Al-Mukhtar Journal of Engineering Research 00 (0): 01-07, 2026
Doi: https://doi.org/10.54172/cknh4p86

Research Article Open Access

3D Ultrasonic Evaluation of Porosity Detection in Carbon Fiber Reinforced Polymer Composites: Effects of Backscattering and Back Reflection

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Received:
09 January 2026

Accepted:
11 May 2026

Abstract

3D ultrasonic C-scan inspections at 50 MHz were conducted to detect porosity in carbon fiber–reinforced polymer (CFRP) composites fabricated under vacuum pressures of 0, −330, and −686 mm Hg, resulting in porosity levels of 7.1%, 6.4%, and 5.8%, respectively. In specimens fabricated at 0 mm Hg, porosity levels of approximately 6–8% were detected near the surface layers, whereas deeper regions exhibited lower detected porosity values of approximately 2–4%. The ability to detect internal porosity decreased with increasing laminate depth because of ultrasonic signal attenuation caused by backscattering and back reflection at fiber–matrix interfaces. The measured porosity percentages from the top to bottom layers were 8.07%, 3.29%, 3.16%, 2.63%, 3.87%, 2.27%, 2.40%, and 5.51%, in sequence. These results revealed fluctuations in ultrasonic detectability at greater depths, reflecting the complex interaction between ultrasonic wave propagation, material anisotropy, and internal microstructural features. Overall, the results demonstrate that 3D ultrasonic imaging is an effective non-destructive evaluation (NDE) technique for surface and near-surface porosity characterization, although its sensitivity decreases in deeper and highly attenuated laminate regions.

Keywords: Carbon Fiber–Reinforced Polymer; Ultrasonic Microscopy; Porosity; Backscattering; Back Reflection.

INTRODUCTION

CFRP composites are widely used in high-performance structural applications due to their high specific strength, stiffness, and corrosion resistance. Despite these advantages, the structural integrity and long-term reliability of CFRP composites are strongly influenced by manufacturing-induced defects, among which porosity remains one of the most common and detrimental. Porosity has been shown to degrade mechanical performance, influence fatigue and fracture behavior, and compromise durability, making its detection and control a critical concern in composite manufacturing and quality assurance (Mehdikhani et al., 2019; Hakim et al., 2016a; Hakim et al., 2016b; Shi et al., 2024).

Vacuum-assisted fabrication techniques, such as hand lay-up vacuum bagging, are commonly employed to reduce porosity by enhancing resin infiltration and minimizing entrapped air during curing. However, variations in vacuum level and processing parameters can lead to non-uniform porosity distributions through the laminate thickness, particularly in relatively thick

CFRP laminates. Accurate characterization of porosity distribution is therefore essential for evaluating manufacturing quality and ensuring structural reliability (Sheu, 2023).

NDE techniques have been shown to be effective tools for detecting and characterizing porosity and other manufacturing-induced discontinuities in carbon fiber–reinforced polymer composites, enabling quantitative assessment of defect populations without damaging the material (Hakim et al., 2016a; Hakim et al., 2016b, Klosterman et al., 2021). Advanced ultrasonic and volumetric NDE methods have further demonstrated strong capability in identifying internal voids, correlating defect distributions with mechanical performance, and supporting quality control in composite manufacturing processes (Hakim et al., 2017a; Schumacher et al., 2017). Among these NDE techniques, ultrasonic testing is one of the most widely used NDE methods for inspecting composite materials because of its sensitivity to internal defects and applicability to large components. Ultrasonic C-scan imaging enables visualization of porosity without damaging the material; however, inspection effectiveness often decreases with increasing laminate thickness due to signal attenuation. This attenuation arises from backscattering, back reflection, and absorption at fiber–matrix interfaces, where acoustic impedance mismatches between carbon fibers, polymer matrix, and porosity result in progressive energy loss (Ono, 2023). Consequently, porosity located in deeper layers may be underestimated or remain undetected.

Previous studies have reported a strong correlation between porosity content and ultrasonic attenuation in CFRP laminates, highlighting challenges associated with deep-layer defect detection (Shi et al., 2024). Nevertheless, many investigations focus on bulk attenuation behavior or surface-dominated measurements, while systematic evaluation of depth-dependent porosity detectability under different fabrication vacuum conditions remains limited. In particular, the combined effects of fabrication-induced porosity variation and ultrasonic backscattering and back reflection on through-thickness porosity detection have not been fully addressed. The objective of this study is to investigate the capability of ultrasonic microscopy to detect porosity through the thickness of CFRP composites fabricated using a hand lay-up vacuum bagging process under three different vacuum levels.

MATERIALS AND METHODS

The carbon fiber–reinforced polymer (CFRP) composite specimens with three predefined porosity levels used in this study were fabricated at vacuum levels of 0% (0 mmHg), 50% (−330 mmHg), and 100% (−660 mmHg) following ASTM standards, using the hand lay-up method at the University of Dayton, Ohio, USA. A full description of the materials and manufacturing procedures is provided in detail in (Hakim et al., 2017a; Hakim, 2017b) and the referenced ASTM standards.

Ultrasonic microscopy inspection was performed on the CFRP specimens using a Sonoscan Gen5 system equipped with an Olympus Panametrics NDT V3193 transducer at Dresden University of Technology, Germany. The experimental setup is illustrated in Figure 1. The measurements were conducted in pulse–echo immersion mode at a center frequency of 50 MHz. During testing, each specimen was fully immersed in a deionized water bath, serving as a coupling medium for the ultrasonic waves. The transducer was programmed to scan the specimen surface in two orthogonal directions, ensuring complete coverage of the inspection area. As the ultrasonic waves propagated through the water and entered the specimen, part of the incident energy was reflected from the specimen’s top surface, producing the surface echo. Subsequent reflections from internal fiber–matrix interfaces and discontinuities such as porosity was also recorded. These reflected signals were analyzed to assess signal attenuation, backscattering, and back reflection patterns, which provided insight into the distribution and severity of porosity across the composite layers.

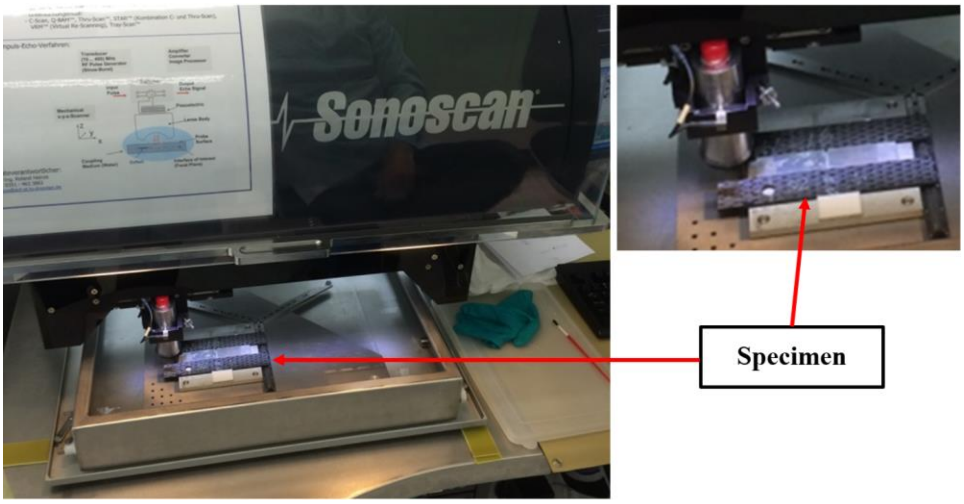

Figure: (1). Ultrasonic microscopy test setup showing the specimen during inspection at the University of Technology Dresden, Germany.

RESULTS

The ultrasonic inspection results showed a progressive decrease in signal intensity as ultrasonic waves propagated through the composite laminate. As illustrated in Figure 2, an ultrasonic image revealing high concentration of white spots, indicating porosity was detected near the surface layer (Layer 1), whereas significantly fewer white spots were observed in the deeper layers toward the laminate center (Layer 4). This trend was consistent across specimens from all three porosity levels, indicating that porosity was more readily detected near the surface, while defect detection became increasingly limited with depth.

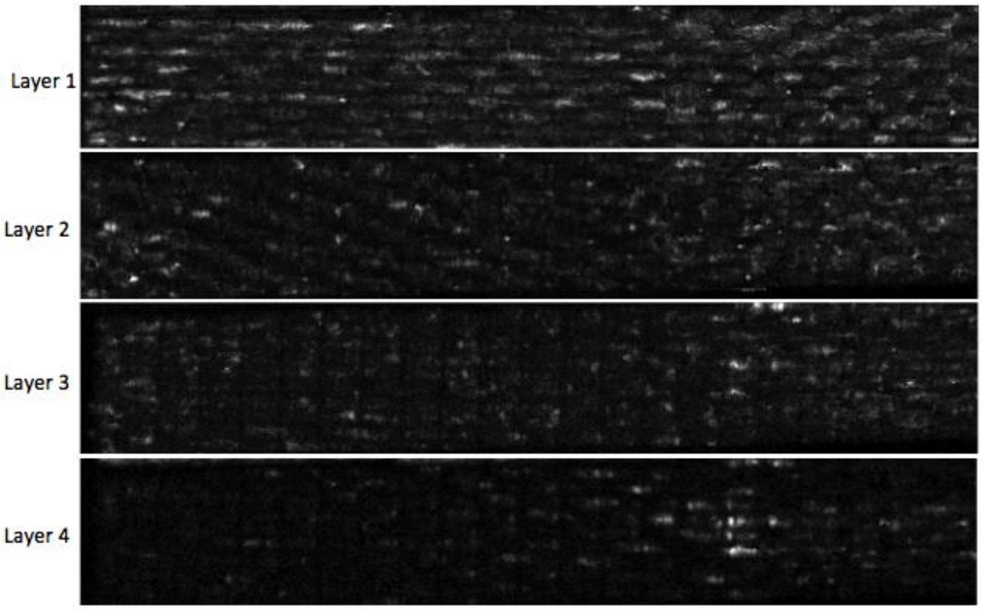

Figure: (2). Ultrasonic images showing porosity distribution in the top four layers, where Layer 1 is adjacent to the surface and Layer 4 is located near the laminate center. The same layering sequence applies to the bottom layers.

Porosity in ultrasonic images acquired from the specimen surface to the laminate center, shown in Figure 2, was quantified using ImageJ software by applying a global threshold segmentation method based on gray-level histogram analysis. To ensure consistency, the same evaluation procedure was applied to all images. Quantitative results for six specimens per vacuum level are presented in Figure 3, which illustrates the variation in porosity percentage as a function of the vacuum level applied during composite fabrication. The results show a clear decreasing trend in porosity with increasing vacuum, from 0 mm Hg (low vacuum) to −330 mm Hg (medium vacuum) and −686 mm Hg (high vacuum), indicating that higher vacuum levels enhance resin infiltration and reduce entrapped air during curing, leading to improved laminate quality.

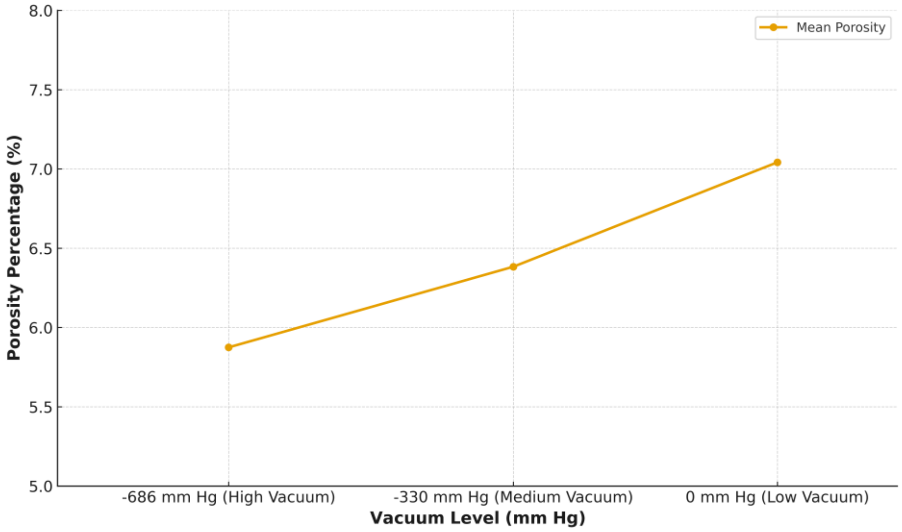

Figure: (3). Variation in porosity percentage as a function of the vacuum level applied during composite processing.

As shown in Figure 3, specimens fabricated with low vacuum (0 mm Hg) exhibited the highest average porosity, approximately 7.1%. In contrast, specimens processed under −330 mm Hg and −686 mm Hg showed reduced porosity levels of about 6.4% and 5.8%, respectively, confirming the effectiveness of increased vacuum in minimizing porosity content. The through-thickness porosity distribution is presented in Figure 4. The smoothed porosity profile from Top Layer 1 (T1) to Bottom Layer 1 (B1) demonstrates a clear decrease in porosity with increasing depth. The highest porosity content was detected near the top surface, while the mid and lower layers exhibit reduced porosity detection, indicating improved compaction toward the laminate interior.

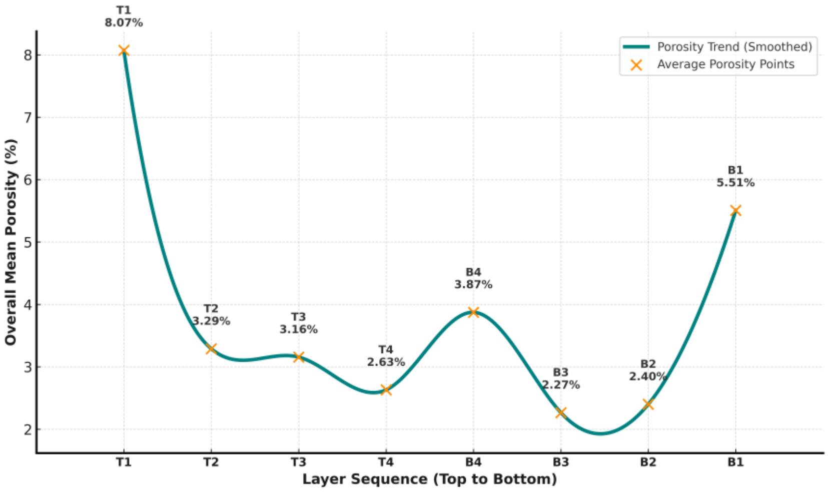

Figure: (4). Smoothed porosity distribution across low vacuum (0 mm Hg) laminate layers (T1–B1).

The measured porosity values in the top region decrease progressively from 8.07% in Top Layer 1 to 3.29% in Top Layer 2, 3.16% in Top Layer 3, and 2.63% in Top Layer 4, indicating a clear reduction in porosity toward the laminate center. A similar decreasing trend is observed in the bottom region from 5.51% in Bottom Layer 1 to 2.40% and 2.27% in Bottom Layers 2 and 3, respectively. However, the porosity measured at Bottom Layer 4 (center) shows a higher value of 3.87%, deviating from the otherwise decreasing through-thickness trend. This result indicates a localized variation in porosity distribution at the laminate center on the bottom side, highlighting a non-uniform through-thickness porosity profile across the composite.

DISCUSSION

The ultrasonic microscopy inspection results demonstrate that porosity detectability in CFRP laminates strongly depends on both laminate depth and porosity content. The progressive reduction in signal intensity with increasing depth reflects cumulative ultrasonic attenuation caused by repeated interactions with carbon fiber layers and porous regions. Backscattering and back reflection at the fiber–matrix interfaces progressively weaken the transmitted signal, thereby limiting porosity detectability in deeper layers. Similar depth-dependent ultrasonic attenuation behavior has been reported in CFRP laminates, where strong acoustic impedance mismatches between fibers, matrix, and voids significantly reduce ultrasonic penetration and signal amplitude (Ono, 2023; Shi et al., 2024).

The higher concentration of detected porosity near the surface layers is therefore influenced by two factors: the actual porosity distribution and the greater ultrasonic sensitivity in near-surface regions. In deeper layers, the reduced amount of porosity does not necessarily indicate the absence of porosity, but rather a limitation in porosity detectability due to ultrasonic signal attenuation. This effect becomes more pronounced toward the laminate deep layers, where multiple reflections and scattering events reduce signal amplitude and contrast in the C-scan images. Notably, the higher porosity values detected in the deep layers deviate from the overall decreasing through-thickness trend, indicating localized randomness in porosity distribution and depth-dependent fluctuations in ultrasonic detectability. Such depth-dependent variability in ultrasonic response is consistent with previous studies showing that porosity-induced scattering and attenuation in heterogeneous CFRP laminates can lead to non-uniform signal behavior through the thickness (Shi et al., 2024). Consequently, the apparent decrease in porosity with depth must be interpreted in the context of ultrasonic wave propagation limitations in anisotropic composite materials, rather than solely as a reflection of the true porosity distribution. The effect of fabrication vacuum level on porosity content is also evident, as specimens processed under higher vacuum exhibited significantly lower average porosity. Increased vacuum promotes improved resin infiltration and reduces entrapped air during curing, resulting in enhanced laminate compaction and reduced void formation. This observation is consistent with previous studies on vacuum-assisted composite processing, which demonstrated that increased vacuum pressure leads to lower void content and improved laminate quality (Sheu, 2023; Shi et al., 2024). Overall, these findings confirm that while 3D ultrasonic imaging is effective for surface and near-surface porosity evaluation, its sensitivity diminishes with depth, underscoring the importance of optimized fabrication conditions and careful interpretation of ultrasonic results in thick CFRP structures.

CONCLUSION

This study investigated the capability of 3D ultrasonic microscopy testing to evaluate porosity distribution through the thickness of CFRP composites fabricated using a hand lay-up vacuum bagging process under three vacuum levels. Based on the experimental results and analysis, the following conclusions can be drawn:

1. Increasing the fabrication vacuum level from 0 mm Hg to −330 mm Hg and −686 mm Hg resulted in a clear reduction in average porosity content of 7.1%, 6.4% and 5.8%, respectively, confirming that higher vacuum levels enhance resin infiltration, reduce entrapped air, and improve laminate compaction.
2. Ultrasonic C-scan imaging successfully identified porosity distribution through the laminate thickness, demonstrating its effectiveness as an NDE technique for assessing CFRP laminate quality.
3. Porosity was predominantly detected near the surface layers (6–8%), while deeper layers exhibited lower detected porosity (2–4%). This through-thickness trend reflects both the influence of the randomly distributed porosity and depth-dependent limitations of ultrasonic inspection.
4. The porosity distribution across the laminate thickness from the upper to lower layers was 8.07%, 3.29%, 3.16%, 2.63%, 3.87%, 2.27%, 2.40%, and 5.51%. Ultrasonic detection sensitivity decreased with increasing laminate depth because of signal attenuation caused by backscattering and back reflection at fiber–matrix interfaces, which limited porosity detectability in the inner layers.
5. The observed reduction in detected porosity with depth should therefore be interpreted cautiously, as it is influenced not only by actual porosity distribution but also by inherent ultrasonic wave propagation constraints in thick CFRP laminates.
6. Overall, the findings confirm that ultrasonic microscopy testing is a practical and cost-effective tool for quality assessment of CFRP composites, while highlighting the importance of optimized fabrication parameters and careful interpretation of ultrasonic data when evaluating thick composite structures.

ACKNOWLEDGEMENT

The authors acknowledge Professor Emeritus Steven Donaldson, University of Dayton, for providing the raw materials used in specimen fabrication and for supervising the initial stages of processing and testing associated with this work. The authors also acknowledge University of Dayton for its support during the early stages of this research. Fraunhofer IKTS is gratefully acknowledged for providing stipend support during the experimental ultrasonic testing conducted in Germany. Technical assistance and laboratory support during ultrasonic measurements at Dresden University of Technology are also sincerely acknowledged.

Ethics Statement: The authors will address and cooperate with the journal in resolving any ethical issues that may arise following publication of this manuscript.

Duality of Interest: The authors declare that they have no duality of interest associated with this manuscript.

Author contributions: I.H. conceptualized the study, fabricated the specimens, designed and conducted the ultrasonic experiments, analyzed the data, and wrote the manuscript. R.A. and A.A. contributed to image processing and preliminary porosity quantification under supervision.

Funding: This research was supported through institutional material support from the University of Dayton, Ohio, USA and stipend support provided by Fraunhofer-IKTS, Berlin, Germany for experimental testing activities conducted in Germany.

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