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Applications And Development Of Infrared Inspection Of Composite Materials: In Review

Fengxia Han[1,2*], Hongjun Wang[1,2], and Jianing Zhang[1,2]

[1] *School of Mechanical and Electrical Engineering, Beijing Information Science and Technology University, 100192, Beijing, China*
[2] *Beijing International Science Cooperation Base of High-end Equipment Intelligent Perception and Control, 100192, Beijing, China*
[*] *Corresponding author. E-mail: fengxiahanfxh@163.com*

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The distinctive characteristics of composite materials make them indispensable across sectors like aviation, transportation, and power generation. However, these materials are subject to the risk of defects and damage during production and usage, affecting their reliability. To address this challenge, early detection and real-time monitoring through active infrared thermography have become essential. The current study offers a comprehensive examination of the latest progress and real-world uses of infrared thermography within the realm of non-destructive testing for composite substances. It focuses on discussing typical excitation sources, excitation methods, and proposing future directions for infrared thermography. Additionally, practical case studies highlighting the technology's application in production settings are presented. The discoveries act as an indispensable guide for scholars aiming to delve into the present state and prospective trends of Non-Destructive Testing (NDT).

Keywords: Composites, Infrared Thermography, Excitation sources, Excitation functions, Development trend

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1. Introduction

Composite materials find extensive application across various sectors including aviation, vehicle manufacturing, and power generation. They are celebrated for their outstanding attributes such as superior stiffness-to-weight ratio, resistance to corrosion, and minimal coefficients of thermal expansion. However, during manufacturing and service, various defects can arise, including delamination, debonding, wrinkles and voids, corrosion cracks, fatigue cracks, impact damage, and matrix fiber cracking. To detect such defects, active thermography methods are essential. Infrared thermography (IRT), a widely employed NDT technique, is particularly effective for evaluating composite materials. IRT technology offers significant advantages for external, online, and in-service testing of composite structures, thanks to its non-contact nature, real-time measurement capabilities, high resolution, and ability to cover large detection areas.

Thermography is based on the differential thermophysical properties of dissimilar materials, which create distinct thermal signatures detectable by an infrared camera. This method takes advantage of the differing thermal responses of various materials, enabling the detection of temperature variations that could suggest the existence of defects. Employing an infrared heat-sensitive camera, it is feasible to document the progression of the surface thermal landscape, enabling the isolation of characteristics and the examination of the thermal wave patterns. This method effectively detects surface damage and internal defects in materials.

Currently, IRT technology development centers on thermal excitation, heat flow modulation, extracting meaningful information from raw data, image analysis, etc [1]. Every one of these elements plays a vital role in enhancing IRT's ability to detect defects. Different excitation sources are established on different physical foundations, thus having different advantages and disadvantages. Much research has been done on IRT. However, a more in-depth exploration of the latest applications and development is required, especially the excitation functions, thermal excitation sources and post-processing methods, which have a profound effect on the inspection. The article comprehensively reviews the principles, advancements, advantages, limitations, and emerging research trends in this area.

2. Infrared thermography with different excitation sources

Various heat-emitting elements are employed in the non-destructive testing of composite substances, encompassing illumination sources (e.g., strobe lights, halogen lamps, laser devices), acoustic sources (like audio or ultrasonic waves), and electromagnetic sources (such as eddy currents thermography).

2.1. Optically Stimulated Thermography

Optically Stimulated Thermography (OST) utilizes high-energy light sources combined with IRT. By using optical energy as an instantaneous thermal excitation, the specimen's surface absorbs this energy, which then propagates as a thermal wave through the material via thermal conduction. zones without defects, warmth is evenly dispersed throughout the substance, yielding a uniform thermal reaction across its exterior. On the other hand, when there are internal flaws like separations, a bounce effect takes place. Upon contacting these imperfections, the thermal energy bounces back towards the sample's outer layer, leading to discrepancies in the surface temperature distribution. By extracting and analyzing the signals from the heat waves, it is possible to assess the size or depth of the defects. Optically Stimulated Thermography is achieved by us in Fig. 1. Laser stimulated thermography (LST) is an OST, which uses laser beam as thermal sources, as depicted in Fig. 2.

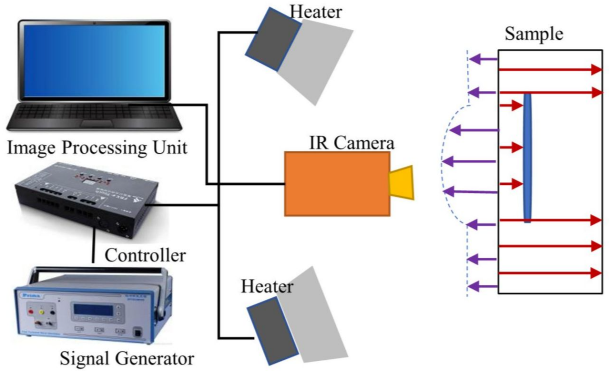


Fig. 1. OST schematic.

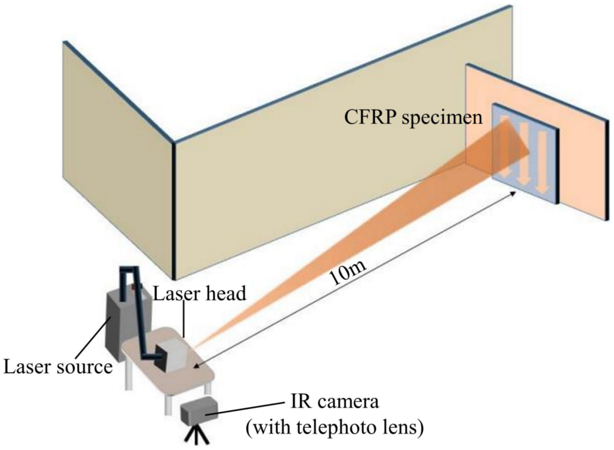


Fig. 2. Setup of LST [2].

Optical sources are the most commonly used physical sources in testing. OST boasts several key capabilities, including non-contact operation, high sensitivity, real-time performance, and its ability to adapt to diverse applications, making it widely applicable in composite material evaluation. When using halogen or flash lamps, the sample requires a nearby heat source to receive sufficient heat energy. LST, renowned for its accuracy in manipulation, can more accurately identify the characteristic size and geometric location of defects in CFRP, significantly enhancing the quality of defect imaging. Long-range identification of composite substances is achievable through LST technology, and in terms of detection efficacy, LST and OST exhibit similar performance when the same amount of thermal input is applied. Implementing laser-based scanning in conjunction with phase transition is a proven strategy for uncovering imperfections within CFRP layered structures, with an operational range extending to a tenth of a kilometer. The micro-laser line thermography approach has demonstrated its prowess in submillimeter-sized porosities located below the surface of a three-dimensional preformed CFRP sample [3]. Nevertheless, neither OST nor LST are proficient in the detection of nascent internal damage or sealed fractures.

2.2. Ultrasonic Infrared Thermography

Ultrasonic infrared thermography (UIT), which combines ultrasonic excitation and infrared thermography, is a volumetric heating method. Compared to the surface heating method of OST, volumetric heating allows for multi-dimensional regional heating. In this technique, high frequency ultrasound (15-40kHz) is coupled to the specimen's interior, as illustrated in Fig. 3. The ultrasound induces heat in internal defects through mechanisms such as plastic deformation, friction, and viscoelastic effects, effectively acting as a heat source. The sound areas generate minimal heat, creating a distinct "bright-dark contrast" between the defected and healthy regions. Consequently, UIT is a dark field technique that focuses on defects. Only defects create an output signal, while other features are mostly suppressed. Compared to OST and LST, a key advantage of ultrasonically generated thermal waves is that they travel a much shorter distance. This is beneficial because of the highly dispersive nature of heat transfer, making it easier to detect micro-cracks and deeper delaminations that may be obscured by shallower defects. UIT is considered advantageous for the detection of ‘kissing’ defects. Applying ultrasonic energy and pressure for thermal excitation can lead to secondary specimen damage.

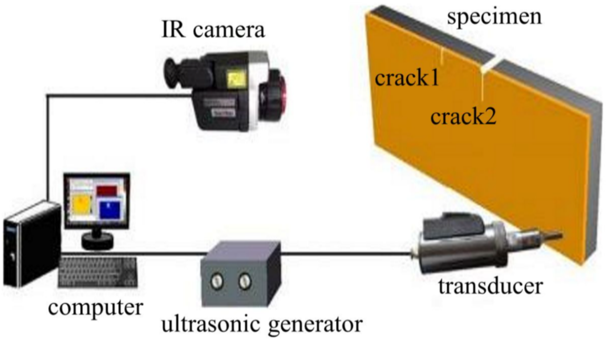


Fig. 3. Configuration of ultrasonic infrared thermography [4].

2.3. Eddy Current Thermography

By combining electromagnetic induction heating and transient infrared thermography, Eddy Current Thermography (ECT) creates a hybrid inspection method. Fig. 4 illustrates the integration of eddy current with thermographic imaging, referred to as ECT thermography. This technique employs an infrared camera to record the thermal map and heat conduction patterns that arise from the Joule effect in either conductive or semi-conductive composite substances when stimulated by eddy currents. Defects alter the eddy current distribution around them, causing uneven heating due to the Joule effect. The focused application of induction heating in the flawed zone amplifies the thermal differentiation between the impaired and intact areas. Compared to other infrared thermal imaging methods, ECT offers a range of physical and temporal characteristics related to electricity, magnetism, and heat, along with rich transient information. CFRP composites exhibit lower thermal diffusivity, which enables them to retain heat more effectively. Additionally, CFRP possess high thermal and electrical properties, allowing for efficient induction heating and facilitating the rapid and uniform diffusion of thermal waves. Electro-thermal thermography, characterized by its bulk heating mechanism, is particularly well-suited for CFRP, given their minimal thermal conductivity and substantial skin effect depth.

Eq. (1) provides the calculation for penetration depth [5]:

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}} \tag{1}$$

In the given context, the variable f represents the simulation frequency, σ denotes the electrical conductivity (s/m), while μ signifies the magnetic permeability (H/m). Considering CFRP, Joule heating can effectively heat the carbon fiber and woven layers. Following heat generation within the carbon fibers, thermal diffusion occurs into the surrounding non-conductive polymer, with a time delay before CFRP reaches thermal equilibrium [6]. A 50 mm skin depth is achieved in CFRP at 100 kHz , attributed to its 1000 S/m conductivity and lack of magnetic characteristics. This capability is particularly beneficial for components with complex geometries, potentially offsetting the increased costs associated with inspection setup. In composite material inspection, ECT is effective for conductive materials such as CFRP but ineffective for non-conductive materials like GFRP. This shows a typical ECT system configuration in Fig. 4.

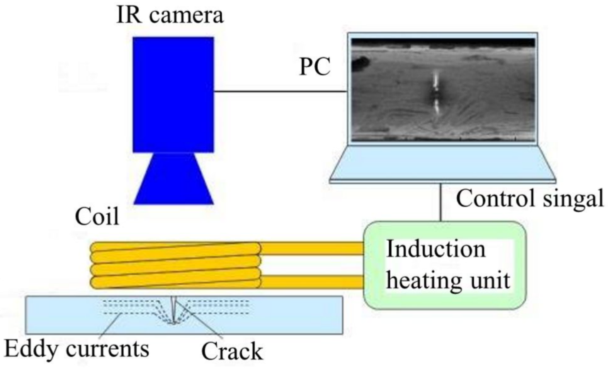


Fig. 4. A basic configuration of ECT system [6].

On account of the intricate structure and inherent physical properties of the composite materials, it is necessary to select a relatively appropriate detection method in practical applications by combining the characteristics of the detection object itself. Table 1 summarizes the advantages and disadvantages of Optical IRT, UIT, and ECT techniques.

Table 1. Comparison of OST, UIT, ECT.

IRT	Advantages	Disadvantages
OST	Non-contact, large detection area, long monitoring distance, easy to implement.	Rely on the surface conditions of materials, uneven heating results in low signal-to-noise ration, not sensitive to cracks.
UIT	High energy transfer efficiency, sensitive to surface defects, accurate quantification of damage and defects, suitable for complicated geometry. with vertical micro-crack.	Contact pressure, various probes required, coupling agent required, low efficiency.
ECT	Non-contact, high speed, high sensitivity.	Limited to conductive materials or semiconductive material, restricted detection depth, excitation system complex.

3. Excitation functions

Conventional stimulation techniques encompass lock-in thermography (LIT), square plus thermography (SPT), pulse thermography (PT) and stepped thermography (ST), amongst others. PT and LIT, in particular, are the predominantly employed methods. Generally, these techniques are effective for detecting shallow planar defects, such as delamination or adhesion issues in surface coatings. In recent years, innovations like multifrequency LIT, pulse-compression thermography and pulsed-phase thermography have emerged. A thermal-wave radar imaging (TWRI) technique combines continuous-wave radar with linear frequency modulation in the frequency domain [7]. This approach greatly improves depth resolution for subsurface features and provides high detection accuracy. Some of these excitation methods are illustrated in Fig. 5.

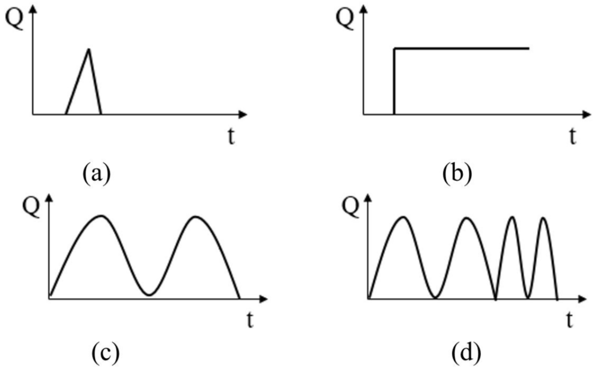


Fig. 5. (a) PT, (b) ST, (c) LIT, (d) chirp radar signal.

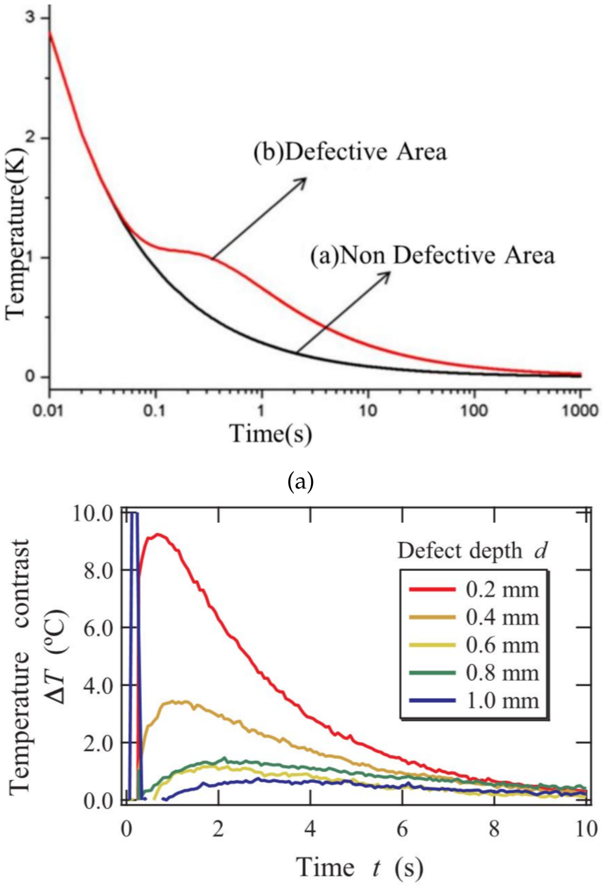
3.1. Pulsed Thermography

Flash thermography entails subjecting the specimen to an instantaneous burst of intense luminosity emitted by a flash lamp, generally persisting for several milliseconds. Following this exposure, the temperature of the surface is meticulously observed throughout the ensuing phase of cooling post-flashing event. The temperature profile at points corresponding to non-defective area differs from that at points corresponding to defective areas, as shown in Fig. 6 (a). The point in time when the peak temperature disparity on the surface is most pronounced can be represented as depicted in Fig. 6 (b). Typically, a more profound imperfection correlates with an extended duration for the temperature differential to culminate.

The duration t, in which the temperature discrepancy becomes evident, is function of the depth d and the thermal diffusivity coefficient α, as expressed by Eq. (2).

$$t \propto \frac{d^2}{\alpha} \tag{2}$$

Where, α denotes thermal diffusivity, d denotes the depth of the defect. Through a rigorous theoretical examination, Almond explored the lower limits of detection achievable with the pulsed technique, uncovering that it is difficult to identify flaws where the ratio of diameter to depth is below 2 [9]. In specific depths, detecting a sizeable slender imperfection, such as a separation, tends to be more challenging compared to a minor yet robust flaw. When carbon fiber-reinforced plastics endure impacts at low velocities, the use of PT is notably proficient in uncovering delamination issues, particularly when dealing with extensive or noncoalesced delaminations. On the other hand, UIT is adept at pinpointing minute damages, including joint delaminations, matrix fractures, and fiber ruptures. The flash heating method is capable of applying only a limited quantity of heat to the sample at once. The thermal signal decays quickly as depth increases, making PT unsuitable for measuring materials where defects are deep, or the material poorly conducts heat. Unlike PT, Long Pulse Thermography (LPT) and ST utilize longer durations, extending the depth range for defect detection. LPT proves highly effective for defect detection in CFRP and GFRP, which exhibit



(a)

(b)

Fig. 6. (a)Temperature decay curve [8]. (b) Temperature comparison chart at different depths [2].

low thermal conductivity and slow thermal response. The ST demonstrated surprisingly effective characterization of defects at increasing depths, including the challenging 6.38 mm defect, near its operational limit [10]. In contrast to PT, both ST and LPT showcase discrepancies in temperature within the defects relative to their adjacent areas, and they engage in heat transfer at varying rates compared to intact sections, enhancing the capability to discern defects with greater accuracy. LPT and ST have key differences. LPT utilizes the cooling phase to acquire thermal images, whereas ST acquires them during the heating phase of the test piece.

3.2. Lock-in Thermography

LIT applies a low-peak-power, periodic harmonic thermal stimulus to excite the sample surface. The method obtains infrared images, extracting both amplitude and phase components, measured at the heating frequency. A significant benefit of utilizing the phase shift is its reduced susceptibility to variations in local lighting conditions or the surface's emissivity. During the LIT imaging stage, it is straightforward to eradicate disruptions. Such disruptions encompass peripheral reflections, inconsistencies in the surface's optical absorption capabilities, as well as discrepancies in the infrared emission factors. Additionally, irregularities in lighting caused by heat sources are also abolished. Additionally, compared to PT, LIT operates at a lower intensity, which helps prevent excessive heating over short time intervals. The scope of flaw identification is affected by the thermal diffusion parameter μ, and its representation can be formulated as the given Eq. (3).

$$\mu = \sqrt{\frac{\alpha}{\pi f}} \tag{3}$$

In this context, α signifies thermal diffusivity, whereas f denotes the wave frequency. Amplitude image depth range is μ and phase image maximum inspectable depth is p, given by Eq. (4) [11].

$$\mathrm{p} = 1.8\mu \tag{4}$$

Due to its reliance on monochromatic stimulation, the depth discernment in detection is governed by a constant frequency. In order to pinpoint imperfections situated at diverse depths within the specimen, it is imperative to conduct examinations across an array of frequencies. If the modulation frequency is too low, a blind frequency may arise, leading to undetected defects near the surface. In response to this challenge, an innovative multi-frequency fused LIT has been proposed. LIT is primarily used for thin components, typically less than 10 millimeters thick. A notable application is in the assessment of aircraft structures, such as fuselages in the aerospace industry. The transmission of heat laterally and the resistance at the point of contact are crucial factors that affect the precision of depth assessments when identifying delamination caused by impact. Depth determination with a high degree of accuracy, specifically deviations of less than 0.5mm, was accomplished for different thicknesses and size of holes [12]. Within substantial glass-fiber-reinforced composite panels, the capability to identify a compromised section escalates when the dimension ratio tends toward unity. Consequently, flaws that are square or circular in shape are generally easier to detect compared to rectangular or elongated discontinuities.

3.3. Thermal-wave Radar Thermography

Wave radar thermography (TWRT) is based on linear frequency modulated thermal. Deemed as a cutting edge advancement in active thermography, the TWRT leverages frequency-modulated excitation, impulse compression, and optimized filtering to maximize detection performance, yielding superior probing range, lateral resolution, and depth resolution [13]. The TWRT amplitude (CC) is calculated by Eq. (5) [14].

$$\mathrm{CC}(\tau) = \mathrm{F}^{-1}\left\{\mathrm{REF}(\omega)^{*}\,\mathrm{S}(\omega)\right\} \tag{5}$$

In this context, the Fourier domain representation of $\mathrm{ref(t)}$ is denoted by $\mathrm{REF}(\omega)$, whereas the Fourier domain $\mathrm{s(t)}$ is representation by $\mathrm{S}(\omega)$. The symbol * signifies the process of complex conjugation. The notation F^{-1} refers to the operators that perform the inverse Fourier transformation, with τ indicating the temporal lag that exists between $\mathrm{ref(t)}$ and $S(\omega)$.

An advanced depth-dependent dynamic-resolution TWRT technique has been utilized to ascertain the alignment of fibers in a single-directional CFRP. The phase attribute of the TWRT signal was established and calculated through the application of a discrete fractional Fourier transformation, showcasing its prowess in delineating the orientation of the fiber layup across diverse depths in the CFRP material. Energy-efficient chirp-modulated radar thermography combines the advantages of impulse stimulation with the technique of linear frequency sweeping. Fast Fourier Transform phase-based 3D tomography offers a rapid, low-energy NDT solution for 3D subsurface defect imaging in CFRP [15]. The simulation results show that selecting a specific central frequency improves the detection probability of deeper defects using the TWRT technique. TWRT provides better depth resolvability than LT [16]. Recently, the implementation of an orthogonal phase-coded line frequency yields a substantial increase in TWRT's SNR and depth resolvability over linear frequency [17].

4. Post-processing techniques of composite

Post-processing techniques are crucial for enhancing data quality and interpretability. These techniques, applied to raw data from various NDT, improve signal-to-noise ratio, image quality, enable quantitative analysis, and promote automation and efficiency.

4.1. Traditional post-processing techniques

Thermal imaging processing has evolved over decades. A variety of post-processing techniques are employed, including thermal signal reconstruction (TSR), principal component analysis (PCA), Pulse phase thermography (PPT), independent component analysis (ICA), total harmonic distortion (THD), quadratic discriminant analysis (QDA) and linear discriminant analysis (LDA), etc [18]. For detecting low-velocity impact damage, PPT excels at finding subsurface defects, while TSR is better for short-pulse thermography. PCA can blur defect details, THD is frequency-sensitive, and LDA assumes uniform covariance. The QDA yields superior defect identification compared to the aforementioned techniques [19]. ICA, more powerful than PCA, decomposes multivariate data into additive subcomponents and finds a new representation basis. For lock-in thermography of CFRP, TSR surpasses FFT in phase accurate and precise as demonstrated by both synthetic and experimental data [20].

The limitations of traditional post-processing techniques, especially their sensitivity to background noise and interference, have led to a shift towards artificial intelligence.

4.2. Deep learning-based post-processing techniques

Deep learning (DL) leverages its complex architectures to efficiently handle high-dimensional data like images, video, and audio. Key DL models include CNN, ResNet, Generative Adversarial Network (GAN), and YOLO, ect. These models can be broadly categorized as supervised or unsupervised. Current research focuses on leveraging advanced neural network structures to improve defect detection, segmentation, and depth prediction.

Spatial feature-based AG-UNet and 3D-UNet prototype for the defect feature extraction of CFRP has been proposed [21]. The method significantly enhances defect detection compared to traditional algorithms like PCA, TSR, and FFT, with smaller diameter-to-depth ratios. A two-stage CNN model for the joint mitigation of sensor noise and background interference was developed by Dong [22]. Tong developed a novel Faster R-CNN that incorporates an attention-based feature fusion network and a flexible fusion strategy [23].

The supervised models introduced above require a large amount of labeled data, are computationally intensive, and have poor generalization ability. Liu introduced a deep autoencoder, an unsupervised model, which handled nonlinear temperature profiles. the method outperformed existing dimensionality reduction-based IRT data processing methods in defect detection accuracy and reliability. Limitations in single feature extraction necessitate a comprehensive approach. Liu introduces a multi-feature perception transformer prototype, improving both accuracy and robustness [24].

Effective IRT testing necessitates AI-driven anomaly detection and analysis. In robot-based additive manufacturing (AM) systems for CFRP printing, The YOLO has been deemed the optimal choice for identifying defects, owing to its exceptional performance in terms of precision and speed, outpacing both Faster R-CNN and Single Shot MultiBox techniques. By enhancing the DL models' capabilities to differentiate between genuine defects and noise, the accuracy and reliability of automated inspections are expected to improve significantly. This evolution improves inspection efficiency and composite material safety, highlighting deep learning's significance in modern material science.

5. Research focus and development directions

With the extensive utilization of composite materials across diverse industrial sectors, there arises an escalating demand for rapid and dependable inspection of large-scale and structurally intricate components. In specific extreme environments, stringent conditions have been imposed upon thermography applications. Notably, limitations related to external excitation energy, such as keeping the temperature increase within a few degrees during testing, present new challenges for NDT methods. These challenges necessitate innovative approaches to ensure accurate and reliable assessments of composite materials. Currently, the achievement of quantitative and efficient defect characterization, along with real-time defect localization, remains a subject of ongoing challenges. Traditional methods often fall short in addressing the complexities of composite structures, leading to a pressing need for more sophisticated techniques. Anticipated future advancements in this domain are set to concentrate on the automated detection. Multi-source information fusion and intelligent detection. Moreover, the development of portable and user-friendly thermography tools could revolutionize field inspections, making them more accessible to a wider range of industries.

5.1. Automated Detection

Automation enhances the efficiency, accuracy, and safety of NDT for composite materials, lowers labor costs, and facilitates real-time monitoring and data analysis. This transition to automation not only makes the inspection process more efficient but also substantially increases the reliability of the outcomes, leading to better maintenance and safety practices in various industries. From an automated inspection perspective, line scan thermography shows significant promise. It creates thermal gradients by uniformly spreading heat flux over the surface. This technique has been utilized to develop a self-propelled NDT system for inspecting large, relatively flat composite aerospace components. Currently, integrating line scan thermography into industrial robots and unmanned aerial vehicles is appealing for in-field inspections of CFRP. The computerized configuration not only enhances the method's viability for large-scale production but also diminishes the likelihood of mistakes caused by human involvement in the process. Furthermore, the implementation of thermographic NDT Advisory and Guidance System provides essential information about the expected performance of the technique for imaging specific defects, allowing NDT engineers without prior thermographic expertise to operate effectively. The democratization of advanced inspection technology empowers more professionals to maintain composite structure integrity, leading to significant improvements in safety standards. As technology progresses, the synergy between automation and NDT will continue to evolve, opening new avenues for research and application.

5.2. Multi-source Information Fusion

A major limitation of NDT is that no single technique can fully satisfy all needs. In contrast, multi-source thermal imaging data can deliver more essential information than individual thermal imaging data. Future research will focus on creating data fusion methodologies that incorporate NDT techniques based on diverse physical principles. Using two NDT techniques can save costs and enhance the overall effectiveness of inspections. The initial examination and identification of superficial flaws are carried out using IRT, while ultrasonic inspection is employed for more in-depth examinations. Together, these methods allow for replacing the costly X-ray computed tomography (XCT) [25]. Moreover, ultrasonic and vibrothermography are applied with common excitation. This approach uncovers both overt and minute damage in CFRP [26]. The suggested imaging integration methods amalgamate LIT with SPT, facilitating the delineation of damage incurred in CFRP panels. Findings indicated a notable decrease in the inaccuracies associated with calculating the equivalent diameter of detected flaws. Additionally, the fusion techniques demonstrated enhanced performance metrics in terms of sensitivity and accuracy. Bilinear interpolation is used to accomplish the merging of 2D data and the 3D model [27]. This innovative approach allows for more precise mapping of defects. The experimental outcomes validated the technique's dependability in detecting flaws and precisely pinpointing their positions on the contoured surfaces of CFRP core sandwiches and high silica oxygen phenolic resin layered specimens. Additionally, a multispectral vision sensing fusion system combines visual testing and infrared thermal testing to address challenges posed by traditional imaging techniques [28]. The obstacles encountered encompass multifaceted settings, unconventional sample shapes, a variety of imperfection categories, and the requirement for swift identification. A novel automated defect detection algorithm, leveraging multifarious infrared feature data fusion, extracts global pertinent features [29]. This comprehensive dataset enhances the robustness of defect detection algorithms. By leveraging advanced data fusion techniques, the future of NDT promises to be more integrated, accurate, and cost-effective, ultimately improving the safety and longevity of critical elements and assemblies.

5.3. Intelligent Detection

With the continuous progression of technological advancements and the proliferation of data science, Artificial Intelligence (AI) in identifying defects in composite materials is poised to grow more precise and reliable. Annually, groundbreaking approaches and strategies are developed to tackle former obstacles, facilitating the revelation of imperfections that could elude the detection of a human examiner. Current AI-based damage detection research heavily emphasizes supervised learning. However, unsupervised learning offers a potentially more effective approach. This is because unsupervised learning can leverage easily accessible data, making it more practical in real-world scenarios. For instance, OST and deep autoencoders are used in unsupervised technique for insulating specimen [30]. This innovative method effectively identifies genuine air-gap defects. The research presents an innovative method termed as 1D deep convolutional autoencoder integrated with active item response theory, significantly enhancing the clarity of internal flaws within CFRP materials. This method's ability to refine images outperforms conventional methods including rapid Fourier transformation, key component examination, autonomous component examination, and segmented least-squares reversion. Although limited, unsupervised learning's potential for precise quantification and localization merits further research and development.

Founding

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