in order to lower the likelihood of internal flaws [10]. Manufacturers may greatly increase the dependability and quality of 3D printed components by fine-tuning these parameters. To further elaborate, looked at the wider difficulties associated with additive manufacturing in the aerospace industry, specifically those pertaining to preserving structural integrity and surface integrity [18,25]. Their research showed that in order to achieve the strict requirements needed in the aerospace industry, continuous advancements in manufacturing procedures and defect mitigation techniques are necessary to ensure that 3D printed components can dependably in difficult circumstances.

MATERIALS AND METHODOLOGY

This study focused on evaluating and optimizing the processing and manufacturing of polymer composites in 3D printed hydrogen storage cylinders, specifically targeting high-pressure applications for Unmanned Aerial Vehicles (UAVs). The materials used, selected based on their mechanical and chemical properties suitable for high-stress environments, included Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PET-G), High-Density Polyethylene (HDPE), and Nylon [13,16,17].

3D Printing and Processing Conditions

The hydrogen storage cylinders were manufactured using Fused Deposition Modelling (FDM), a widely adopted additive manufacturing method for polymer composites due to its ability to build complex geometries layer-by-layer. To enhance the structural and surface quality of the final parts, the printing parameters were optimized for each material, including adjustments to print speed, extrusion temperature, layer height, and infill density. The goal was to minimize layer lines, inter-layer gaps, and microscopic voids—common issues that can degrade performance under high-pressure conditions.

Material Reinforcement and Post-Processing

To further improve the mechanical strength of the cylinders, selected 3D printed models were reinforced using carbon fiber wrapping. Epoxy resin was applied to the cylinder surface to bond the carbon fiber securely, followed by controlled curing to ensure strong adhesion. This composite reinforcement technique aimed to increase pressure resistance and overall structural durability. Post-processing of the cylinders also included surface smoothing and coating to reduce roughness, which was assessed as a potential source of stress concentration. [22,24.26.27].

Finite Element Analysis (FEA)

Prior to experimental testing, Finite Element Analysis (FEA) was conducted on all four materials to simulate their response under high-pressure loading of 35 MPa. This analysis provided insights into stress distribution and deformation patterns, guiding the selection of PET-G and ABS for further testing. FEA results indicated that these materials had superior mechanical performance, showing consistent stress management and deformation control suitable for UAV application. [19,20.21].

NON-DESTRUCTIVE TESTING (NDT) TECHNIQUES

To assess the manufacturing quality and integrity of the printed cylinders, multiple non-destructive testing (NDT) techniques were employed:

- *Multi-spectral analysis*: This method was used to examine the surface roughness and reflectance of the cylinders. A multi-spectral imaging setup allowed for detailed inspection of surface irregularities, providing data on reflectance variances that could indicate roughness levels and layer bonding inconsistencies.
- *Ultrasonic flaw detection*: An ultrasonic flaw detector with a couplant gel was applied to identify internal voids, delaminations, and material distribution inconsistencies. High-frequency waves were introduced into the cylinder, and reflections from internal flaws were captured to assess the integrity of the composite material structure.
- *Dye penetrant testing*: Surface-level flaws, such as micro-cracks and porosity, were identified using dye penetrant testing. A red dye penetrant was applied to the surface, and after a developer was used, the test revealed visible indications of flaws where dye had penetrated surface discontinuities.

EXPERIMENTAL VALIDATION

Each material's manufacturing quality was evaluated through these combined methods to analyze defect presence, potential weak points, and overall suitability for UAV hydrogen storage. The combination of 3D printing with reinforcement and NDT evaluations provided a comprehensive approach to assess the effects of manufacturing processes on the integrity and performance of polymer composites. The testing results indicated that current additive manufacturing and post-processing methods require further refinement to address surface defects and internal inconsistencies. Insights gained from this study underscore the necessity of developing improved manufacturing protocols and post-processing techniques to enhance the surface finish, internal material uniformity, and pressure resistance of polymer composites in high-stress applications.

3D Printing of ABS and PET-G Hydrogen Storage Cylinder

Figure 1 shows the 3D printing a hydrogen storage tank made especially for UAV applications utilizing ABS and PET-G materials is depicted in the diagram. The cylinder is first designed in CAD software, and then the model is sliced into layers to produce the G-code that the printer needs. PET-G, which is prized for its flexibility and chemical resistance, or ABS, which is renowned for toughness and heat resistance, is selected as the filament based on the application. Layer by layer, the heated filament is extruded by the 3D printer using fused deposition modelling (FDM) to construct the cylindrical shape from the base up. The photos display the cylinder in its initial printing state, the finished ABS print with its bed still attached, and the final PET-G print following its removal. Following printing, the cylinder is put through post-processing, which involves the removal of support structures and possible coating or smoothing of the surface to improve durability and polish. The end result is a robust, lightweight hydrogen storage cylinder that is prepared for integration into a UAV. It is made to endure flight stress and is optimized for effective fuel storage. This procedure demonstrates how precisely and versatile 3D printing is when it comes to creating high-performing aircraft parts.

Figure 1. 3D printing of ABS & PET-G hydrogen storage cylinder.

Figure 2. Wrapping of carbon fiber in ABS & PET-G cylinder.

WRAPPING OF CARBON FIBRE

As seen in the Figure 2, covering a 3D-printed ABS or PET-G hydrogen storage tank with carbon fibre is an important step that greatly improves the cylinder's mechanical strength and endurance, making it more appropriate for high-pressure applications like those found in unmanned aerial vehicles (UAVs). The cylinder must first be prepared to ensure that its surface is clean and appropriate for bonding. The cylinder is coated with a coating of resin, usually epoxy, which acts as an adhesive to attach the carbon fibre to the surface. The cylinder is then completely encircled with tightly wound carbon fibre strands or tapes, meticulously orientated to maximize the mechanical qualities (longitudinal layers improve axial strength, while circular layers strengthen the hoop). The carbon fibres are securely bonded to the cylinder during the curing process, which the cylinder goes through after wrapping. This creates a composite structure that is far more durable and rigid than the initial 3D-printed item. The cylinder's resistance to high internal pressures is greatly increased by this wrapping, which also offers a layer of protection against impacts, abrasions, and environmental damage. The end product is a strong, lightweight hydrogen storage tank that satisfies the rigorous operational standards of unmanned aerial vehicles (UAVs) while guaranteeing dependable and safe operation. In crucial aerospace applications, carbon fibre wrapping is a useful technique to improve the performance and security of 3D-printed parts.

MULTI SPECTRA ANALYSIS EXPERIMENTAL SETUP

The Figure 3 displays the multi-spectral analysis experimental setup that is used for surface evaluation of a 3D-printed hydrogen storage cylinder, specifically for UAV applications, composed of ABS and PET-G materials. Using specialised lights that emit at various wavelengths, the cylinder is illuminated in this manner such that a multi-spectral camera can take detailed pictures of the exterior of the cylinder. The procedure entails examining these pictures to find any flaws or irregularities in the material that can impair the structural integrity and operation of the cylinder. After the data is processed and shown on a computer, it is analysed to find possible defects like gaps, fractures, or changes in the material's composition. To make sure that the hydrogen storage tanks fulfil the strict quality and safety requirements needed for UAV operations, this non-destructive testing technique is essential. Multi-spectral analysis helps to guarantee the dependability and durability of these crucial components in high-stress situations by exposing flaws that might not be apparent using traditional inspection techniques.

Figure 3. Multi spectra analysis experimental setup.

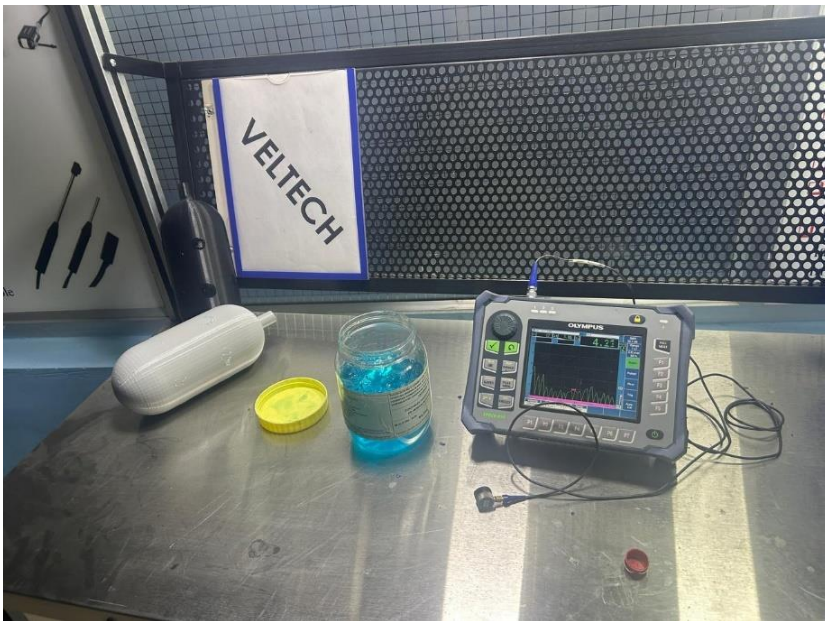


Figure 4. Ultrasonic flaw detector experimental setup

Journal of Polymer & Composites
Volume 13, Special Issue 3
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

ULTRASONIC FLAW DETECTOR EXPERIMENTAL SETUP

In order to verify a 3D-printed hydrogen storage tank composed of ABS and PET-G materials is suitable for use in UAV applications, the figure 4 displays an experimental setup for an ultrasonic defect detector. To begin this process, the cylinder is cleaned and coated with a couplant gel, which makes it easier for ultrasonic waves to enter the substance. When the transducer-equipped ultrasonic flaw detector detects any internal problems, like cracks or voids, it sends out high-frequency waves that enter the cylinder and bounce back. The detector's screen shows these reflections as waveforms, which the operator can use to determine whether any flaws are present and where they are located. This non-destructive testing technique is essential for locating internal problems that can jeopardise the structural integrity of the cylinder and guaranteeing that it satisfies the strict performance and safety requirements needed for UAV hydrogen storage systems. Ultrasonic testing helps guarantee the dependability and longevity of the cylinders in difficult operating settings by identifying and resolving these problems early on.

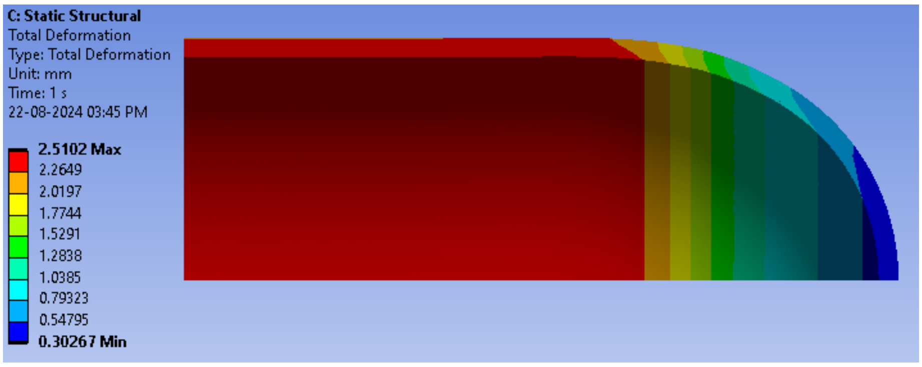
DYE PENETRANT TEST EXPERIMENTAL SETUP

In order to verify the integrity of a 3D-printed hydrogen storage tank constructed of ABS and PET-G materials for use in unmanned aerial vehicle applications, the figure 5 depicts the dye penetrant testing procedure. To avoid impurities interfering with the test, the cylinder must first be carefully cleaned. After that, the surface is treated with a visible red dye penetrant, which seeps into any surface-breaking flaws like fractures or porosities. The surplus dye is carefully removed after a predetermined dwell time, leaving only the dye that has penetrated flaws. The flaws are then apparent as red lines on the white powder surfaces when a developer is applied, which extracts the dye that has been trapped in the flaws. In order to make whether the cylinder satisfies the necessary safety and performance criteria, these indications are examined to determine the size, shape, and placement of flaws. The use of dye penetrant testing, a simple yet reliable technique for spotting surface imperfections that can jeopardise the cylinder's dependability, is essential to the quality control of hydrogen storage devices in unmanned aerial vehicles.

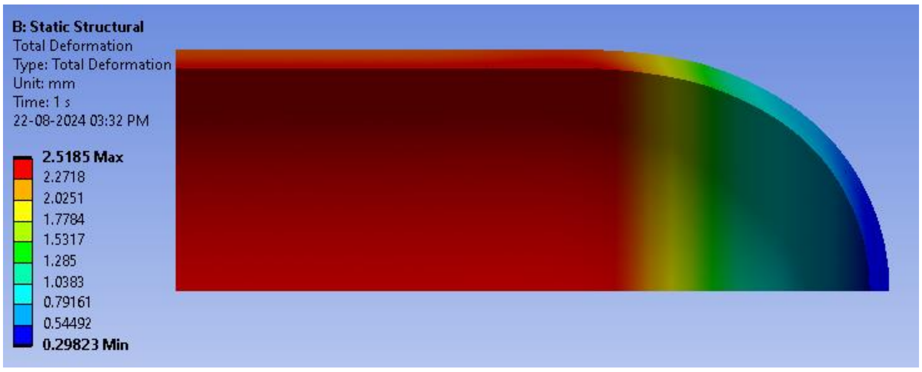
RESULTS AND DISCUSSION

The strength of the material plays a vital role in UAV systems under high pressure environment. The figure 6 shows the contour image indicates the total deformation of hydrogen storage vessels made from the material such as ABS, PET-G, HDPE, and Nylon at a pressure of 35 MPa. With peak deformations of 2.6318 mm and 2.6341 mm, respectively, the graph show that ABS and PET-G have uniform deformation trends. This graph that these two materials retain a comparatively stable structure under pressure, with the greatest deformation happening in the centre and decreasing towards the edges. While maintaining a comparable deformation profile, HDPE exhibits a little more deformation at 2.6361 mm, demonstrating that it is slightly less rigid than ABS and PET-G. This suggests that HDPE may be useful in some applications when its other qualities may be advantageous. Nevertheless, nylon exhibits the most deformation (2.6779 mm), which makes it more vulnerable to structural alterations under pressure. This could be a disadvantage for its employment in UAVs that require high-pressure hydrogen storage. In order to maintain safety and performance in UAV operations, materials should be carefully chosen with consideration for the balance between deformation and other material qualities. This is indicated by a transition from highest to lowest deformation across all materials, even if they can sustain large pressure.

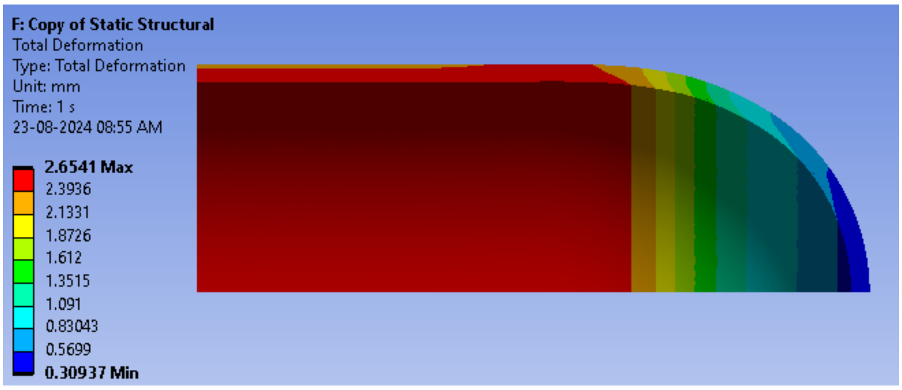
Figure 5. Dye penetrant test experimental setup.



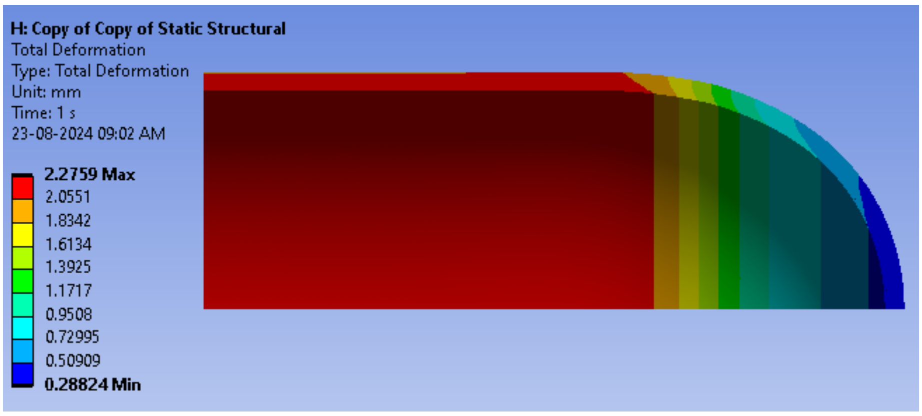
ABS



PET-G

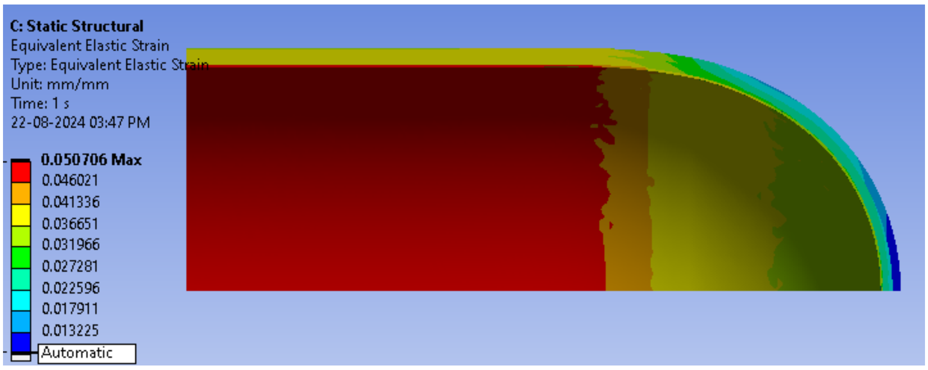


HDPE

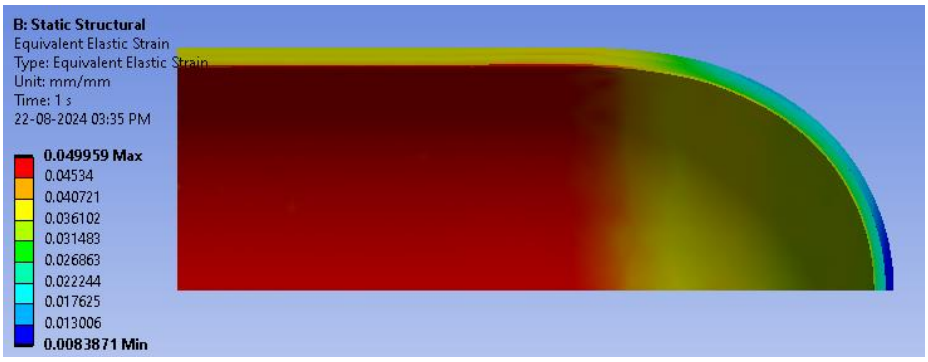


NYLON

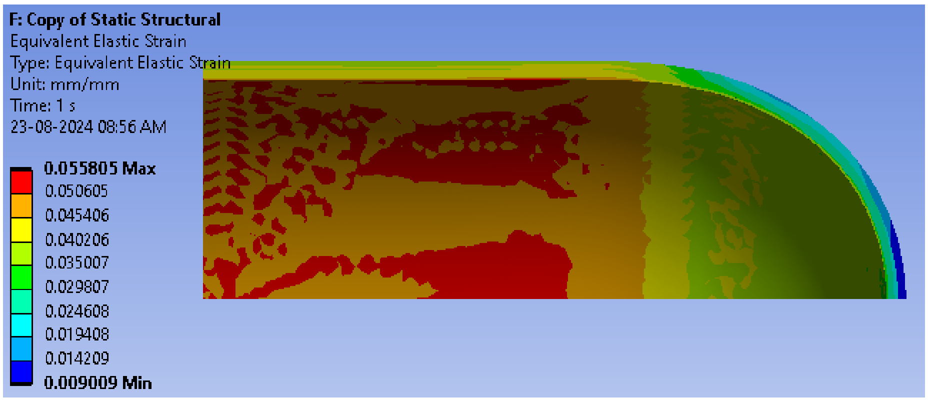
Figure 6. Total deformation in mm at 35 MPa pressure.



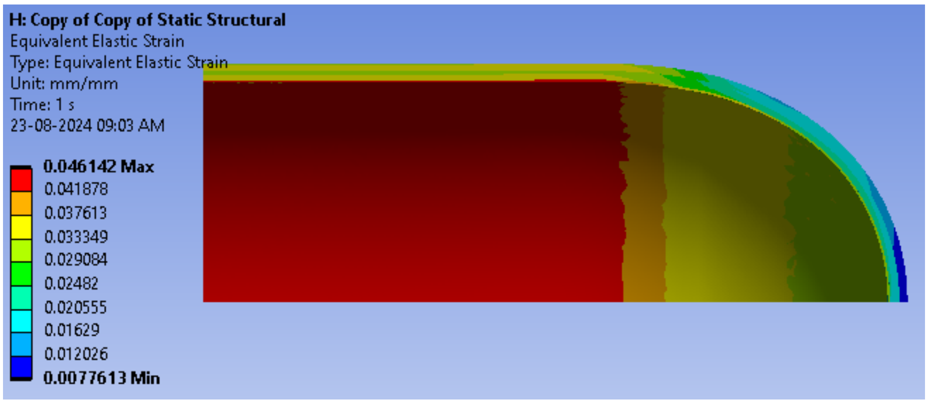
ABS



PET-G



HDPE



NYLON

Figure 7. Equivalent elastic strain at 35 MPa.

The Figure 7 shows the contour graphs show the equivalent elastic strain that hydrogen storage tanks composed of ABS, PET-G, HDPE, and nylon experienced at 35 MPa of pressure. This is important information for UAV applications where high-pressure structural integrity is crucial. With the highest strain of 0.0032959, the ABS tank has a homogeneous strain distribution, showing moderate flexibility and strong structural integrity. The strain is largely centred in the middle portions of the tank. With a marginally greater peak strain of 0.0034503, PET-G exhibits a strain distribution pattern resembling that of ABS but affecting a larger region. This suggests PET-G is more flexible while maintaining structural integrity under stress. HDPE exhibits a more uneven strain distribution with an elevated maximum strain of 0.0055035. This suggests the presence of potential weak areas and a higher sensitivity to localised deformation, which could jeopardise the dependability of the tank when under pressure. With an ultimate strain of 0.0041655, nylon has a strain distribution that is less erratic than HDPE but greater than ABS and PET-G, providing a compromise between structural integrity and flexibility. Nonetheless, Nylon may be more prone to deformation than ABS and PET-G because to its greater strain levels, which may affect its applicability for high-pressure applications. These insights are essential for choosing the right material for UAV hydrogen storage tanks since they have a direct impact on the tanks' dependability, safety, and performance under the demanding operating conditions.

The Figure 8 shows a comparative investigation of the overall deformation of several materials used in hydrogen storage vessels for UAV (Unmanned Aerial Vehicle) applications: ABS, PET-G, HDPE, and Nylon. The bar graph illustrates the deformation of these materials under three distinct pressures (10 MPa, 20 MPa, and 35 MPa). The data show unequivocally that higher pressures cause more deformation for all investigated materials, with the deformation measured in millimetres. In particular, the figure shows that the deformation patterns of ABS and PET-G are comparable, with both materials demonstrating appreciable increases in deformation with increasing pressure. In contrast to the other materials, HDPE exhibits the greatest distortion at 35 MPa, which makes it less suitable for high-pressure applications. While nylon exhibits comparatively less deformation at 20 MPa, it generally exhibits greater deformation at higher pressures. This information is essential for UAV applications, as the material selection for hydrogen storage containers must weigh safety, weight efficiency, and structural integrity against changing operating pressures.

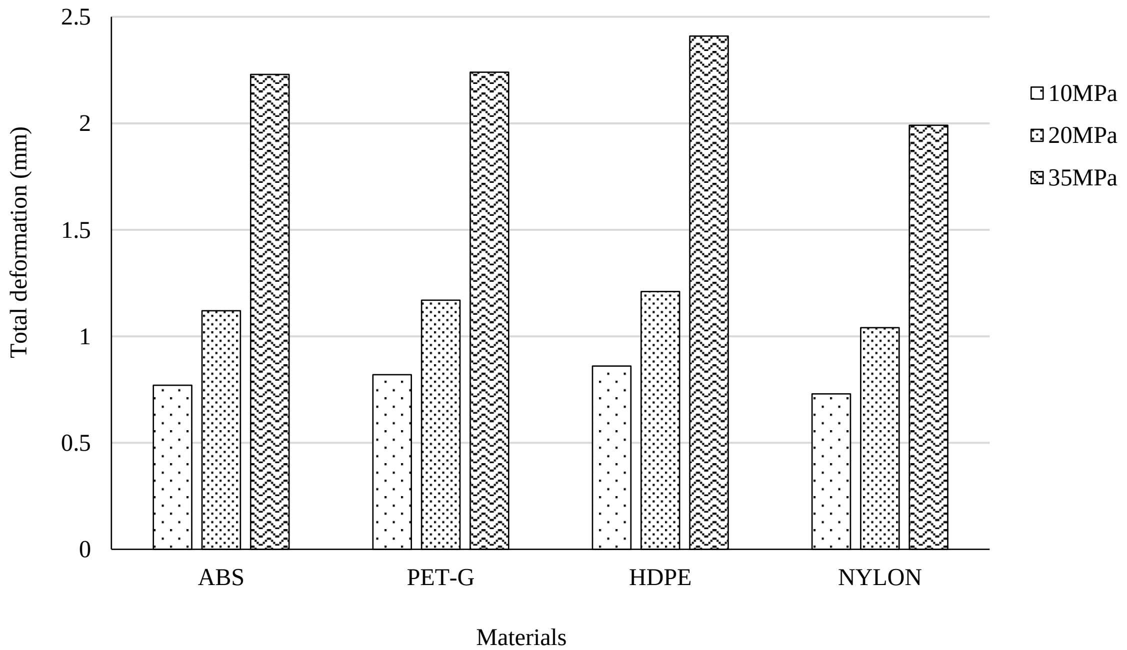


Figure 8. The total deformation of different materials.

Journal of Polymer & Composites
Volume 13, Special Issue 3
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

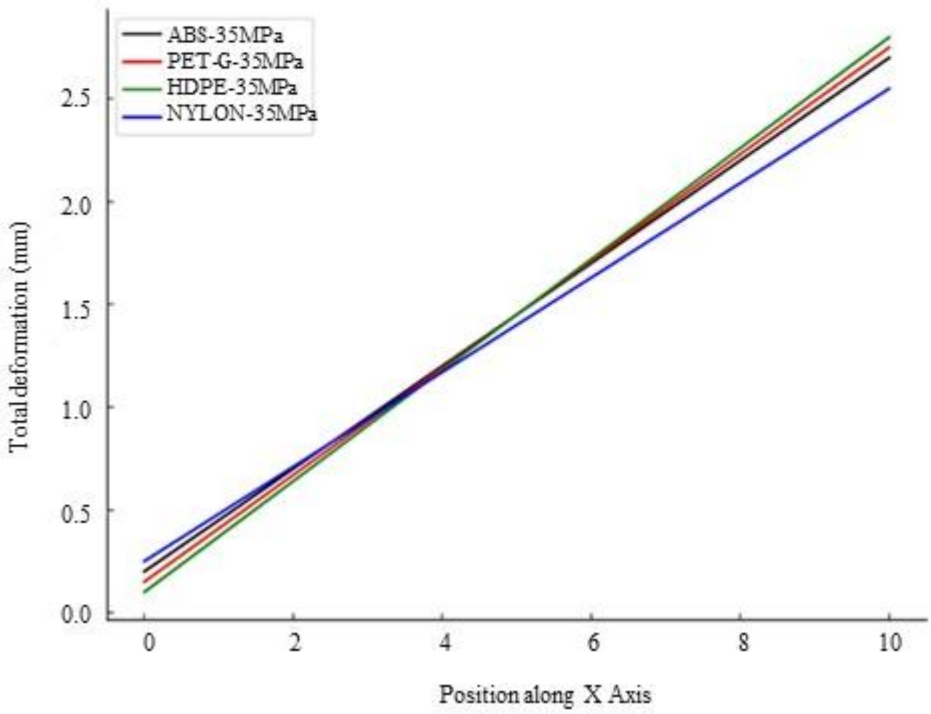


Figure 9. Total deformation of different materials at 35MPa.

The total deformation of four distinct materials—ABS, PET-G, HDPE, and Nylon—used in hydrogen storage vessels for UAV (Unmanned Aerial Vehicle) applications is compared in the figure 9. The graph illustrates the deformation of each material under 35 MPa pressure along the tank's X-axis. The findings show that for all materials, distortion rises exponentially with position along the X-axis. Out of all of them, HDPE shows the most deformation, indicating that it is more likely to undergo structural alterations while under strain. Nylon, on the other hand, exhibits the least amount of distortion, demonstrating its higher resistance to deformation and perhaps making it the superior material for high-pressure hydrogen storage uses in unmanned aerial vehicles. PET-G outperforms ABS in terms of reduced deformation, however both materials exhibit moderate degrees of deformation. This research aids in the selection of the best material to guarantee the safety and structural integrity of hydrogen storage containers in UAVs operating at high pressure.

The image compares the directional deformation of four materials used in hydrogen storage tanks for Unmanned Aerial Vehicle (UAV) applications: ABS, PET-G, HDPE, and Nylon. The figure 10 shows the deformation of each material as the cylinder's internal pressure rises from 10 MPa to 35 MPa. It demonstrates that all materials distort more at higher pressures; HDPE, for example, has the largest deformation at 35 MPa, suggesting that it is more susceptible to deformation at high pressures. Nylon, on the other hand, exhibits the least amount of distortion at all pressure levels, indicating that it is more resistant to deformation brought on by pressure. PET-G outperforms ABS marginally under pressure, while ABS is in the middle. In order to preserve structural integrity and guarantee safe operation, it is imperative that the best materials for hydrogen storage in unmanned aerial vehicles (UAVs) be chosen after careful consideration of deformation under pressure. Because of its reduced deformation profile, nylon is a great option for high-pressure applications.

The corresponding elastic strains of four materials—ABS, PET-G, HDPE, and Nylon—used in hydrogen storage vessels for UAV (Unmanned Aerial Vehicle) applications are compared in the figure 11. The graph illustrates how these materials react to cylinder pressures of 10 MPa, 25 MPa, and 35 MPa. All materials show increased elastic strain as pressure rises, but HDPE consistently shows the highest strain at all pressure levels, suggesting that it is more likely to deform under stress. While Nylon has the lowest strain and is therefore the most robust material under high-pressure settings, ABS and PET-G show moderate degrees of strain. This data is critical for choosing the best material for storing hydrogen in unmanned aerial vehicles (UAVs), where a lesser strain under pressure is necessary to preserve structural integrity and guarantee the tank's safety. Because of its reduced strain profile, nylon is especially well-suited for high-pressure applications; HDPE might not be as good under these conditions.

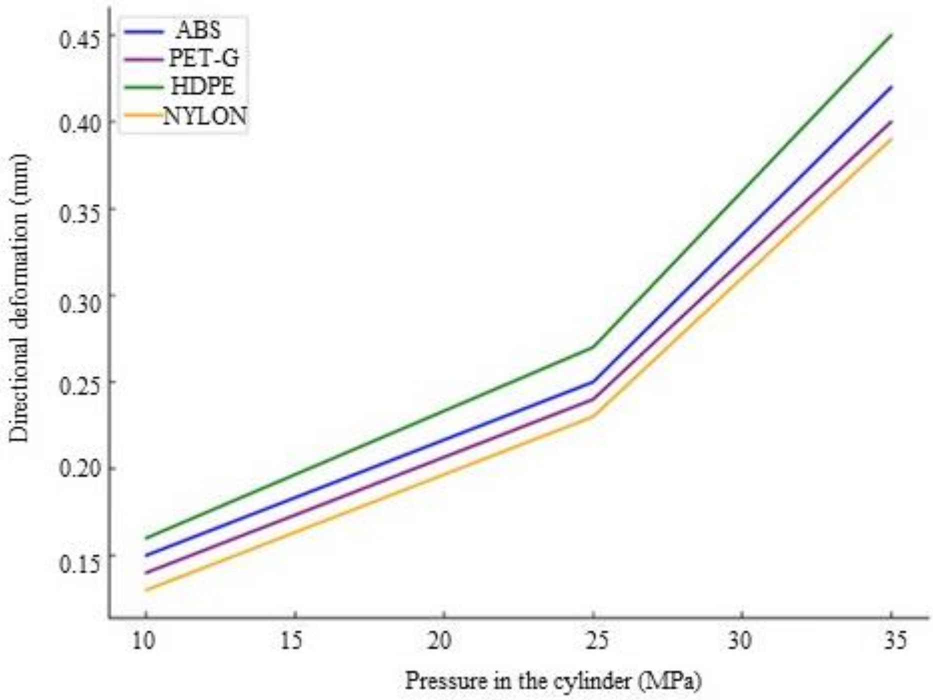


Figure 10. Directional deformation of four materials.

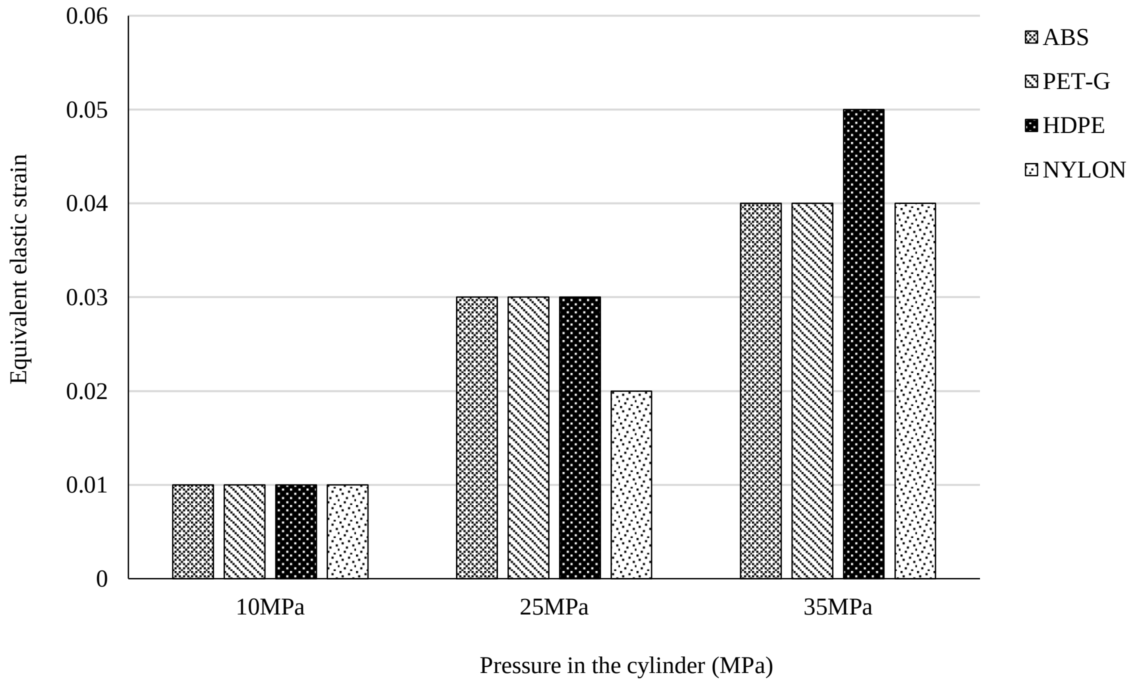


Figure 11. Equivalent elastic strain of four materiel.

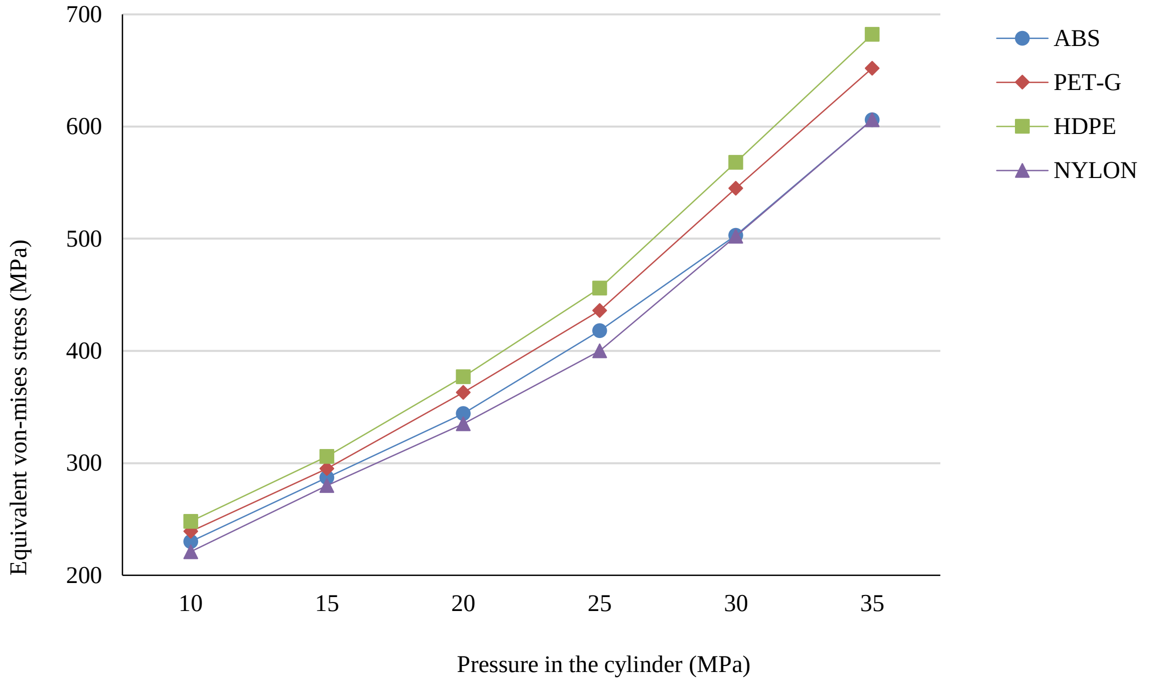


Figure12. Equivalent von mises stress four materials.

The image presents a comparison of the equivalent von Mises stress of four different materials that are utilized in hydrogen storage vessels for Unmanned Aerial Vehicle (UAV) applications: ABS, PET-G, HDPE, and Nylon. The Figure 12 indicates an increased probability of yielding or failure under these circumstances as the von Mises stress increases for all materials as the internal pressure inside the cylinder rises from 10 MPa to 35 MPa. At 35 MPa, HDPE and PET-G show the highest stress levels, indicating that, under extreme pressure, they may be nearer to their yield points. ABS is next behind, exhibiting marginally less stress. Conversely, nylon has the lowest von Mises stress at all pressure points, demonstrating its exceptional robustness and perhaps making it a more long-lasting material for high-pressure applications. This study is essential for choosing materials that guarantee the longevity and safety of hydrogen storage containers in unmanned aerial vehicles (UAVs). Nylon stands out as a particularly good option because of its decreased stress levels under pressure.

The strain energy accumulated by four materials—ABS, PET-G, HDPE, and Nylon—used in hydrogen storage vessels for unmanned aerial vehicle applications is compared in the figure as the pressure inside the cylinder rises. The figure 13 indicates that all materials experience a rise in strain energy as pressure increases, but PET-G displays a particularly sharp increase, particularly between 25 and 35 MPa, suggesting that it retains a notably greater amount of energy during deformation. This may indicate that there is a greater chance of material failure in harsh environments because of the possibility of stored energy being released. ABS, HDPE, and Nylon, on the other hand, exhibit far lower and more constant strain energy levels at all pressures, which may make them safer and more stable in high-pressure environments. This implies that ABS, HDPE, and Nylon would be more appropriate for preserving structural integrity and guaranteeing protection for hydrogen storage vessels for UAVs, even though PET-G might have some advantages.

EXPERIMENTAL ANALYSIS

Multi Spectra Analysis

The ABS material utilised for a hydrogen storage tank for UAV applications is shown in a multi-spectral analysis figure 14 that provides information about the material's optical characteristics by displaying reflectance data at various wavelengths. Three sections of the material (shown by red, blue, and green boxes) where spectral data was obtained are highlighted in the upper portion of the figure.

The region indicated with the red box has the maximum reflectance across the spectrum, whereas the region highlighted with the green box has the lowest, according to the bottom graph, which graphs reflectance versus wavelength. Every region shows a decrease in reflectance between 500 and 550 nm, which is followed by a rise in reflectance in the near-infrared (750-900 nm) range. This investigation is essential for evaluating the optical properties and homogeneity of the ABS material, as these factors can affect the safety and functionality of the hydrogen storage tank in UAV applications. Variations in surface qualities could be indicated by differences in reflectance between the regions, which are crucial for guaranteeing the material's dependability under operating settings.

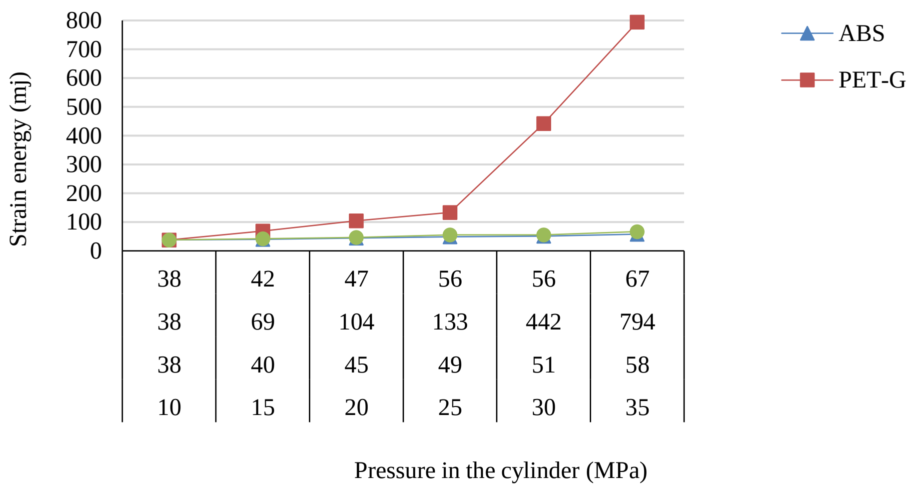


Figure 13. Energy stored in four materials.

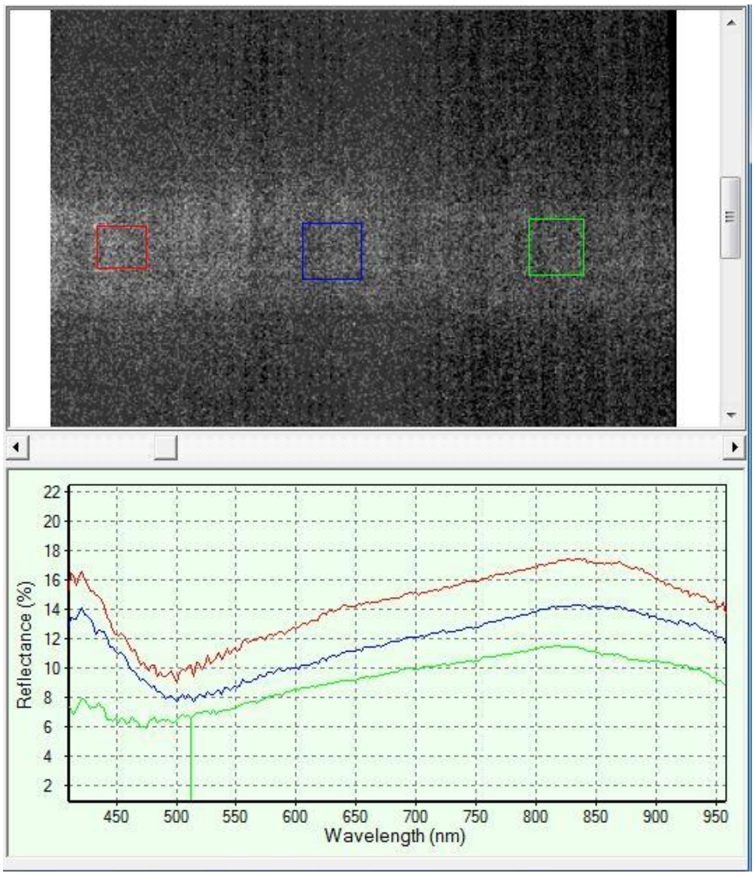


Figure 14. Multi spectra analysis image of ABS in different longitudinal variation

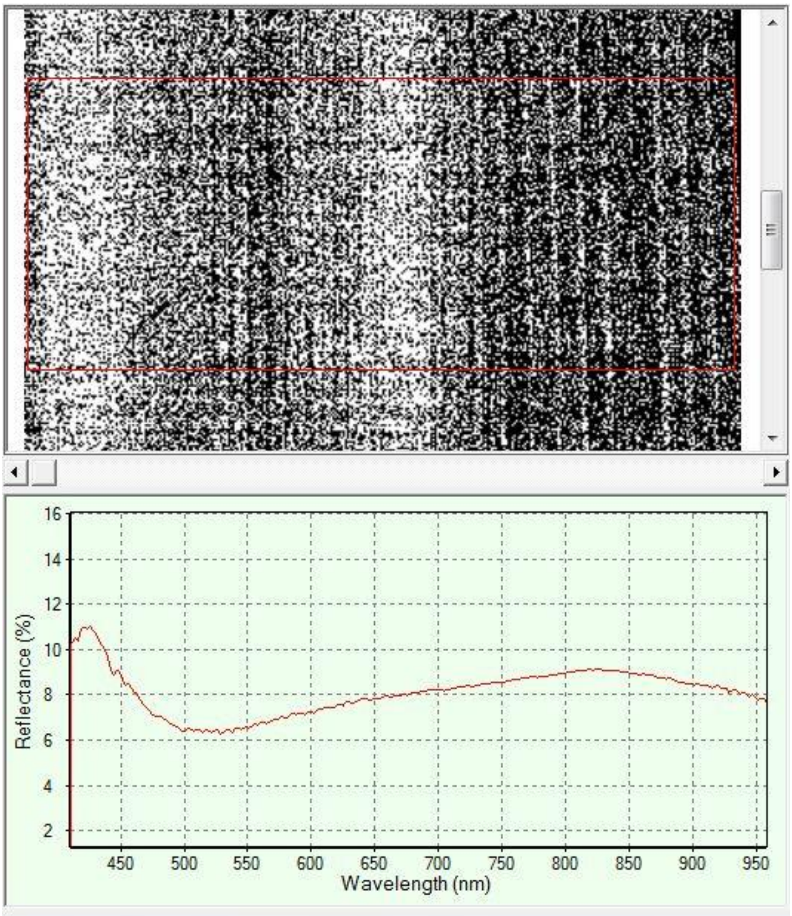


Figure 15. Multi spectra analysis image of ABS in longitudinal axis

Important information about the optical characteristics of the ABS material utilised for a hydrogen storage tank for UAV applications is revealed by a multispectral examination of the material. The following figure 15 exhibits the material's reflectance inside wavelengths ranging from 400 nm to 950 nm, while the greyscale spectral image displays fluctuations in reflectance within a scanned region. The ABS material's greatest reflectance is observed between 450 and 800-850 nm, with a decrease in reflectance observed about 550 nm. These observations show how the material interacts with various light wavelengths. Understanding the reflectance fluctuations is essential to comprehending the behaviour of the material under various environmental circumstances, which might impact its durability and performance in UAV applications. This investigation helps to optimise the material's use in hydrogen storage tanks within UAVs by confirming that it satisfies the relevant reliability and safety standards.

Through the use of a spectrum classification map and matching reflectance spectra, the multi-spectral study of the ABS material utilised in a hydrogen storage tank for UAV applications exposes important differences in optical properties throughout the material's surface. Regions with unique spectral properties, such as variations in surface composition, appearance, or possible flaws, are highlighted in the categorization map figure 16. The reflectance spectrum graph further quantifies these variations by showing areas with lower reflectance as potentially rough textures, varied compositions, or flaws, and areas with higher reflectance, indicated by the red line, suggesting smoother or uniformly distributed surfaces. These variances are critical to the material's operation in the harsh UAV environment, where safety, dependability, and structural integrity are critical. Comprehending these optical disparities aids in guaranteeing that the ABS substance is tailored to endure environmental strains and preserve the efficiency of the hydrogen storage tank across diverse operational scenarios.

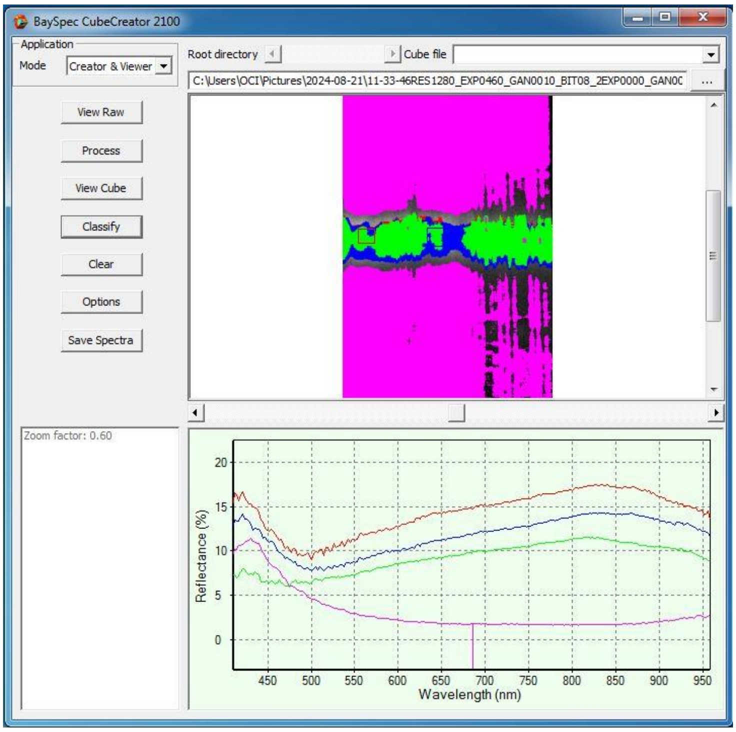


Figure 16. Multi spectra analysis image of ABS

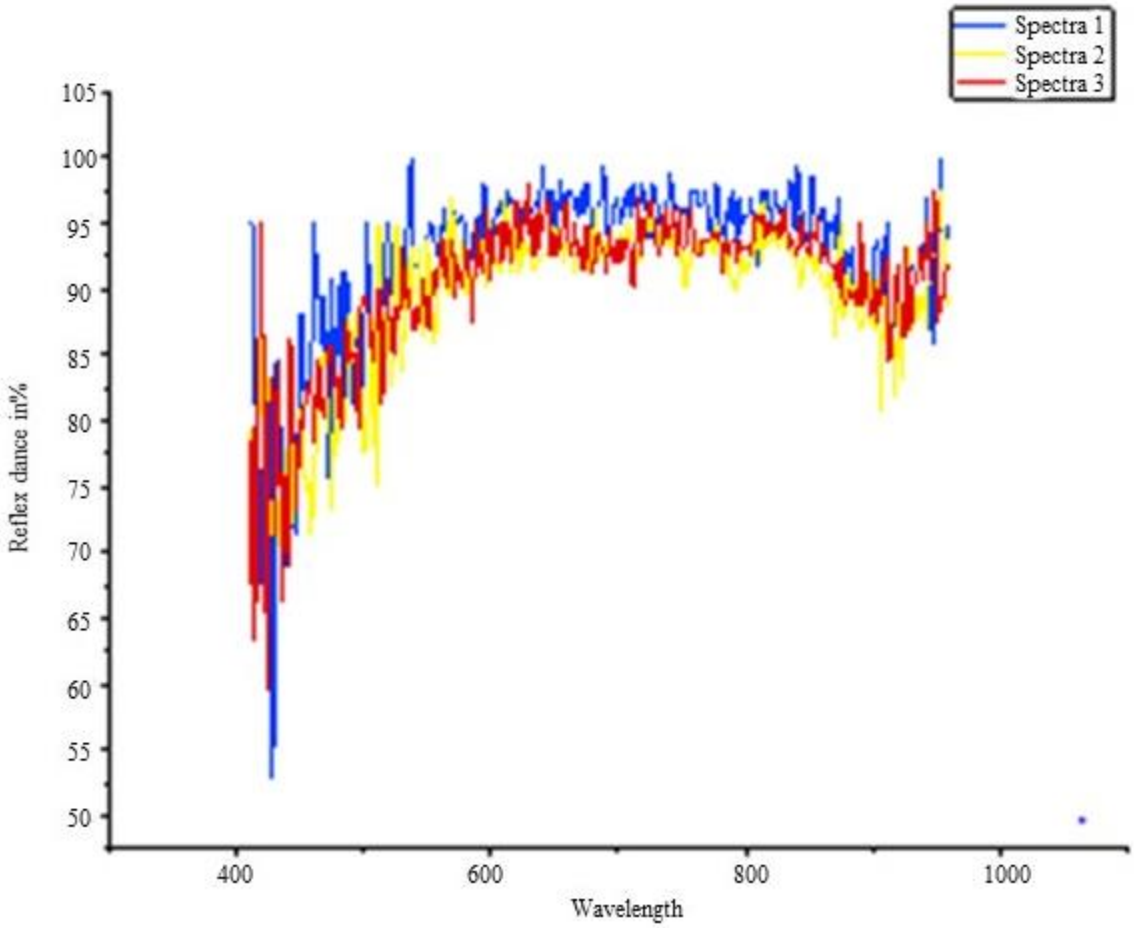


Figure 17. Multi spectra analysis of reflection in ABS

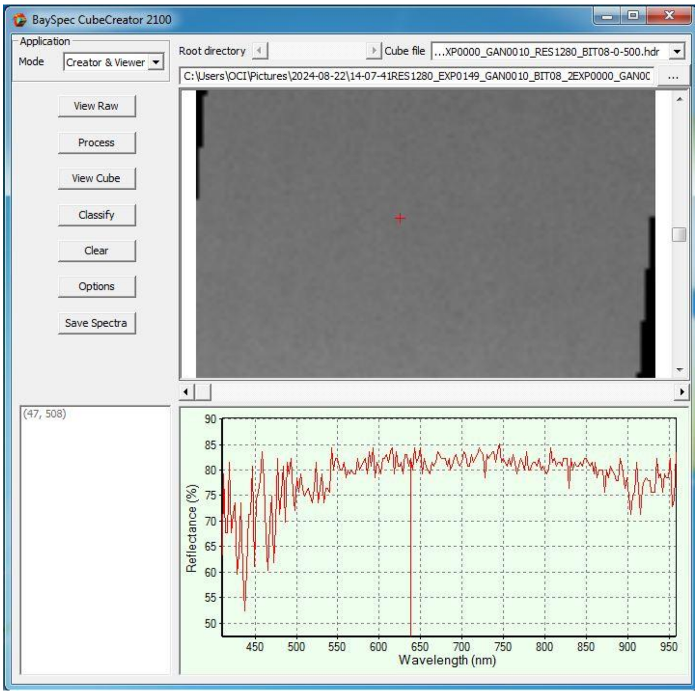


Figure 18. Multi spectra analysis of PET-G material.

Figure 17 shows an overall elevated reflectance across the visible to near-infrared spectrum is revealed by the multi-spectral analysis of the ABS material utilised for hydrogen storage cylinders for UAV applications. Reflectance values start within 50-80% in the violet-blue region (400-500 nm) and stabilise approximately 90-100% in the green to near-infrared region (500-1000 nm). This high reflectance means that the ABS material is highly reflective in these wavelength ranges, which is important for UAV applications because it minimises heat absorption and improves visibility under different lighting situations. All three spectra, however, exhibit minor differences in the analysis, especially at shorter wavelengths, where spectra 1 (blue) has a lower initial reflectance than spectra 2 (yellow) and spectra 3 (red). These variances point to possible irregularities in the thickness or surface finish of the material, which can affect its performance and homogeneity in UAV operations. The material is suitable with infrared sensors that are frequently employed in unmanned aerial vehicles (UAVs) for thermal imaging, navigation, and surveillance despite these variances since it exhibits consistent behaviour in the mid- and near-infrared ranges. The material's applicability for crucial UAV applications could be further improved by addressing the modest discrepancies in the shorter wavelengths. This would provide consistent optical and thermal properties across the spectrum.

Figure 18 shows the grasp of the material's optical characteristics and surface homogeneity is provided by the multi-spectral study of the PET-G material utilised in a hydrogen storage tank for UAV applications. A fairly uniform surface with little variances in reflectance is revealed by the greyscale spectral image, suggesting a smooth, homogenous surface free from noticeable flaws or abnormalities. Ensuring consistent performance in real-world applications depends on this consistency. The PET-G material has an elevated reflectance, spanning from 80 to 90 percent throughout the visible to near-infrared spectrum, according to the related reflectance spectrum graph. The material appears to have steady and homogeneous optical characteristics since the reflectance curve shows low variation and continuous light reflection without noticeable absorption features. This high degree of reflectance also suggests that the material is resistant to deterioration from light exposure, which is crucial for its durability and dependability in UAV applications. PET-G is a suitable material option for hydrogen storage tanks where consistency, longevity, and reliability are crucial because of its consistent surface qualities, which guarantee that it can preserve structural integrity and work dependably under the challenging conditions encountered by UAVs.

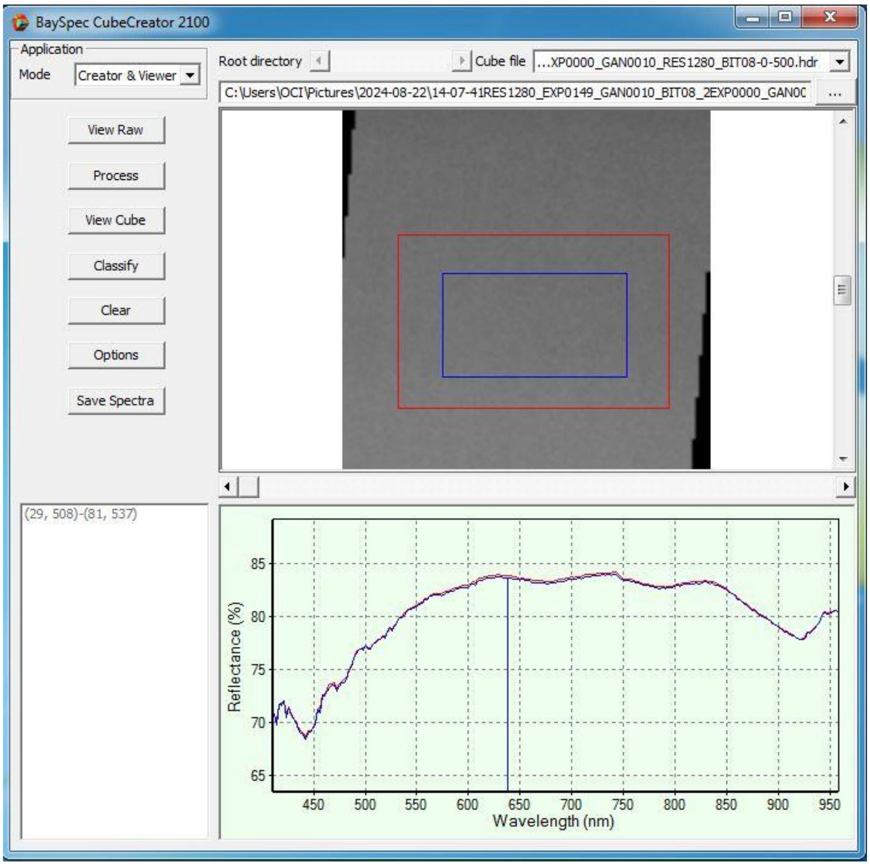


Figure 19. Multi spectra analysis of PET-G material.

The surface uniformity and optical properties of the PET-G material utilised for hydrogen storage tanks for UAV applications are thoroughly examined by means of multispectral analysis in figure 19. The consistent grey tone throughout the greyscale spectral image draws attention to the homogenous surface with few changes that is seen. There are two areas with consistent reflection (red and blue rectangles), suggesting that the material's surface is flawless and free of major flaws or imperfections. The material reflects light equally over the spectrum, as seen by the associated reflectance spectrum plot, which spans wavelengths between 400 nm to 950 nm. Reflectance increases from approximately 65 percent in the visible region to roughly 85–90% in the near-infrared region. The reflectance curve's smoothness, devoid of noticeable peaks or dips, indicates that the material's optical characteristics are stable and consistent and that it lacks any significant absorption features. Due to its high reflectivity, especially in the near-infrared spectrum, PET-G is a material that is highly suitable for upholding structural integrity and durability under the harsh conditions of unmanned aerial vehicle operations. It is also resistant to damage from environmental variables such as UV exposure. All things considered, this investigation confirms that PET-G is a suitable material to employ in hydrogen storage cylinders, guaranteeing dependability and safety in drone usage.

There are significant differences between the horizontal and circumferential positions, as shown in Figure 20 and 21 by the multi-spectral examination of the ABS material utilised in hydrogen storage tanks for UAV applications. In the longitudinal examination, the reflectance spectra consistently reveal high reflectivity over the studied locations, with values ranging from 70% to 95%, and the greyscale image displays a relatively uniform surface with little intensity differences. This suggests that the material's optical and surface characteristics are stable throughout its longitudinal axis, which is essential for withstanding longitudinal forces while it is in use. On the other hand, the greyscale image and reflectance spectra in the circumferential analysis exhibit somewhat greater fluctuation, with reflectance values varying from 65% to 90%. The circumferential analysis indicates that there are minor variations in the material's properties throughout the circumference of the cylinder. The green region exhibits the most reflectance, while the red zone shows the lowest. These slight variances may have an impact on the cylinder's capacity to tolerate circumferential stresses. They could be the result of distinct material properties or variations in manufacturing procedures. The study emphasises how crucial it is to preserve consistent material qualities in both horizontal and circumferential directions in order to guarantee the structural integrity and dependability of the hydrogen storage tank in unmanned aerial vehicle applications.

There are notable variations among the horizontal and circumferential locations according to the multi-spectral study of the ABS material utilised for hydrogen storage tanks for UAV applications in figure 22. The spectral classification map in the longitudinal analysis displays a range of colours that represent different regions with different spectral properties, implying surface composition or textural heterogeneity along the length of the cylinder. The reflectance spectra, which display a broad range of reflectance values between 70% to 100%, with certain regions showing more reflectance in the near-infrared spectrum, further support this variability. These differences suggest that the material's characteristics are not completely uniform along the longitudinal axis, which may have an impact on the cylinder's capacity to tolerate longitudinal stresses and preserve its strength under load. The spectral categorisation map produced by the circumferential analysis, on the other hand, is more consistent and nearly 95% reflectance, especially in the prominent blue zone. On the other hand, the existence of a red area with noticeably reduced reflectivity draws attention to possible variations in the surface conditions or material characteristics surrounding the perimeter. The red region's variability may have an effect on the cylinder's behaviour under circumferential loads, despite the blue region's general uniformity suggesting that the material's circumferential properties are more consistent. These results highlight how crucial it is to guarantee consistent material characteristics along the circumferential and longitudinal axes in order to preserve the dependability and security of hydrogen storage tanks in UAV applications. The observed differences in reflectance and spectral properties highlight the necessity of a comprehensive material assessment to find potential weak areas and guarantee optimal performance in the challenging environments that UAVs operate in.

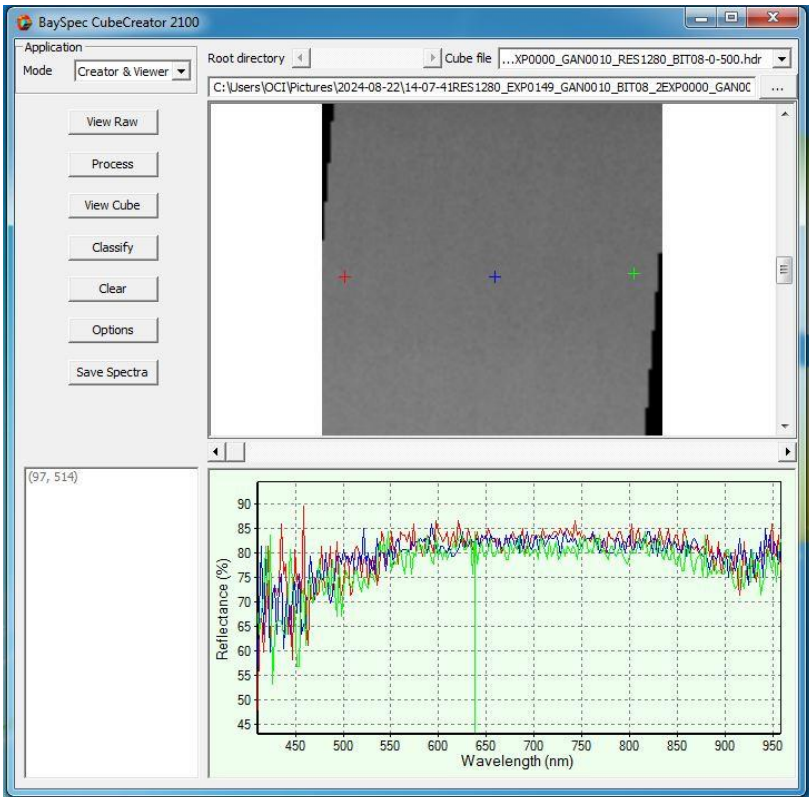


Figure 20. Multi spectra analysis image of PET-G in longitudinal axis

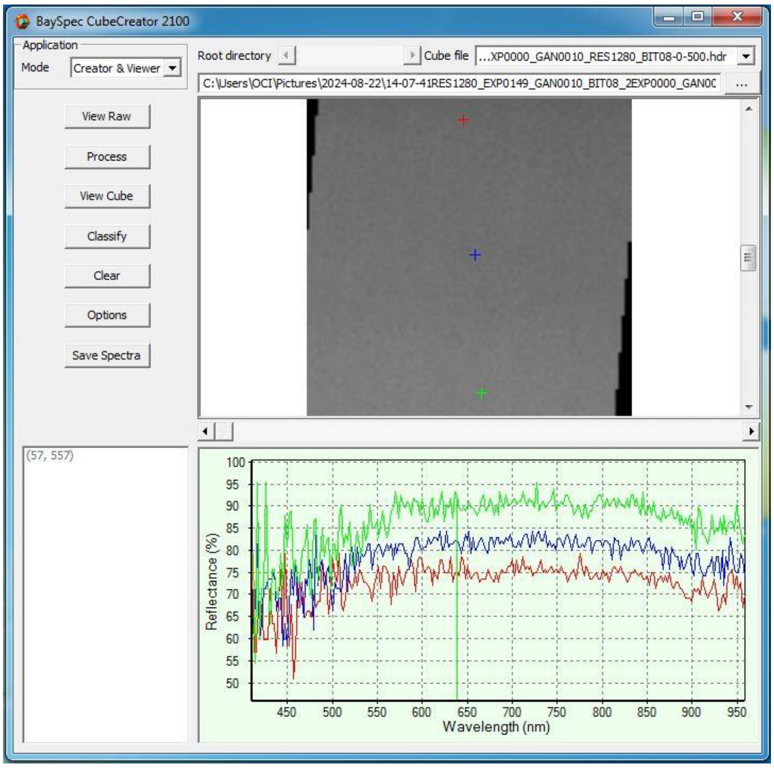


Figure 21. Multi spectra analysis image of PET-G in circumferential axis

Pet-G Material Wrapped with Carbon Fiber

The Figure 23 displays a carbon-fiber-wrapped PET-G material inside a multispectral experimental setup meant to examine the composite material's optical and surface characteristics at different light wavelengths. In order to improve its structural integrity, PET-G—which is renowned for its toughness and chemical resistance—is reinforced with carbon fibre, particularly for challenging uses like hydrogen storage tanks in unmanned aerial vehicles (UAVs). Furthermore, adding robustness and resilience to mechanical stresses is the carbon fibre wrapping. The setup's greyscale image brings out the surface features of the wrapped material, displaying changes in brightness that might point to variances in the carbon fiber's thickness or application or irregularities in the PET-G substance underneath. This thorough surface examination is essential for locating any flaws that can affect the hydrogen storage cylinder's performance, especially given the dynamic circumstances seen during UAV flights. The material's strength is preserved throughout its whole surface thanks to the multi-spectral analysis, which enables researchers to evaluate how the carbon fibre influences the PET-G core's optical characteristics. This procedure is essential for enhancing production procedures and guaranteeing the dependability and safety of the finished product in high-stress situations.

Figure 24 shows the Major differences in surface reflectance and possible inconsistencies in the PET-G material coated with carbon fibre for hydrogen storage tanks in UAV applications are revealed by the multi-spectral analysis of the material. Areas inside the blue-colored analysed zone are highlighted in the greyscale spectral image, suggesting changes in the fundamental PET-G material or the uneven placement of the carbon fibre wrap. The darker parts contrast with these blue patches, which could be indicative of less reflecting PET-G or carbon fibre coated more densely. The reflectance spectrum has a notable dip about 450–500 nm and a peak near 650–700 nm, indicating moderate reflectance ranging between 6% and 12% spanning the visible to near-infrared spectrum. These spectrum fluctuations suggest that the material might not have been applied evenly, which raises questions regarding possible weak areas that might have an impact on the cylinder's performance in high-stress scenarios like those seen in UAV operations. Ensuring the strength and dependability of the hydrogen storage tank in these demanding applications requires paying close attention to any material discrepancies and making sure that the carbon fibre wrap is applied consistently.

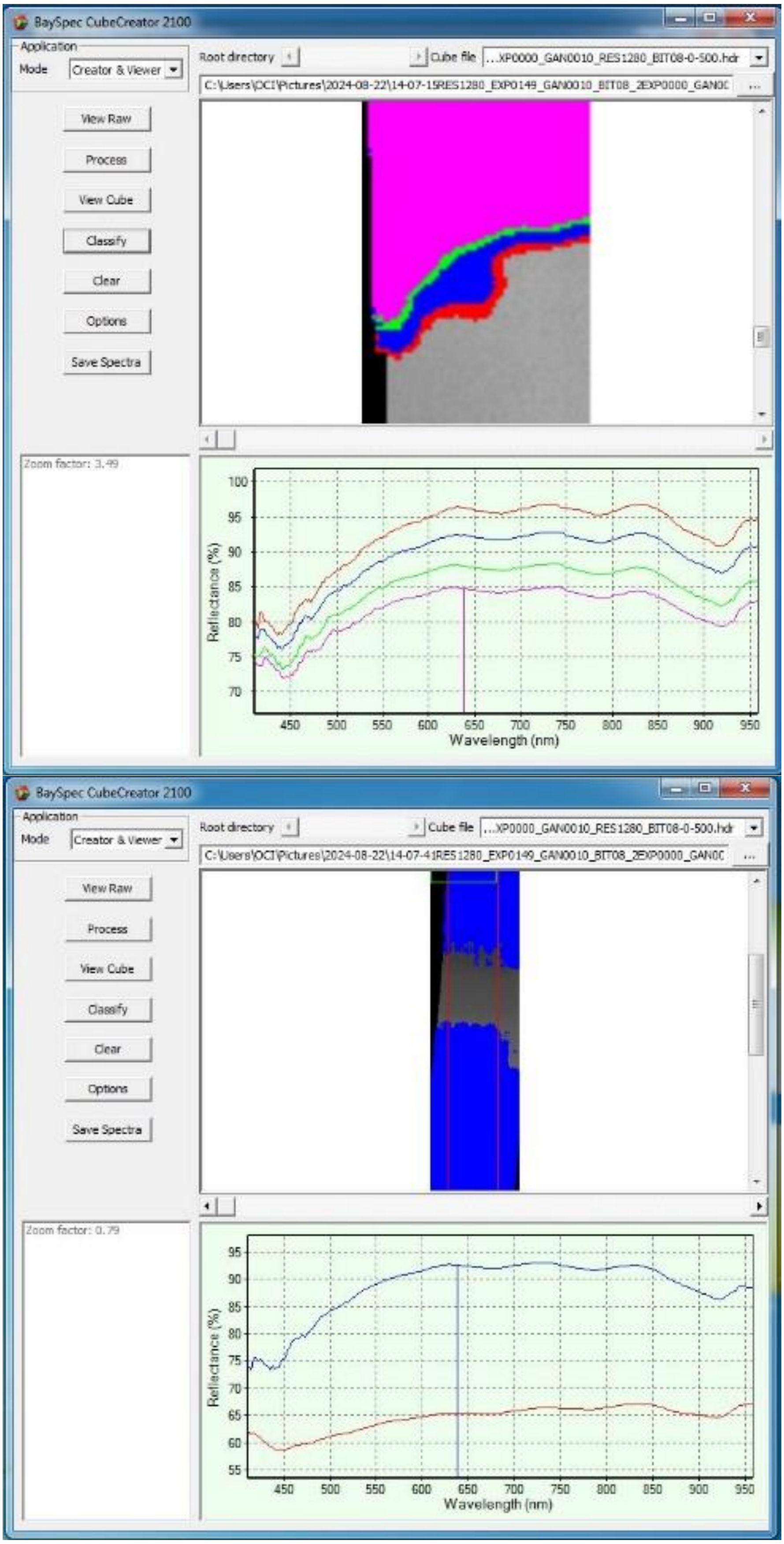


Figure 22. Multi spectra reflection analysis of PET-G.

Figure 25 shows the Considerable unevenness in the material's surface and optical properties is shown by the multispectral study of the PET-G material wrapped in carbon fibre for use in hydrogen storage cylinders in unmanned aerial vehicle applications. A wide spectrum of colours may be seen in the spectral classification map, which could be an indication of variances in the application, thickness, or underlying PET-G material of the carbon fibre wrap. Pink patches might indicate thinner carbon fibre layers or better reflectivity from the underlying material, while central sections dominated by black and deeper hues show regions with reduced reflectance, probably where the carbon fibre is placed more densely. This non-uniformity is highlighted even more by the reflectance spectrum, which shows early high reflectance values of 12% to 16% at shorter wavelengths (400-450 nm) that rapidly decrease as the wavelength increases, especially close to 500 nm, before progressively increasing again in the near-infrared region. This variation implies that the material becomes more reflective in the near-infrared while absorbing more light in the blue range. The spectral map and the reflectance variations that have been noticed point to possible material flaws that could jeopardise the structural stability and functionality of the hydrogen storage tank in UAV applications. Under the high-stress circumstances characteristic of UAV operations, maintaining the cylinder's dependability and safety depends on maintaining an even usage of the carbon fibre wrap with similar material attributes.

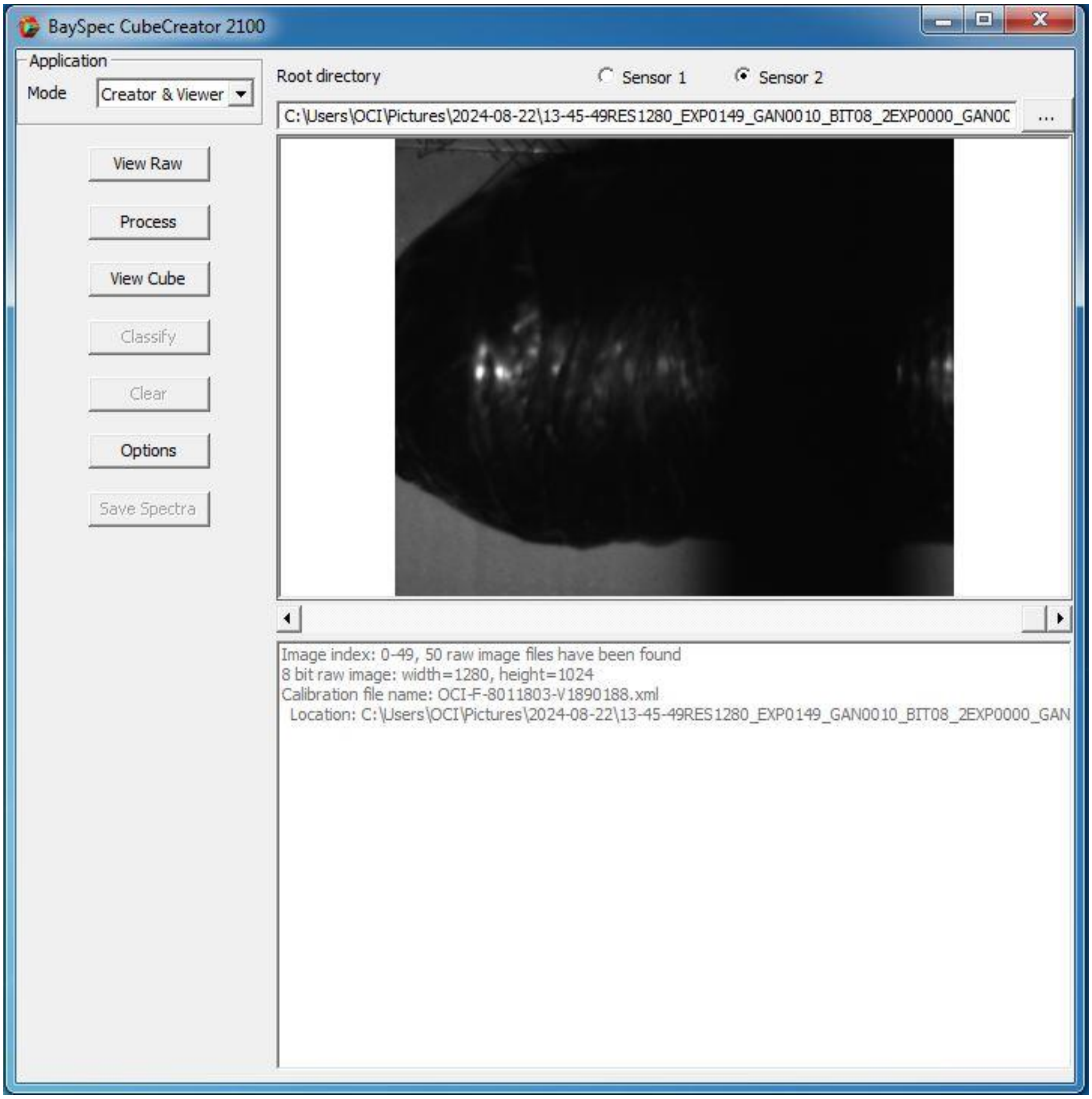


Figure 23. Multi spectra reflection analysis of carbon fibre wrapped PET-G material

The reflectance spectra of ABS and PET-G, which are utilised in hydrogen storage tanks for UAV uses, are compared using a multispectral analysis, which reveals different optical behaviors between the two materials. In comparison to PET-G, ABS, which is figure 26 shown by red data points, has higher reflectance in the violet to blue area about 400 nm, up to 11–12%. This means that ABS reflects more light and absorbs less at these shorter wavelengths. ABS has a significant decrease in reflectance with wavelength, peaking at approximately 6% around 500-600 nm. This indicates a higher absorbance in the blue-green spectrum, that may have an impact on the material's heat sensitivity in certain lighting scenarios. ABS's reflectance steadily rises beyond 600 nm, peaks at about 800 nm, and then tapers down as it gets closer to 1000 nm, indicating higher variation in the near-infrared spectrum. PET-G, on the other hand, is shown by yellow data points and begins with lower reflectance at 400 nm. As the wavelength climbs towards 600–700 nm, it steadily increases and reaches values similar to ABS in the red spectrum (about 8–9%). PET-G exhibits constant optical performance throughout the near-infrared band, as seen by its relatively stable reflectance. The ABS's mid-spectrum reflectance reduction is more pronounced, indicating that it may absorb more heat. This could be important to take into account for thermal management in applications for unmanned aerial vehicles. Both materials have near-infrared reflectance that is equivalent, which qualifies them for use with infrared detectors or sensors. In the end, these optical characteristics should be taken into account when deciding between ABS and PET-G. ABS may be more advantageous in UV-exposed environments because of its higher reflectance at lower wavelengths, while PET-G's consistent reflectance throughout the spectrum is helpful for applications that need consistent optical behaviors.

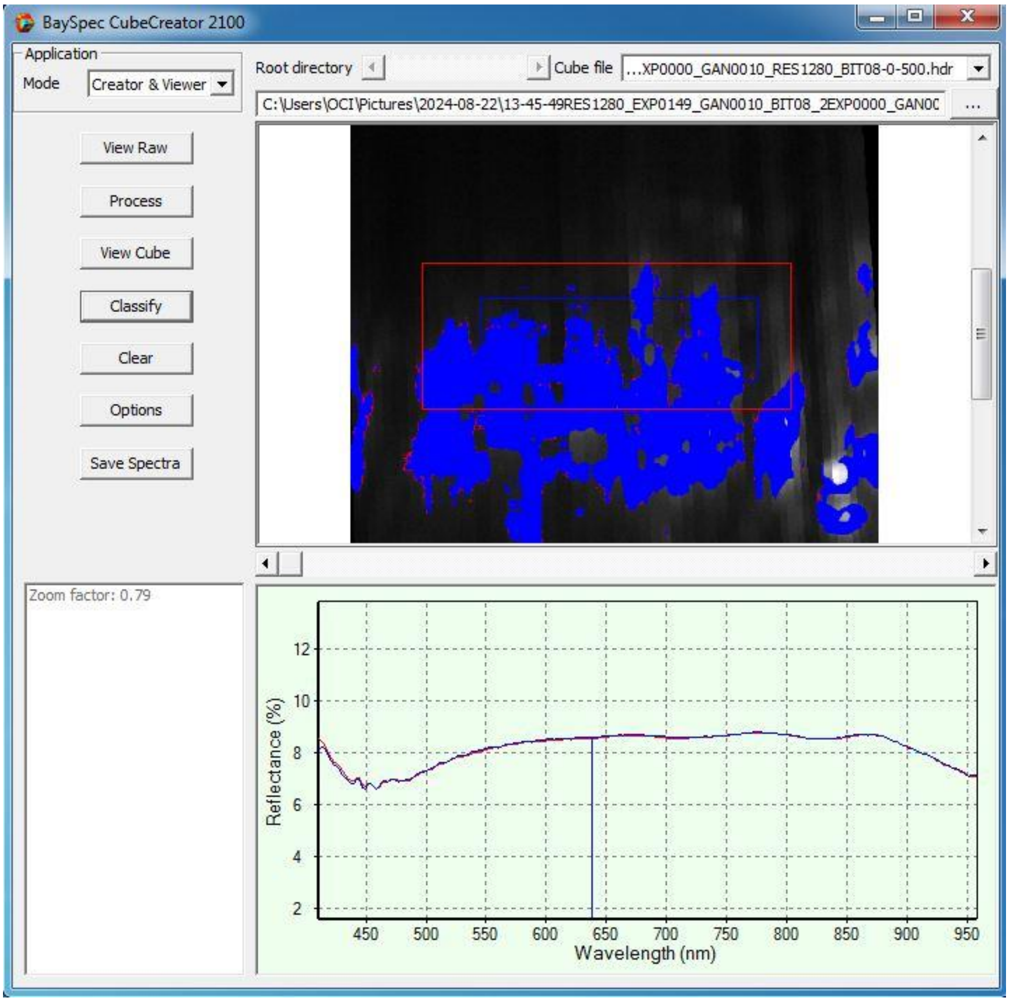


Figure 24. Multi spectra reflection analysis of carbon fibre wrapped PET-G material in longitudinal axis

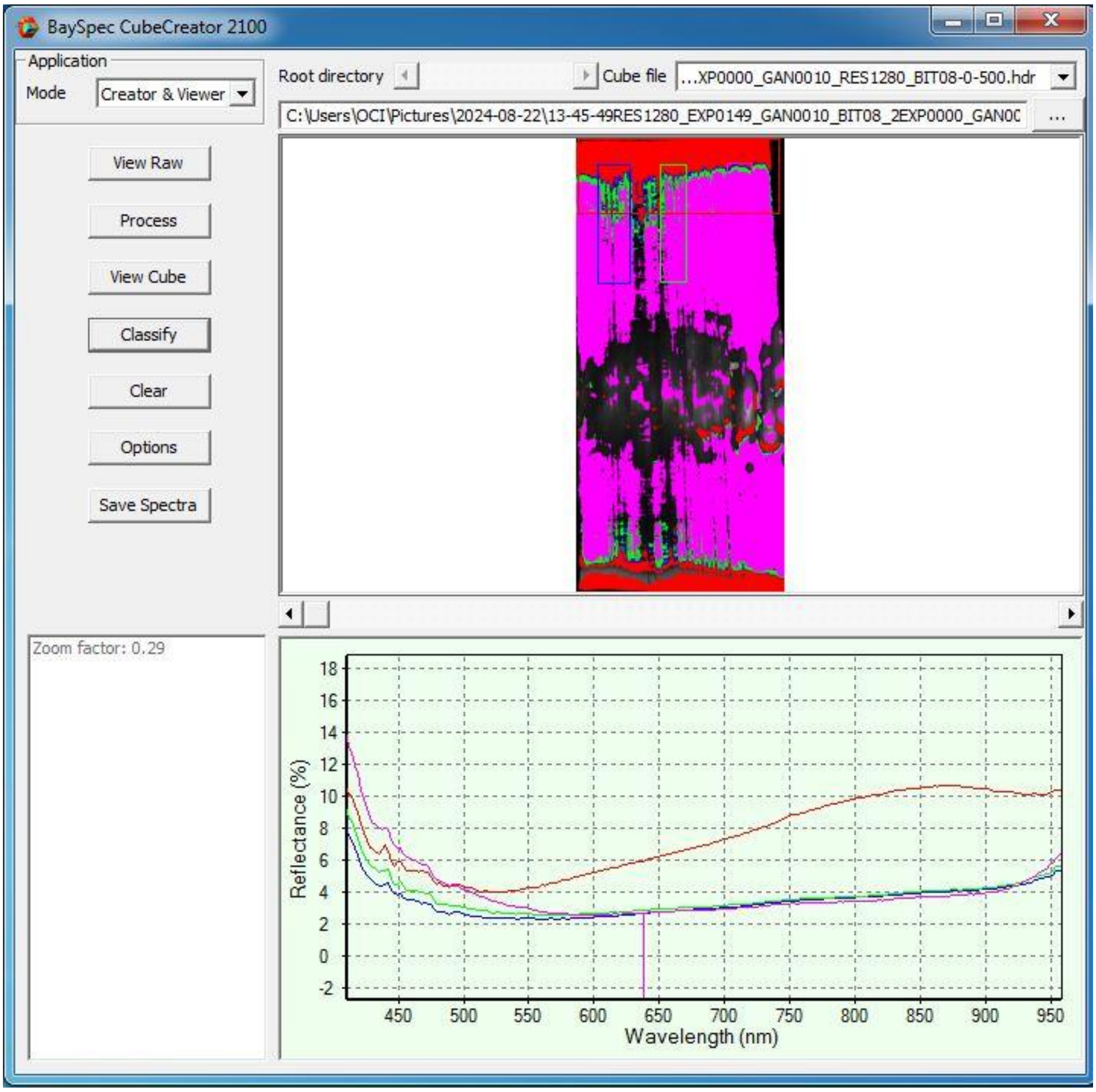


Figure 25. Multi spectra reflection analysis of carbon fibre wrapped PET-G material in longitudinal and circumferential axis

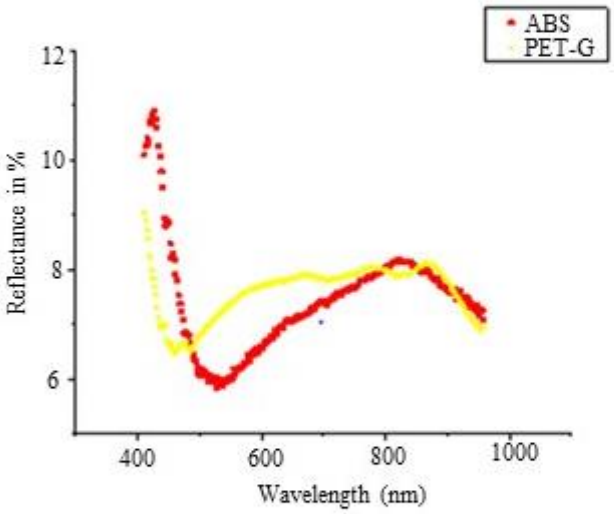


Figure 26. Multi spectra over all reflection analysis of carbon fibre wrapped PET-G

Journal of Polymer & Composites
Volume 13, Special Issue 3
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

DYE PENETRANT TEST

The Figure 27 shows the findings from a dye penetrant test (DPT) on a PET-G hydrogen storage tank intended for unmanned aerial vehicle use. Using a dye penetrant, surface-breaking flaws like fractures or pores are found on the cylinder using this non-destructive testing technique. Once the surplus penetrant has been removed, the penetrant seeps into any faults. The defects are then visible as coloured indicators against the white background of the developer. The cylinder is covered in a white, powdery developer in the picture, and the lower part of the cylinder shows red or pink indications, which point to the existence of surface flaws wherein the penetrant has permeated in. These flaws suggest that the cylinder's surface integrity may be compromised, most likely in the form of tiny pores or fissures. The accumulation of these flaws close to the cylinder's bottom may indicate places that are more susceptible to stress or inconsistent production. The occurrence of these faults is concerning for UAV uses, where the strength of hydrogen storage tanks is crucial. These results imply that additional examination, maintenance, or even rejection of the cylinder could be necessary to guarantee its dependability and safety while in use, since surface flaws could spread under operating pressures and result in failure.

Figure 27. Dye penetrant test of PET-G.

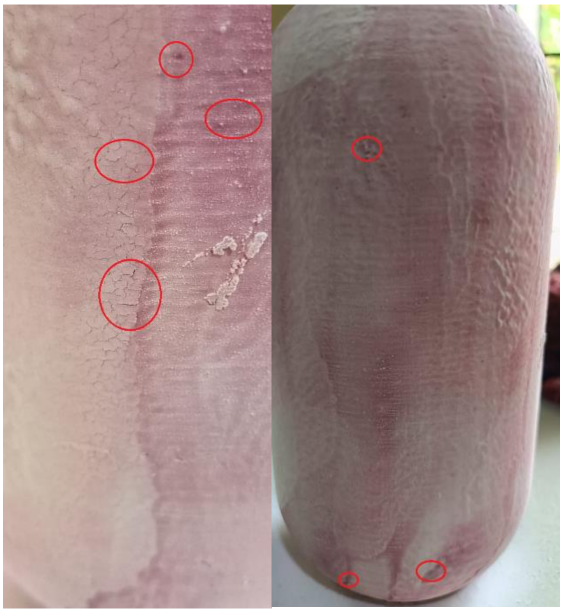


Figure 28. Defect finding in Dye penetrant test of PET-G.

A PET-G hydrogen storage tank meant for UAV applications has several surface-breaking faults, as seen by the dye penetrant testing findings shown in the two figure 28. The cylinder's surface is seen up close in the first shot, where a number of red indicators draw attention to tiny fissures and potential pores. These surface-wide flaws create a network of possible weak spots that could jeopardize the material's strength, especially in high-pressure situations like those seen in UAV operations. While concentrating on a different location of the cylinder, the second image likewise shows red indicators, especially in the vicinity of the bottom, which is a crucial area because of the forces it would experience during use. These flaws are seen throughout the cylinder, which may indicate variations in the material or tensions brought on during production or handling. These results are alarming because hydrogen storage tanks play a crucial role in unmanned aerial vehicles (UAVs), and any malfunction could have disastrous repercussions. The cylinder may fail as a result of the detected flaws spreading during operating loads. In order to make sure the cylinder satisfies the strict safety and performance requirements required for UAV applications, it is therefore likely in need of additional inspection, repair, or even rejection.

The ABS hydrogen storage tank meant for UAV applications has major surface-breaking defects, as shown in figure 29 by the dye penetrant testing findings. These defects are visible as uneven, web-like designs and textures all over the cylinder's surface. The pinkish-red colour denotes the locations wherein the dye penetrant has penetrated surface pores or cracks and been pulled out by the developer, especially in the vicinity of the cylinder's crucial neck and shoulder regions. Because of the extreme strains these areas experience during pressurisation and operation, they are particularly susceptible. Such flaws in these crucial places are alarming because they point to possible weaknesses that can give way under the mechanical loads common to UAV operations, ultimately resulting in structural failure. The cylinder's capacity to securely hold and release hydrogen, which is crucial for the UAV's functionality and safety, could be seriously jeopardised if these flaws are not fixed. In order to make sure the cylinder satisfies the strict safety requirements required for UAV applications, it probably needs to be inspected, repaired, or even rejected. Maintaining the hydrogen storage cylinder's structural integrity is essential to averting disastrous malfunctions while UAV operations are underway.

Figure 29. Dye penetrant test of ABS material

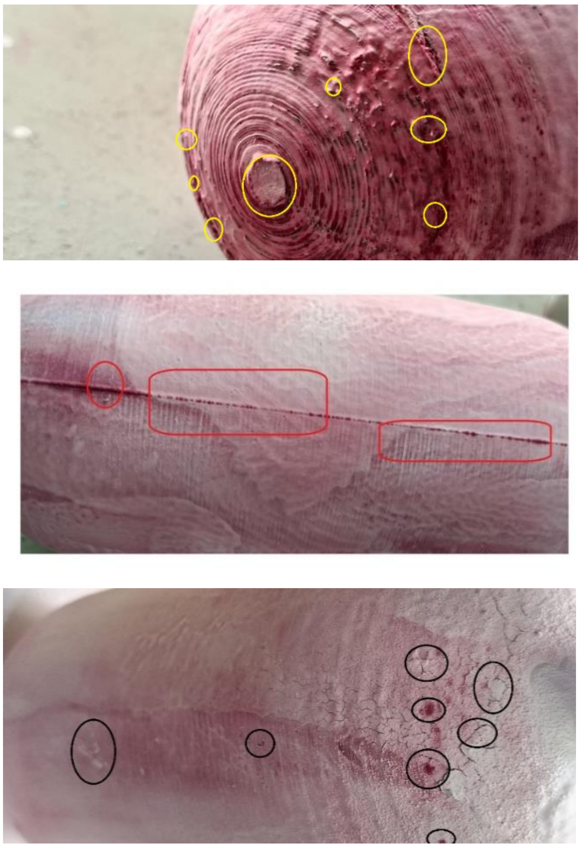


Figure 30. Defect finding in Dye penetrant test of ABS.

Figure 30 shows the ABS hydrogen storage tank meant for use in UAV applications has multiple serious surface-breaking flaws that raise serious questions regarding the structural integrity of the cylinder, according to the results of dye penetrant tests. A noticeable linear flaw that appears to be a crack or seam runs along the surface of the cylinder in the first image, suggesting a significant potential weak point that might spread under load. The subsequent image displays a number of tiny, circular flaws grouped in particular regions, indicating localised material weaknesses like pores or tiny cracks that could act as starting locations for more damage when operating forces increase. The third picture, which focusses on the cylinder's base, shows a large number of tiny flaws grouped in the centre, an important spot that experiences a lot of pressure when in use. If the cylinder gets exposed to the extreme pressures and mechanical strains typical of UAV operations, these faults, particularly in the base, could result in a catastrophic failure. The tank may not be safe for use without additional inspection, repair, or rejection, as the combined presence of a linear crack, grouped defects, and base anomalies may compromise its capacity to safely hold and release hydrogen, posing a serious risk during UAV flights.

ULTRASONIC FLAW DETECTOR

Figure 31 shows the Images captured by the Olympus Epoch 650 ultrasonic flaw detector offers vital information on the internal consistency of a hydrogen storage cylinder made of ABS (Acrylonitrile Butadiene Styrene), which is especially useful for unmanned aerial vehicle (UAV) applications. The reflection peaks in the ABS material can be seen on the detector screens at depths of 3.86 and 3.91 mm. These peaks show the existence of reflective surfaces, which are probably caused by inclusions, voids, or other internal faults in the material. The fact that these peaks are consistently detected in various measurements implies that these intrinsic features are important and common in the material structure. These peaks' large amplitudes suggest significant internal reflections, which may be a symptom of serious defects endangering the cylinder's structural integrity. The existence of such defects is especially concerning in the context of UAV uses, where hydrogen storage tanks must tolerate high pressures and guarantee safety. The little variance in the depth readings (3.86 mm and 3.91 mm) may be explained by variations in the location of the faults or in the thickness of the material, which is indicative of the inherent variability in the production process. These results highlight how crucial comprehensive non-destructive testing is to guaranteeing the dependability of hydrogen storage tanks. In order to find any potential problems prior to the cylinders are installed in UAVs, the ultrasonic defect detection technology employed here is crucial. The possibility of failure under operational settings resulting from faults discovered at these depths highlights the necessity of strict quality control measures during the production process. Early detection of these defects enables producers to improve the material's ability to perform and guarantee the security and dependability of the UAVs using these cylinders.

The Figure 32 show the findings from an ultrasonic defect detector that was used to examine a PET-G hydrogen storage tank intended for unmanned aerial vehicle use. The thickness of the material is shown by the gadget in multiple locations, displaying values between 4.06 and 4.22 mm. In order to preserve the structural strength of the hydrogen storage cylinder under extreme circumstances, these measurements indicate the evenness and integrity of the material's thickness. The material does not appear to have any substantial internal faults, such as cavities or cracks, that could hinder its performance, based on the consistent readings. To best identify any discontinuities in the material, the instrument's settings (gain, range, and velocity) are changed. The right transmission of ultrasonic waves within the material is ensured by the employment of a couplant, as demonstrated by the bottle of blue liquid. In UAV applications where safety is of the utmost importance, this technology is crucial for identifying subsurface faults that might not be obvious through alternative inspection methods, ensuring the cylinder's reliability.

Figure 31. Ultrasonic flaw detector analysis of ABS.

Figure 32. Ultrasonic flaw detector analysis of PET-G.

CONCLUSION

This study's research offers a thorough examination of the advantages and disadvantages of employing 3D printed hydrogen storage tanks for UAV applications. Finite Element Analysis (FEA) was used to thoroughly examine four different materials: ABS, PET-G, HDPE, and Nylon. The results showed that PET-G and ABS had better mechanical properties at high pressure, making them excellent candidates for additional experimental validation. But this study also showed that 3D printed components' intrinsic surface quality problems pose serious threats to their long-term structural stability and functionality. The results of the experimental tests, which included dye penetrant testing, ultrasonic flaw identification, and multispectral analysis, were crucial in determining the kind and extent of faults connected to 3D printed hydrogen storage tanks. Variations in reflectance associated with surface roughness and possible subsurface voids were shown by multispectral analysis, suggesting that the method of additive manufacturing may introduce irregularities that impact material behaviors under operating circumstances. By exposing internal flaws including voids, delamination's, and uneven material distribution—symptoms of the layer-by-layer deposition techniques utilized in 3D printing—ultrasonic fault detection further supported these conclusions. Additional surface-level crack and porosity indications from dye penetrant tests raised doubts regarding the structural integrity of these parts. The combination of these results emphasizes a crucial conclusion: the overall dependability and protection of the storage cylinders are seriously compromised by the surface imperfections inherent in the 3D printing process, even though PET-G and ABS are mechanically feasible materials for hydrogen storage. These flaws jeopardise the cylinders' mechanical integrity in addition to posing a risk throughout high-pressure processes, which are essential for UAV applications. The present study underscores the pressing want for progress in 3D printing technology, specifically for the enhancement of surface polish and material consistency. The surface imperfections compromising the strength of parts that are 3D printed might not be adequately addressed by the post-processing methods available today. Therefore, in order to reduce the likelihood of faults that could cause failure under operating loads, future research should concentrate on creating improved post-processing processes or investigating alternative manufacturing methods that can generate smoother, more uniform surfaces. In conclusion, there are still a lot of obstacles to overcome before 3D printed hydrogen storage tanks can be used in lightweight, effective UAV applications. The study's conclusions are an important reminder that the viability of such creative solutions hinges not only on the choice of suitable materials but also on the development of manufacturing techniques that yield flawless parts that can withstand the harsh circumstances of UAV operations.

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