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REVOLUTIONIZING COMPOSITE MATERIAL ANALYSIS THROUGH SEM-BASED DEFECT DETECTION AND CLASSIFICATION

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ABSTRACT

This study investigates defect detection and classification in composite materials using Scanning Electron Microscopy (SEM) imaging. An experimental study design is applied to enhance SEM picture quality through preprocessing techniques such as Gaussian filtering and histogram equalization. The research focuses on identifying and quantifying defects, including cracks, voids, fiber misalignment, and delamination, by employing edge detection algorithms (Canny and Sobel) and thresholding methods (global and adaptive). Quantitative analysis is performed to determine defect density, size distribution, and classification accuracy. The study aims to provide a comprehensive evaluation of defect detection and classification processes, contributing to improved material quality assessment in composite materials.

Keywords: Composite Material Analysis, Sem-Based Defect Detection, Scanning Electron Microscopy (Sem), Global and Adaptive,Fiber Misalignment, Delamination, Quantifying Defects.

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1. INTRODUCTION

In the aircraft sector, polymer matrix composites with reinforcements comprised of carbon fibres, glass fibres, Kevlar, and other materials are commonly employed. For example, carbon fibre-reinforced polymer (CFRP) was originally used in Boeing airplanes in the 1950s. When compared to other materials, the utilization of composite materials in the aircraft industry has increased noticeably over time. The new Boeing 787 Dreamliner is made up of more than half composite materials by weight. Composite materials' primary advantages are their high specific strengths and stiffness. Composite materials, for example, are stronger and stiffer than aluminium, while being lighter. This weight reduction allows for increased passenger and freight capacity while using less fuel. Corrosion, as well as many other highly reactive chemicals often utilized in aircraft applications, are not a problem for composite materials. Moreover, they are thermally durable and can withstand exposure to extreme weather conditions, such as the vast temperature variations encountered during airplane operations. Another significant benefit of composite materials is their design flexibility. Composite constructions are produced in large single pieces and then cut to their intended final shapes, obviating the need for drilling, bolting, and riveting, which are usually used to assemble metallic structures. Infrared thermography, often known as thermal imaging or just thermography, is a non-destructive testing (NDT) technology that has attracted a lot of attention in the last several decades for diagnostics and monitoring. This is mostly due to the fact that commercial infrared or thermal cameras, the primary tool for performing infrared thermography, are constantly increasing in terms of sensitivity and spatial resolution, as well as becoming faster and more affordable. Every year or so, a better camera may be had for roughly the same price as the previous model from the previous year. The same statement may be made about computers, which are needed for control, data processing, and picture display, and which deliver more computational power at a cheaper price year after year. As a result, the range of applications is broadening, from traditional building or electronic component monitoring to more current applications such as artwork inspection or composite materials inspection. In addition, Montanini employed lock-in and pulse phase infrared thermography to quantify subsurface flaws in a Plexiglas reference specimen. Thermal pictures captured at various frequencies (frequency domain) were post-processed, and the thermal diffusivity of the material was directly measured. Montanini believed the findings were encouraging and proposed active thermography as a practical, quick, and powerful contactless NDT technology for detecting subsurface faults. A control unit is required to synchronize the energy source with the acquisition system, and a computer system can be used to display and/or process images. In the case of active thermography, signal processing is frequently required to improve contrast and quantification. In general, the reflection configuration is best suited to detect defects close to the heated surface, whereas the transmission configuration allows for the detection of defects close to the rear surface due to the spreading effect of the thermal front. Obviously, the transmission approach is not always simple or feasible. Nonetheless, some specific applications can be found. For example, if the part is hollow, it may be advantageous to use internal stimulation with a liquid (water) or gas flow (air). Because of the delayed arrival of the thermal perturbation, changes in flow temperature (hot to cold or the reverse) allow the detection of abnormal variations in wall thickness or blocking passages in this configuration. However, it should be noted that the defect depth cannot be estimated in transmission mode because the heat front travels the same distance whether a defect is present or not, and regardless of its depth. Recently, thermal deep learning algorithms were used to examine and detect surface and subsurface damage in composite materials. Previous research has shown, however, that traditional machine learning (ML) approaches, such as Support Vector Machine (SVM), still require a pre-processing algorithm to properly handle real-world data in order to overcome the trade-off between overall accuracy and generalization. With this in mind, Erazo-Aux et al. proposed using cubic spine SVM to identify/classify damages in specifically manufactured composites with various health conditions. In high-dimensional characteristic spaces, SVM is a useful tool for ML linear predictors. The high dimensionality of the feature space increases sample complexity and computational complexity. By seeking “substantial margin” separators, the SVM algorithmic paradigm tackles the sample complexity problem. If the entire set of cases is not only on the right side of the separating hyperplane but also far away from it, a half-space separates a training set with a substantial margin. Even though the dimensionality of the characteristic space is vast, limiting the method to produce a significant margin separator could result in a low sample complexity (and even an unlimited one). It should

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be emphasized that all aspects of the SVM algorithms' computing complexity, mathematical correlations, etc. are adequately covered in the implementation. Different linear and kernel functions (linear or radial), constant widths (σ), and limiting terms (C) are commonly tested when training the SVM model. In contrast to linear SVM models, cubic kernel functions are commonly used in cubic SVM algorithms. This will result in increased classification accuracy in a shorter computational time.

2. LITERATURE REVIEW

Kaufmann, K., et.al., (2020)provided a route to machine learning coupled phase mapping as more and more potential space groups, chemistry shifts, and lattice parameter variations are covered by databases of EBSD patterns. With the advent of commercial electron backscatter diffraction (EBSD) technology, an age of highly informative maps containing the orientation of user-selected crystal structures was brought about. Since then, the quality, rate of detection, and interpretation of these diffraction patterns have undergone a technological revolution. The capacity to directly and high-throughput use the information-rich diffraction patterns is the next big thing in EBSD. As seen below, this innovative technology, with the help of machine learning tools, can accurately separate phases in a material by chemistry, crystal symmetry, and even lattice characteristics, requiring fewer human decisions. This work tackles many of the primary issues in contemporary EBSD and is the first demonstration of such capabilities. A convolutional neural network, a kind of machine learning system, is taught to automatically detect the minute variations in the diffraction patterns and output phase maps of the material. Diffraction patterns are obtained from a range of samples.

Ali, K., et.al., (2022)examined the industry Total Quality Management (TQM) procedures have been completely transformed by Industry 4.0 (I4.0), a technology advancement in the manufacturing sector. Empirical research on TQM's multidimensional perspective is scarce. So, the purpose of this study is to empirically investigate how small and medium-sized (SMEs) manufacturing enterprises' I4.0 preparedness is impacted by the multidimensional (soft and hard) perspective of TQM. A framework, grounded in the sociotechnical systems (STS) theory, has been created and empirically validated by means of an online survey conducted among 209

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manufacturing enterprises that are SMEs in Malaysia. In contrast to previous TQM research that employed structural equation modeling (SEM), this study's analysis was done in two stages. First, the variable that strongly influences I4.0 readiness was identified using the SEM technique. Second, the relative influence of relevant predictors derived from SEM was ranked using the artificial neural network (ANN) technique. The findings demonstrate how both hard and soft TQM procedures have helped to ensure I4.0 preparedness. Furthermore, the findings demonstrate the mediating effect that hard TQM practices play between I4.0 readiness and soft TQM practices. The ANN results confirmed that advanced manufacturing technology is regarded an operational readiness factor for I4.0 managerial readiness, top management commitment for technological readiness, and customer focus is considered a significant TQM component. To put it briefly, the SEM-ANN technique makes a novel contribution to the literature on TQM and I4.0. Lastly, the results, particularly in emerging economies, can assist managers in giving enterprises' hard and soft quality practices that support I4.0 deployment top priority.

Kineber, A. F., et.al., (2022)showed that the drivers of robotics have a significant, albeit small-scale, impact on the use of robotics in Nigeria's building industry, with an impact of 14.5%. To maximize benefits without sacrificing project goals, sustainability principles should be implemented through innovative technology. In this study, they conducted an empirical investigation into the impact of the identified determinants on the adoption of robotics in developing nations' building industries. To this purpose, the drivers of robotics were identified from the literature with an eye on sustainable building projects. These were then contextually altered through the use of a survey method and the exploratory factor analysis (EFA) approach. The drivers of robotics can be categorized into three main components, according to the EFA results: technology, industry, and culture. Nonetheless, the advantages of robotics application can be classified into two main categories: environment and resources. For this reason, we used partial least squares structural equation modeling (PLS-SEM) in this study to assess the relationships between robotics applications and drivers in Nigeria's building sector. Policymakers aiming to enhance their projects and boost sustainability using robotics in the building industry should use the study's results as a reference.

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McCue, I. D. (2022)closed by going over the prospects and difficulties for QMA's further development, including the creation of instruments, the measurement of uncertainty, and the automatic parsing of data from the literature. Quantitative multi-image analysis (QMA) is the process of simultaneously analyzing several linked images in order to systematically extract new information and insights. We give examples of how QMA can be used to further materials research in areas such as automatic feature identification, multi-image characterisation, and the identification of new correlations between processing structure and property.

3. RESEARCH METHODOLOGY

3.1. Research Design

This work uses an experimental research approach and focuses on employing scanning electron microscopy (SEM) imaging techniques to analyze and classify flaws in composite materials. First, preprocessing is used to improve the quality of SEM pictures; next, material defects are identified and quantitatively analyzed. To accurately identify defects, the method integrates image processing techniques such as thresholding, edge detection, contrast enhancement, and noise reduction. The methodology' dependability is assessed using a range of measures, including classification accuracy, fault density, and size distribution.

3.2. Data Collection

SEM photography of composite material samples that underwent various production procedures was used to gather data. The imaging method was centered on taking high-resolution pictures of the material surfaces in order to categorize and detect common flaws like as delamination, cracks, and voids. Several photos were taken of each sample to guarantee that there would be enough information for a quantitative analysis. After that, the raw photos underwent processing to improve contrast and lower noise, which allowed for more precise flaw identification. The main dataset used in this study is the SEM-generated photos.

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3.3. Data Analysis

To guarantee accuracy and dependability, the data analysis procedure for SEM-based flaw detection and classification goes through numerous crucial steps. First, image preprocessing methods such as histogram equalization and Gaussian filtering (Table 1) were used to improve contrast and minimize noise in the images. Following that, in order to precisely identify and separate defects from the background, defect identification was performed using thresholding techniques (global and adaptive) and edge detection algorithms (Canny and Sobel), as shown in Table 2. Lastly, defect density was computed, size distribution was examined using histogram analysis, and classification accuracy was assessed using metrics like precision, recall, and F1-score as part of the quantitative study (Table 3). This all-encompassing method offers a strong assessment of defect identification and categorization, which adds to a full evaluation of material quality.

4. DATA ANALYSIS

4.1. Image Preprocessing

The primary image processing methods used to improve image quality for SEM-based defect analysis are listed in Table 1. Gaussian filtering, a method intended to smooth the image by lowering random noise, reduces noise and enhances the visibility of identified flaws. Histogram Equalization is used to boost contrast by adjusting the image's contrast to emphasize characteristics and draw attention to disparities between areas that are defective and those that are not. When combined, these methods increase the precision and dependability of SEM imaging-based flaw detection in composite materials.

Table 1.Methods of Image Improvement for SEM-Based Defect Identification

Step	Description	Technique
Noise Reduction	Reduce image noise	Gaussian Filtering
Contrast Enhancement	Enhance image contrast	Histogram Equalization

4.2. Defect Detection

An overview of two popular image processing techniques for composite material defect detection is given in the table. The first technique, edge detection, is essential for precisely identifying defect borders because it uses the Canny and Sobel algorithms to recognize and define the edges of flaws. The second approach, called thresholding, uses global and adaptive algorithms to separate the faults from the background in an efficient manner, making it easier to isolate the defects for additional analysis. When combined, these techniques improve the accuracy of identifying flaws in imaging procedures such as Scanning Electron Microscopy (SEM).

Table 2. Techniques for Image Processing to Identify Defects in Composite Materials

Method	Algorithm/Technique	Description
Edge Detection	Canny, Sobel	Detect edges of defects
Thresholding	Global, Adaptive	Segment defects from background

4.3. Quantitative Analysis

Three essential metrics for analyzing flaws in composite materials are shown in the table. Defect density, which is computed by dividing the total number of defects by the area being examined, is the number of defects per unit area. Histogram analysis is used to study the size distribution, which focuses on the range of defect sizes and offers insights into the frequency and range of defect dimensions. Last but not least, classification accuracy assesses how well defect classification models perform by comparing their ability to discover and classify flaws using metrics like precision, recall, and F1-score. awareness the effectiveness and dependability of the material inspection procedure requires an awareness of these measures.

Table 3.Important Metrics and Methods of Calculation for Composite Material Defect Analysis

Metric	Description	Calculation Method

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Defect Density	Number of defects per unit area	Total Defects / Area
Size Distribution	Distribution of defect sizes	Histogram Analysis
Classification Accuracy	Performance of classification models	Precision, Recall, F1-Score

5. CONCLUSION

The study shows that SEM imaging works well for identifying and categorizing flaws in composite materials when combined with sophisticated image processing methods. The quality of SEM pictures is considerably increased by using techniques for noise reduction and contrast enhancement, making it possible to identify flaws more precisely. The accuracy of defect delineation and segmentation is improved by the application of edge detection and thresholding techniques. Quantitative measures provide a strong framework for assessing material quality; these metrics include defect density, size distribution, and classification accuracy. The assessment of composite materials can be advanced by integrating advanced flaw identification algorithms with image preprocessing techniques, as demonstrated in this work. It also identifies promising areas for future research and development in the field of material inspection technologies.

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