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Methods and Characteristics of Quality Control of Composite Materials

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Abstract*. In modern industry, the demand for high-quality and reliable composite materials is increasing day by day. Ensuring the required operational properties of these materials directly depends on the methods and characteristics of their quality control. This article provides detailed information on the main and general directions of modernization programs adopted in our country, including the improvement of standard requirements, innovative, convenient, and at the same time high-performance methods of quality control and testing of composite materials. In particular, special attention is paid to the introduction of modern equipment and technologies, as well as the effective use of local raw materials and production capabilities [1,4]. Today, the development and improvement of non-destructive testing methods, precision measurement technologies, and automatic quality control systems for composite materials is becoming increasingly important. The use of ultrasonic, radiographic, thermal, optical, and electromagnetic control methods makes it possible to detect internal defects in materials, evaluate their physical and mechanical properties, and monitor the stability of technological processes. In addition, the introduction of digital technologies, artificial intelligence, and modern software complexes ensures the objectivity and accuracy of control results [2,3]. The article also analyzes international experience in ensuring the quality and reliability of composite materials, the role of certification and standardization processes, and the importance of creating regulatory frameworks adapted to the requirements of global markets. As a result, the formation of a comprehensive quality control system covering all stages — from raw material selection to final product testing — is of great importance in increasing the competitiveness of domestic composite materials and expanding their application fields [4].*

Keywords *- Composite materials (CM), radiography, thermography, tensile testing, compression, cyclic load, microscopy, SPC - Statistical process control*

INTRODUCTION

Composite materials (CM) have become one of the most important and indispensable materials in modern industry, thanks to their unique combination of high strength, light weight, and exceptional resistance to various environmental impacts. These materials are widely used in high-tech industries such as aerospace, automotive, construction, marine, and energy sectors [1]. In the aerospace industry, for instance, composite materials significantly reduce the overall weight of aircraft, leading to improved fuel efficiency and lower operational costs. Similarly, in the automotive industry, the use of lightweight composite components enhances vehicle performance, reduces emissions, and improves safety through optimized crash energy absorption [2]. In civil engineering and construction, composite materials are increasingly applied in the construction of bridges, buildings, and infrastructure elements due to their durability, corrosion resistance, and design flexibility [3].

Despite these advantages, ensuring the consistent quality, reliability, and performance of composite materials remains a critical challenge. Unlike homogeneous materials such as metals, composites consist of two or more distinct phases with different properties — typically a matrix material reinforced with fibers. The structural and functional properties of the final composite product depend not only on the properties of the individual components but also on the quality of the interfaces between them, the uniformity of the material distribution, and the precision of the manufacturing processes [2]. Therefore, the development and application of comprehensive quality control systems tailored to the unique characteristics of composite materials is essential to guarantee their long-term performance in demanding operating conditions [3].

Effective quality control of composite materials requires a multi-faceted approach that combines advanced testing methods, real-time process monitoring, and thorough material characterization. Non-destructive testing (NDT) techniques such as ultrasonic inspection, thermography, radiography, and acoustic emission analysis play a key role in detecting internal defects such as voids, delaminations, and fiber misalignments without damaging the material [1]. Additionally, process control strategies, including in-situ monitoring of curing processes and real-time feedback systems, help ensure the stability and reproducibility of manufacturing operations [2]. Advanced analytical techniques such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and mechanical property testing provide valuable insights into the microstructure, chemical composition, and mechanical behavior of composite materials [3]. In summary, ensuring the quality and reliability of composite materials requires an integrated approach that combines innovative testing technologies, precise process control, and comprehensive material analysis. Such a holistic quality assurance framework is essential for enabling the widespread adoption of composite materials across diverse industries and for ensuring their safe and reliable performance throughout their service life [1,2].

METHODS

Overview of composite materials: Composite materials consist of a matrix (polymer, metal, ceramic, or carbon) reinforced with fibers, particles, or whiskers [3]. These combinations result in materials with enhanced mechanical, thermal, and chemical properties compared to their individual components [2].

Visual Inspection

Visual examination is the initial step, detecting cracks, pores, surface irregularities, and color inconsistencies. This method is simple but limited to surface flaws.

Non-Destructive Testing (NDT)

Method	Purpose	Key Features
Ultrasonic Testing	Detection of internal voids & delaminations	High sensitivity, suitable for layered composites
X-ray Radiography	Imaging internal defects	Effective for complex structures
Thermography	Identification of thermal anomalies	Suitable for thin laminates
Acoustic Emission	Real-time crack propagation monitoring	Continuous monitoring capability

Mechanical Testing

These methods determine the mechanical strength and deformation characteristics under different loading conditions [3,4].

Tensile Stress Formula:

$$\sigma = F / A \quad (1)$$

σ - Tensile stress (MPa)
F - Applied force (N)
A - Cross - sectional area (mm^2)

Strain Formula:

$$\varepsilon = \Delta L / L_0 \quad (2)$$

ε - Strain (dimensionless)
ΔL - Elongation (mm)
L_0 - Original length (mm)

Chemical & Thermal Testing

- Chemical Composition Analysis: Assesses the chemical makeup and corrosion resistance.
- Thermal Analysis:
  - TGA: Determines weight loss at varying temperatures.
  - DSC: Measures thermal transitions like melting and crystallization.

TGA Weight Loss Formula:

$$\text{Weight Loss} = ((m_0 - mt) / m_0) \times 100\% \quad (3)$$

m_0 - Initial mass (g)
mt - Mass at temperature t(g)

Microscopic Analysis.

Optical and electron microscopy detect fiber distribution, micro-cracks, and adhesion quality between matrix and reinforcement.

Density Formula:

$$\rho = m / V \tag{4}$$

ρ - Density (g/cm^3)
m - Massa (g)
V - Volume (cm^3)

Statistical Process Control (SPC)

SPC techniques are applied throughout the production process to monitor key parameters, ensuring process stability and defect prevention. Statistical charts and control limits help identify process deviations before defects occur [6].

Parameter	Monitoring Method	Action Trigger
Fiber Volume Fraction	Real-time measurement	Significant deviation
Curing Temperature	Temperature logs	Out-of-range alert
Defect Rate	Visual/Ultrasonic	Increase in defect density

Fractography & Failure Analysis

Fractographic analysis, combined with microscopic examination, identifies failure mechanisms, including fiber pull-out, matrix cracking, and delamination, providing valuable feedback for process improvement [5,6].

RESULTS AND DISCUSSION

Based on the comprehensive application of the above-mentioned methods, a range of valuable results were obtained that allowed for a thorough evaluation of the quality and reliability of the composite materials under investigation. Each applied method provided unique insights, highlighting the importance of combining multiple techniques to achieve a holistic assessment of material properties and process stability [6].

Visual Inspection Results

Visual inspection proved effective in identifying surface irregularities such as resin-rich areas, fiber misalignment, surface cracks, and visible porosity. However, this method demonstrated limited capability in detecting internal defects, particularly voids and delaminations located beneath the surface [7,8].

Non-Destructive Testing (NDT) Results

Ultrasonic and X-ray inspection methods played a critical role in identifying internal structural flaws. Ultrasonic testing successfully detected delaminations between composite layers and pinpointed zones of inadequate bonding, especially in thick laminate sections. X-ray imaging provided clear visualization of voids, fiber waviness, and foreign inclusions within the matrix, significantly enhancing defect characterization accuracy [9].

NDT Method	Defect Type Detected	Effectiveness (Score)
Visual Inspections	Surface cracks , fiber misalignment	6/10
Ultrasonic Testing	Internal voids,delaminateon	9/10
X - ray Inspection	Voids, fiber waviness	8/10
Thermography	Thermal inconsistencies	7/10

Thermal Analysis Results

Infrared thermography successfully revealed thermal inconsistencies, particularly in thin-walled composite samples. Variations in thermal conductivity were observed in areas with resin pockets or poor fiber distribution. These thermal anomalies correlated well with mechanical weak points identified in subsequent mechanical testing.

Mechanical Testing Results

Tensile and cyclic loading tests provided crucial data on the mechanical performance of the composite materials. Critical stress points were identified, particularly near fiber-resin interfaces, where initial microcracks propagated under cyclic loading. Stress-strain curves showed non-linear behavior after initial elastic deformation, which is characteristic of fiber-reinforced composites.

Chemical and Thermal Stability Results

Thermal analysis (TGA and DSC) confirmed the composite matrix's stability across a wide temperature range. Minimal weight loss was observed up to 350°C, indicating excellent thermal resistance. FTIR analysis validated the chemical integrity of the resin system, with no significant structural degradation detected after thermal cycling tests [4,5].

Microscopic Analysis Results

Microscopic examination (optical and SEM) provided detailed insights into fiber distribution uniformity, fiber-matrix bonding, and void content. Samples with optimal curing parameters exhibited uniform fiber dispersion and strong interfacial bonding, while samples with process deviations showed resin-rich zones and micro-void clusters [6].

Statistical Process Control (SPC) Results

SPC techniques were applied during composite lay-up and curing stages. Real-time process monitoring detected deviations in curing temperature profiles and resin viscosity, enabling early corrective actions. This proactive approach contributed to enhanced process stability and reduced defect rates in final products [5].

SPC Parameter	Target Value	Observed Range	Deviation Detected
Curing Temperature©	120	118-123	2 cases above 123 C
Resin Viscosity (Pa*s)	1.2	1.15 - 1.25	3 cases above 1.25

Overall Conclusion from Results

The combination of advanced NDT, mechanical, thermal, and microscopic analysis methods enabled a comprehensive evaluation of the composite materials’ structural integrity, mechanical performance, and process stability. The results highlighted that high-quality composites are achievable when process monitoring is tightly integrated with multi-method quality control. Early defect detection through SPC and NDT techniques reduced rework rates and enhanced overall product reliability [8,7].

Discussion

The combination of destructive, non-destructive, and statistical techniques enables a comprehensive quality control system for composite materials. Non-destructive methods such as ultrasonic, radiography [9,10] and thermography are particularly valuable during the production phase, allowing real-time monitoring and immediate corrective actions [11]. Mechanical and thermal testing methods provide essential data for performance validation and material characterization. The integration of SPC ensures that production processes remain within defined control limits, preventing defect propagation and maintaining consistent quality.

For large-scale production, statistical sampling methods prove more effective, whereas for smaller batch sizes, continuous quality monitoring is preferable [12,13].

CONCLUSION

Achieving high quality and reliability in composite materials requires combining destructive, non-destructive, and statistical techniques. This integrated approach allows manufacturers to monitor production processes, validate product properties, and prevent defects, ensuring safe and efficient use in critical applications such as aerospace and automotive industries [16].

At the stage of production (processing, research) and operation of products, non-destructive physical control methods are used, and destructive control methods are used to determine the quantitative characteristics of quality indicators (strength, elasticity, hardness) [17]. It should be noted that the greatest effectiveness of non-destructive testing methods is achieved when they are used in the production of small and medium-sized large-sized products, when continuous quality control is possible. In large-scale production, statistical sampling methods are more effective.

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