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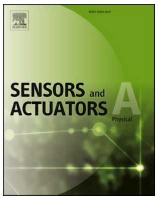

Research progress on the curing process and degree-of-cure monitoring techniques of UV-CIPP resin-based composites

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ABSTRACT

Ultraviolet cured in-place pipe (UV-CIPP) rehabilitation technology, as an efficient and environmentally friendly trenchless pipeline repair method, relies critically on the degree of cure of resin-based composite materials to ensure repair quality. Inadequate curing can compromise mechanical properties and increase long-term service risks, highlighting the necessity for reliable and precise cure-monitoring techniques. This review systematically examines recent advance in degree-of-cure monitoring technologies for UV-CIPP resin-based composites. First, the photoinitiated free-radical polymerization mechanisms of UV resins are detailed, along with the corresponding structure–property relationships. Next, both conventional characterization methods and emerging online monitoring techniques are comprehensively compared, covering their underlying principles, key features, applicability, and limitations. It is noted that while conventional approaches offer high accuracy, they lack real-time feedback capability. In contrast, online monitoring enables in-situ surveillance but remains constrained by challenges such as environmental interference, elevated implementation costs, and limited model generalizability. Finally, future directions are discussed, focusing on integrated multi-technology strategies, artificial intelligence and digital twin-enabled methodologies, as well as flexible sensor design and enhanced engineering applicability. These developments are anticipated to facilitate intelligent closed-loop process control and robust quality assurance in UV-CIPP rehabilitation.

1. Introduction

With the widespread aging of urban underground pipeline systems, structural failures, leakage, and associated safety incidents have increasingly threatened urban operation and public safety. Since its introduction into China in 2008, ultraviolet-cured in-place pipe (UV-CIPP) technology has become a widely adopted trenchless rehabilitation method. Owing to its rapid curing capability and excellent corrosion resistance, UV-CIPP enables the efficient restoration of the structural integrity and service functions of stormwater and wastewater pipelines, significantly extending pipeline service life and reducing long-term maintenance costs. As a result, this technology plays an important role in enhancing the reliability and sustainability of urban pipeline systems [1–3].

Resin–glass fiber composites constitute the core materials of UV-CIPP systems and exhibit superior tensile and compressive strengths [4]. Among the various performance indicators, the degree of cure is a critical parameter for evaluating rehabilitation quality, as it directly governs the post-repair mechanical performance and service life of pipelines. Xia *et al.* [5]demonstrated through three-point bending tests and microscopic morphology analysis that insufficient curing significantly reduces the flexural strength of UV-CIPP composites. Within a certain range, the flexural performance improves with increasing UV irradiation time and lamp intensity. However, once the curing conditions exceed the optimal window, excessive exothermic reaction temperatures may induce matrix cracking, interfacial debonding, and interlaminar delamination, ultimately leading to reductions in flexural strength and modulus. Akderya [6] reported that the flexural strength of UV-cured composites gradually increases with post-curing time and reaches a peak at approximately 30 min; further extension of irradiation time results in a decrease in strength due to surface aging and internal structural defects. Mohammed *et al.*[7] further indicated that excessively severe curing conditions can trigger excessive exothermic reactions, leading to degradation of the resin cross-linked network. As a

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consequence, the elongation at break decreases significantly and the brittleness of the material increases. Therefore, insufficient curing leads to incomplete crosslinking of the material, making it difficult for the pipeline to meet the design requirements in terms of strength, stiffness, and corrosion resistance. Conversely, excessive curing may increase material brittleness and reduce toughness, which can also adversely affect the long-term reliability of the pipeline.

Online monitoring of the degree of cure in UV-CIPP composites faces multiple technical challenges. First, the curing process is highly dynamic, requiring real-time tracking of its evolution to enable timely adjustment of process parameters, such as ultraviolet light intensity and curing duration, thereby ensuring curing quality [8]. Second, monitoring techniques must provide high accuracy and reliability, with measured results faithfully reflecting the actual curing state of the material to support sound engineering decision-making. In addition, owing to the complex geometry and diverse dimensions of pipelines, non-uniform curing may occur within the composite during the curing process, necessitating comprehensive monitoring of different material regions [9].

Furthermore, underground pipeline environments are typically characterized by high humidity, darkness, confined spaces, and the possible presence of corrosive media, which impose stringent requirements on the corrosion resistance, stability, and environmental adaptability of monitoring devices. Meanwhile, the curing process involves the coupling of multiple physicochemical phenomena, including photochemical reactions, heat transfer, and mechanical deformation, leading to complex relationships between the degree of cure and monitoring signals and making it difficult to establish accurate characterization models [10]. Moreover, UV-CIPP composites composed of different resin matrices and reinforcing materials exhibit distinct curing behaviors, rendering generic monitoring methods and models often inapplicable and necessitating customized investigations tailored to specific material systems.

Although existing reviews have summarized curing monitoring technologies for composites, most focus on general composite systems. Few studies take UV-CIPP trenchless pipeline rehabilitation as a specific engineering scenario to systematically clarify degree of curing monitoring, engineering applicability, field deployment challenges, and correlations with long-term performance. Based on practical UV-CIPP construction requirements. This paper reviews the recent research progress in monitoring technologies for the curing process of composite materials used in UV-CIPP rehabilitation. The fundamental mechanisms of composite curing reactions are systematically analyzed, and key physical parameters that are directly correlated with the degree of cure are identified. In conjunction with the physicochemical characteristics at different curing stages, two major categories of degree-of-cure monitoring approaches—conventional methods and emerging techniques—are comprehensively discussed. The principles, features, applicable scenarios, and practical engineering value of each technique in real construction processes are critically elucidated.

2. Curing mechanisms of UV-CIPP resins

2.1. Photoinitiated free-radical polymerization mechanism

Resin curing refers to the transformation of a mixture of unsaturated polyester and crosslinking agents, under the action of initiators and accelerators, from a viscous linear liquid into an infusible and insoluble solid with a three-dimensional crosslinked network through free-radical polymerization reactions [11], as schematically illustrated in Fig. 1. Modern ultraviolet curing technologies are mainly based on two types of chemical reactions, namely free-radical polymerization and cationic polymerization, among which the former represents the most widely commercialized system. This process relies on the photodecomposition of photoinitiators under ultraviolet irradiation to generate free radicals, which subsequently initiate monomer polymerization reactions [12].

For unsaturated polyester resins, the dominant curing reaction involves free-radical copolymerization between the unsaturated groups in polyester oligomers and reactive diluents, such as styrene. The unsaturated moieties along the polyester backbone provide active sites for free-radical addition, while styrene acts as a crosslinking agent participating in the copolymerization process. Upon ultraviolet exposure,

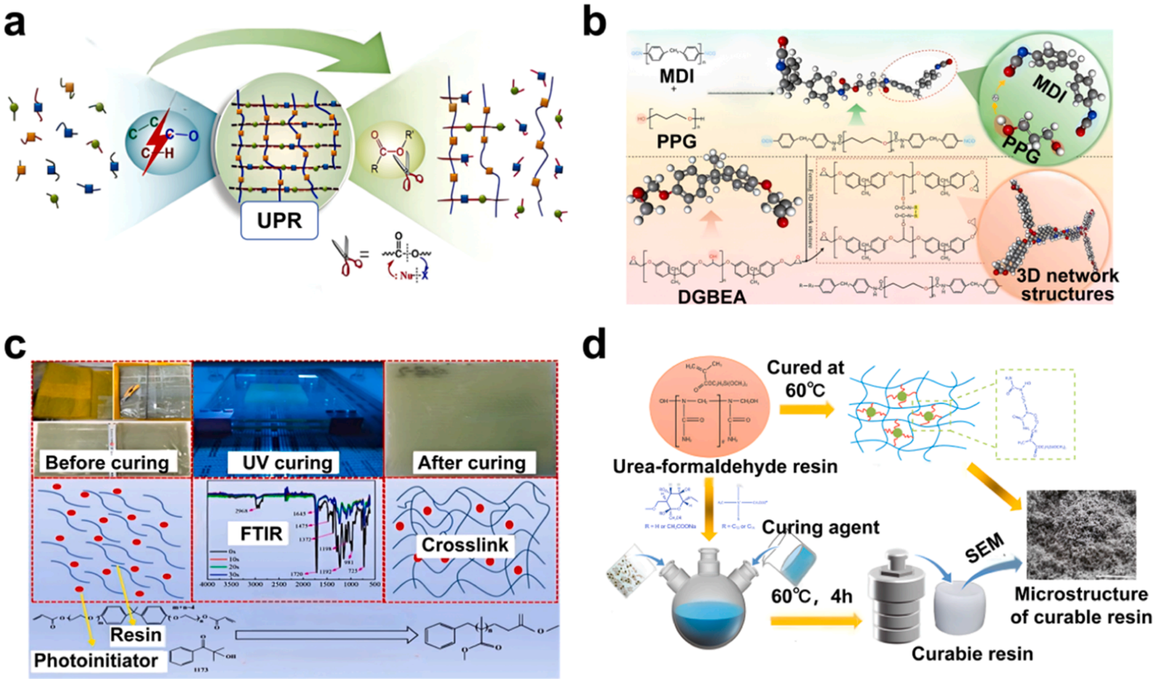

Fig. 1. Crosslinking reaction mechanism of UV-curable resins. (a) Main chemical bonds involved in the curing reaction of unsaturated polyester resin. (b) Molecular crosslinking process of unsaturated polyester resin. (c) Fabrication and curing process of UV-CIPP composite materials. (d) Synthesis, curing and microstructure of curable resins [14–17].

photoinitiators decompose to generate free radicals, which attack the carbon–carbon double bonds of polyester and styrene molecules, thereby initiating chain growth and triggering resin curing. As photoinitiator decomposition continues, the polymerization reaction accelerates progressively. Ultimately, polyester macromolecules undergo copolymerization and crosslinking with styrene, forming a stable three-dimensional network structure and completing the curing process [13].

2.2. *Degree of cure*

2.2.1.

The degree of cure (DoC) is a quantitative parameter used to characterize the extent of crosslinking polymerization in thermoset resin-based composites during the curing process. It is commonly defined as the fraction of reacted functional groups relative to the total number of reactive groups in the system, or equivalently as the ratio of the actual reaction heat released to the theoretical total heat of reaction corresponding to complete curing. The DoC ranges from 0 to 1, where 0 indicates that no curing reaction has occurred and 1 represents a fully cured resin forming a stable three-dimensional cross-linked network [18]. The curing process of thermoset resin matrices is essentially an exothermic polymerization reaction and involves a complex multi-physics coupling process, including heat transfer, mass transport, rheological evolution, and chemical reactions. During this process, the material typically undergoes phase transitions from the liquid state to the gel state and eventually to the glassy state (Figs. 2 and 3 accompanied by continuous changes in the mechanical and rheological properties of the resin [19].

Improper control of curing process parameters can severely disrupt the crosslinking reaction, leading to potential defects such as cracking, wear, hydrolysis, or aging. Moreover, interactions between the composite material and the mold may generate substantial residual stresses, resulting in warpage, matrix cracking, or even internal delamination after curing [20]. The combined effects of these factors often lead to substandard product quality and increased material waste. Notably, although the complex physicochemical transformations occurring during curing pose significant challenges for precise analysis, they also provide critical response signals and physical bases for the development of curing monitoring technologies [21].

2.3. *Curing behavior: physical quantities and monitoring approaches*

Common methods for investigating the curing process and degree of cure of composite materials include differential scanning calorimetry (DSC), ultrasonic techniques, electrical methods, and optical fiber-based sensing approaches. During composite curing, parameters such as residual stress, internal temperature, and resin flow front evolution are closely correlated with curing characteristics. Due to mismatches in the coefficients of thermal expansion between the matrix and fibers, as well as resin shrinkage during curing, residual stresses inevitably develop within the composite [24]. Therefore, real-time monitoring of internal strain evolution during curing can be used to indirectly characterize the degree of cure, thereby enabling process optimization and improved composite quality [25].Various optical fiber sensors, including wavelength-modulated, phase-modulated, and distributed sensing fibers, have been widely employed to monitor the evolution of residual stress in real time during curing [26]. In addition, resin curing is inherently accompanied by exothermic reactions, and localized overheating can exacerbate the development of residual stresses [27]. Among various temperature monitoring techniques, thermal methods are the most straightforward, albeit with notable limitations. According to existing literature, optical fiber-based temperature monitoring represents a particularly promising approach due to its immunity to electromagnetic interference and suitability for in-situ measurements.

In summary, the curing state and quality of composite materials can be evaluated by monitoring several key physical quantities. These mainly include the degree of cure, temperature, and residual stress. Their mutual relationships and corresponding monitoring methods are summarized in Table 1.

3. Conventional characterization methods

3.1. *Fourier transform infrared spectroscopy (FTIR)*

Fourier transform infrared spectroscopy (FTIR) analyzes changes in chemical structure before and after curing by probing the vibrational absorption bands of chemical bonds. As a mid-infrared responsive analytical technique, FTIR is based on the selective absorption of infrared radiation at different wavelengths by molecular functional groups, enabling the identification of molecular structures and chemical compositions. During testing, infrared radiation passes through the specimen, where specific covalent bonds absorb characteristic wavelengths, while the remaining radiation is collected to generate a spectrum. The resulting spectrum reflects molecular absorption and transmission characteristics, forming a distinctive “molecular fingerprint” for chemical identification [29].

In curing studies, FTIR is commonly employed to monitor the evolution of characteristic functional groups, such as carbon–carbon double bonds in unsaturated polyester resins, by tracking changes in absorption peak intensities. Previous studies have shown that gelation occurs when approximately 5% of the C═C bonds in the resin system participate in the reaction, about 50% are consumed during the intermediate curing stage, and more than 90% are converted at the end of curing [30].

Accordingly, the degree of cure can be determined from variations in

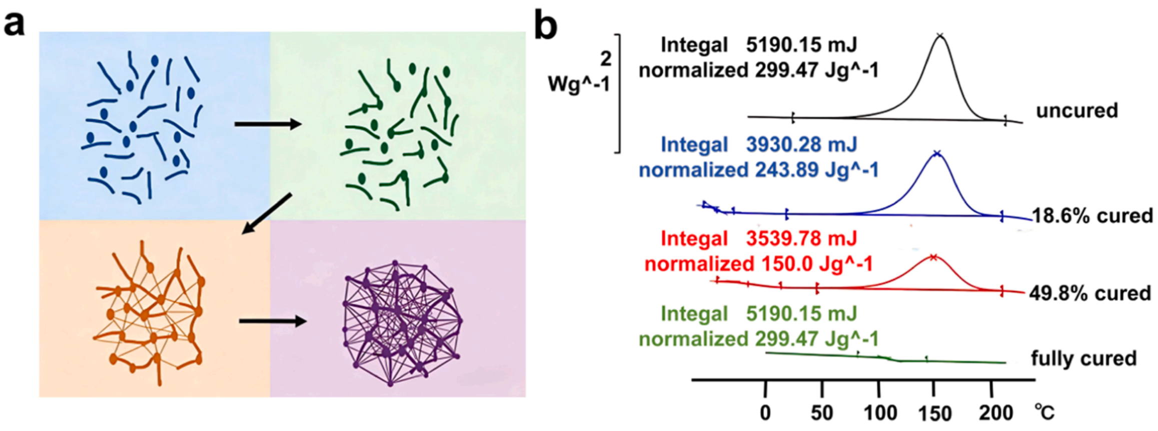

Fig. 2. Resin curing and exothermic process. (a) Four stages of resin curing: liquid-gelation-crosslinking–solidification. (b) DSC exothermic behavior at different degrees of cure [22,23].

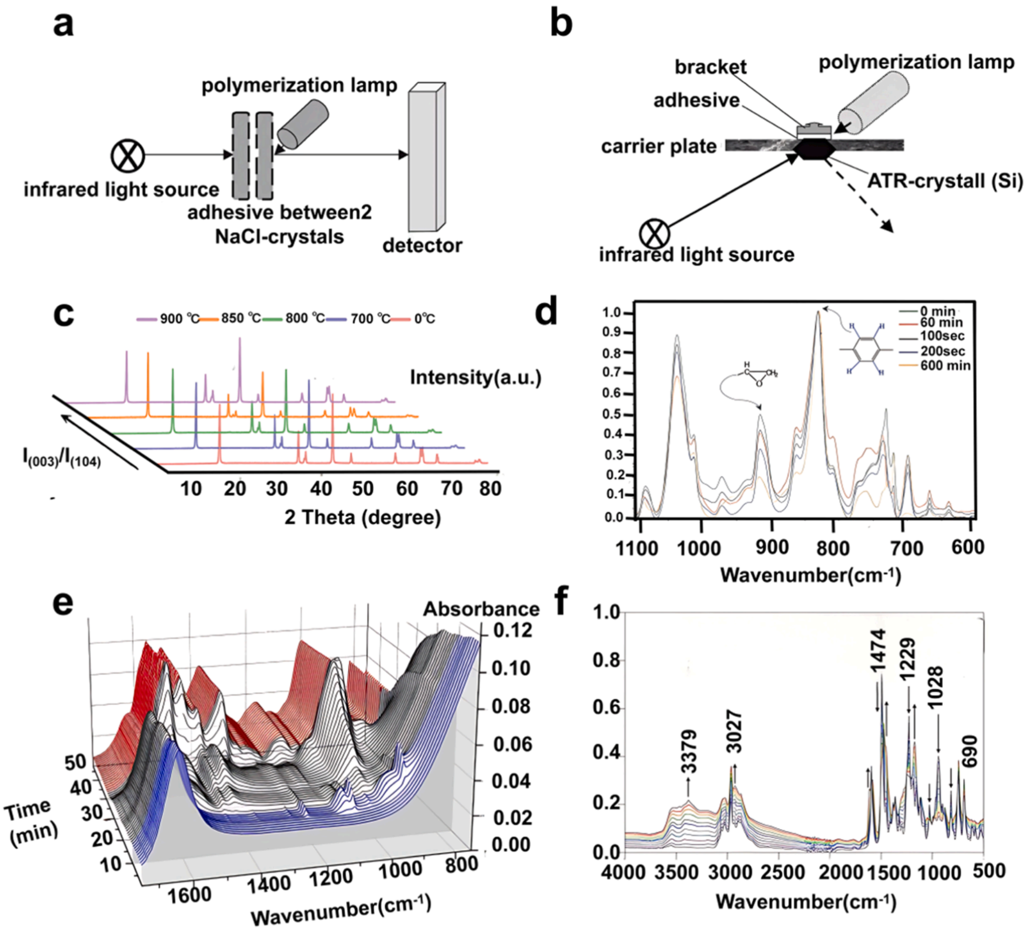

Fig. 3. FTIR monitoring of composite curing processes and representative spectra. (a) (b)Schematic diagram of the in-situ FTIR testing system. (c) FTIR spectral results under different temperature conditions. (c) Evolution of specific functional groups in resin at different curing times. (d) Three-Dimensional FTIR spectra during the resin synthesis process. (e)Schematic diagram of the in-situ FTIR testing system. [31–35].

characteristic peak intensities and calculated using Eq. (1):

$$\alpha = 1 - \frac{M'/R'}{M/R} \tag{1}$$

Where M'/R' is the ratio of the measured peak to the reference peak after curing, and M/R is the corresponding ratio for the uncured liquid resin.

In epoxy resin curing studies, spectroscopic techniques have become indispensable tools due to their ability to directly track chemical bond transformations. Achilias *et al.* [34] compared curing kinetics derived from FTIR and DSC measurements and found that kinetic parameters obtained from FTIR were more representative of the intrinsic chemical reaction, whereas activation energies derived from DSC, which are based on thermal effects, tended to be overestimated. Although both techniques can effectively characterize curing behavior, their applicability should be selected according to specific research objectives. Yin [35] employed FTIR to evaluate degree of cure by comparing functional group evolution during microwave and thermal curing, thereby elucidating the curing mechanism of microwave processing. Zou [36] used FTIR-determined degree of cure as a reference to establish a linear correlation between fiberglass-reinforced plastic hardness and degree of cure, enabling quantitative linkage between material properties and curing state.

To achieve real-time monitoring of curing processes, spectroscopic techniques have increasingly been combined with other in-situ and online methods. Lachenal *et al.* [37] reported that near-infrared spectroscopy (FT-NIR) offers both laboratory analytical capability and industrial online monitoring potential, while its microscopic modes allow nondestructive characterization of heterogeneous materials, demonstrating significant promise for polymer process optimization. Duemichen *et al.* [38] integrated a heated in-situ NIR cell with DSC and demonstrated that NIR spectroscopy enables in-situ curing analysis through direct monitoring of structural changes, outperforming DSC particularly in slow-curing systems. Yuste-Sanchez *et al.* [39] combined broadband dielectric spectroscopy (BDS), in-situ FT-IR, and Raman spectroscopy to confirm the acceleration effect of graphene on epoxy curing, revealing that multimodal spectroscopic techniques can effectively correlate chemical evolution with molecular dynamics. George *et al.* [40] employed fiber-optic FT-IR in the near-infrared region to monitor the primary amine absorption band at 5067 cm^{-1} , achieving rapid and accurate tracking of the curing reaction up to the gel point, with activation energies consistent with DSC results.

At the industrial application level, the online monitoring potential of near-infrared spectroscopy has been further validated. Salzmann *et al.* [41] integrated a miniaturized NIR spectrometer into resin transfer molding (RTM) processes, indirectly reflecting curing progression through spectral baseline shifts and characteristic band variations, thereby providing real-time feedback for process control. Erdmann *et al.* [42] combined in-situ NIR monitoring with DSC validation and demonstrated that an nth-order autocatalytic model accurately describes epoxy resin curing behavior. Wendl *et al.* [43] compared curing efficiencies of different polymerization lamps using transmission and attenuated total reflectance (ATR)-FTIR, confirming the effectiveness of FTIR techniques for evaluating composite degree of cures. Fernández-Francos *et al.* [44] developed a novel ATR-FTIR-based method capable of simultaneously measuring degree of cure and volumetric shrinkage,

Table 1
Relationships among key physical quantities during composite curing and corresponding monitoring techniques [28].

Physical quantity	Mutual influence (bidirectional relationship)	Monitoring difficulty and characteristics	Main monitoring methods	Monitoring principle / key features
Degree of cure (α)	Temperature directly governs reaction kinetics, controlling curing rate and extent. Non-uniform curing and cure shrinkage are primary sources of residual stress. Variations in degree of cure are directly associated with dielectric and rheological property transitions (e.g., viscosity).	Difficult; critical parameter. Main challenge lies in characterizing internal chemical crosslinking states, typically requiring indirect measurements.	Differential scanning calorimetry (DSC)	Principle: determination of residual reaction heat of uncured resin to calculate degree of cure. Features: laboratory-standard method with high accuracy, but destructive and offline.
			Fourier transform infrared spectroscopy (FTIR)	Principle: monitoring changes in characteristic absorption peaks of functional groups to infer reaction extent. Features: commonly used for offline or in-situ analysis.
			Dielectric analysis (DEA)	Principle: real-time monitoring of ionic viscosity, loss factor, and other electrical parameters to indirectly reflect curing evolution. Features: suitable for online process monitoring and widely used in industry.
			Ultrasonic methods	Principle: acoustic velocity and attenuation depend on modulus, density, and viscosity, enabling indirect inference of curing state. Features: non-contact and rapid, but require complex modeling and calibration.
Temperature (T)	Dominates curing reaction progress and directly affects curing rate and uniformity. Temperature gradients induce thermal stresses, while heating/cooling rates control stress magnitude.	Easy; fundamental parameter. Mature sensing technologies enable high-precision, distributed, real-time monitoring.	Thermocouples	Features: traditional point-based measurement; low cost and easy installation; sensitive to electromagnetic interference and long-term stability issues.
			Resistance temperature detectors (e.g., PT100)	Features: generally higher accuracy and stability than thermocouples; still point-based.
			Fiber Bragg grating (FBG) temperature sensors	Features: immune to electromagnetic interference; enable distributed multi-point sensing using a single fiber; easily embedded in composites, suitable for intelligent monitoring.
			Infrared thermography	Features: non-contact measurement providing full-field surface temperature distribution; unable to measure internal temperature.
Residual stress (S)	Formed due to non-uniform cure shrinkage and mismatched thermal expansion coefficients, and “frozen” during processing. Jointly governed by temperature history and degree-of-cure evolution.	Very difficult; integrated result of multi-physics coupling. Direct measurement is intrusive.	Fiber Bragg grating (FBG) sensors	Principle: residual stress is inferred from real-time strain evolution during curing combined with constitutive modeling. Features: one of the most promising in-situ/online monitoring approaches, suitable for embedded applications.
			Ultrasonic methods	Principle: stress alters ultrasonic wave velocity; calibrated measurements allow stress estimation. Features: suitable for surface or near-surface stress evaluation and rapid field inspection.
			Process simulation	Principle: finite element simulations driven by real-time temperature and degree-of-cure data to predict stress field development. Features: virtual monitoring approach and a core component of intelligent process control.

applicable to both thermally and UV-cured systems.

With the advancement of intelligent data analysis techniques, spectroscopic monitoring has increasingly been integrated with data-driven modeling approaches. Nash *et al.* [9] combined infrared thermography with recursive Bayesian filtering to achieve real-time monitoring of composite degree of cure and defect localization. Xu Xu *et al.* [45] employed multichannel in-situ infrared spectroscopy to establish curing kinetic models for epoxy coatings at different temperatures, further validating the effectiveness of spectroscopic techniques in polymer curing studies.

FTIR is a powerful tool for investigating resin curing mechanisms and analyzing functional group evolution. However, it also exhibits certain limitations. Conventional FTIR measurements are typically performed offline on cured specimens, making real-time process monitoring challenging, and measurement accuracy is sensitive to specimen preparation, thickness, and homogeneity. Although near-infrared spectroscopy and ATR-FTIR enable in-situ and online monitoring, their high equipment costs and susceptibility to interference from ambient moisture and impurities remain obstacles. Overall, FTIR spectroscopy provides direct insight into functional group conversion and curing kinetics; however, its dependence on optical instrumentation and controlled environments limits its applicability for in situ monitoring in UV-CIPP rehabilitation.

The integration of FTIR spectroscopy with intelligent algorithms has become an emerging approach for curing monitoring of polymer composites. In such methods, characteristic spectral features related to functional group conversion are extracted from FTIR spectra and correlated with the degree of cure using data-driven models. Multivariate regression techniques, such as partial least squares (PLS) and principal component regression (PCR), have been widely used to establish quantitative relationships between spectral variables and curing parameters [46]. In addition, machine learning algorithms including artificial neural networks and support vector regression have been employed to capture the nonlinear relationship between FTIR spectral features and curing states [47]. These approaches enable more accurate prediction of curing kinetics and provide a promising pathway toward intelligent monitoring and control of composite curing processes [48, 49].

3.2. Differential scanning calorimetry (DSC)

Differential scanning calorimetry (DSC) analyzes the thermal behavior of materials by monitoring heat flow variations during programmed temperature control. In resin curing studies, DSC is typically conducted in both isothermal and non-isothermal modes, which are often combined to comprehensively characterize curing behavior [50]. During crosslinking reactions, resins release heat, and DSC records the corresponding exothermic peaks and reaction enthalpy changes. Characteristic temperatures, including onset, peak, and termination temperatures, can be extracted from the exothermic curves, while the magnitude of reaction enthalpy directly reflects the extent of curing. Under identical testing conditions, a higher exothermic heat release generally indicates a more complete curing reaction [51].

Accordingly, DSC is widely employed to systematically investigate the effects of processing parameters—such as temperature, formulation, and curing time—on curing behavior, thereby enabling optimization of curing processes. Moreover, DSC provides a powerful tool for curing kinetics analysis, in which the degree of cure can be calculated through kinetic modeling. The degree of cure at a given time t can be expressed as:

$$\alpha_{\mathrm{DSC}} = \frac{\Delta \mathrm{H}(\mathrm{t})}{\Delta \mathrm{H}_{\mathrm{TOT}}} = \frac{1}{\Delta \mathrm{H}_{\mathrm{TOT}}}\int_0^{\mathrm{t}} \frac{\mathrm{dH}}{\mathrm{dt}}\mathrm{dt} \tag{2}$$

where α is the degree of cure, t is the curing time, $\Delta \mathrm{H}(\mathrm{t})$ is the heat released up to time t measured under isothermal conditions, $\Delta \mathrm{H}_{\mathrm{TOT}}$ is the total reaction enthalpy measured under non−isothermal conditions, and dH/dt is the heat flow rate.

In curing kinetics research, DSC directly measures the thermal effects associated with chemical reactions and is therefore frequently combined with other characterization techniques. Puchleitner and Bao *et al.* [52] investigated the curing behavior of epoxy resin composites with enhanced thermal resistance using DSC coupled with thermogravimetric analysis (TGA), determining optimal processing temperatures and thermal stability, which provided guidance for material optimization. To further assess the accuracy of kinetic parameters, Achilias *et al.* [34] compared DSC and FTIR for epoxy curing kinetics analysis. Activation energies derived from non-isothermal DSC data using the Kissinger method and isoconversional analysis exhibited deviations from FTIR-based results obtained through direct chemical bond monitoring; however, both methods consistently showed an increasing trend of activation energy with degree of cure.

Methodologically, data processing and analysis techniques for DSC continue to evolve. Wu *et al.* [53] integrated DSC data with genetic algorithms to successfully identify and reconstruct kinetic equations for a novel thermosetting resin exhibiting two-stage curing behavior, providing a powerful tool for modeling and optimization of complex curing processes. In addition, advanced techniques such as modulated differential scanning calorimetry (MDSC) have demonstrated distinct advantages. Leyva-Porras *et al.* [54] reported that MDSC, by modulating the heating rate, effectively distinguishes reversible and irreversible thermal processes during curing and offers higher sensitivity than conventional DSC when analyzing complex thermal behaviors.

Multi-technique integration has become a common strategy for gaining deeper insights into curing mechanisms. Hardis *et al.* [55] combined DSC, Raman spectroscopy, and dielectric analysis (DEA) to investigate epoxy curing behavior, validating the applicability of autocatalytic models and demonstrating good consistency in activation energies obtained from different methods, thereby highlighting the importance of multi-perspective characterization for model verification and result reliability. Peng *et al.* [56] employed a DSC system equipped with an external UV light source to investigate photocuring behavior under different light intensities and temperatures. By introducing both curing temperature and light intensity into kinetic model assumptions and validating them through experimental measurements and finite element curing simulations, the proposed model was shown to be reliable.

DSC enables accurate quantification of the thermal effects associated with curing reactions and plays a crucial role in elucidating curing kinetics and mechanisms. Tests can be conducted under various temperatures and heating rates to simulate realistic curing conditions, providing valuable guidance for process optimization. However, for UV-curable resins that rely on ultraviolet initiation, DSC monitors curing indirectly through thermal responses. Once a stable network structure has formed under UV irradiation, secondary reactions induced by thermal stimulation and residual uncured components are difficult to distinguish, potentially leading to deviations in degree-of-cure calculations. From an engineering perspective, DSC requires sampling from cured materials, rendering it a destructive, offline technique with stringent specimen preparation requirements, and sample representativeness strongly influences measurement accuracy. Furthermore, DSC instruments are relatively expensive and require specialized expertise for operation and data interpretation, limiting their applicability in field environments. In addition, DSC results only represent the average degree of cure of the sample and cannot resolve the spatial variation of curing within composite structures.

4. New monitoring techniques

4.1. Optical fiber sensing methods

In recent years, advances in optical fiber technology have provided important support for monitoring the curing processes of composite materials. Optical fiber sensors operate by exploiting the light-guiding characteristics of optical fibers, converting variations in physical or chemical parameters of the measured object into corresponding changes in optical signals. For curing monitoring of composite materials, commonly used optical fiber sensors include refractive index sensors, infrared absorption spectroscopy sensors, micro-bending fiber sensors, fiber Bragg grating (FBG) sensors, and fiber Fabry-Pérot sensors [57,58].

Fiber Bragg grating (FBG) sensors, a type of reflective optical sensor, have received considerable attention in composite monitoring applications. Their advantages include immunity to electromagnetic interference, high durability, stable signal transmission, and good compatibility with composite materials. In addition, their small physical dimensions enable embedding within composites with minimal influence on the mechanical properties of the host structure.

The operating principle of an FBG sensor is illustrated in Figs. 4,5,6,7,8,9 and 10. When broadband light propagates through an optical fiber containing a Bragg grating, the wavelength component that satisfies the Bragg condition is selectively reflected, while the remaining wavelengths continue to propagate along the fiber. For a uniform FBG with a grating period Λ, the central reflected wavelength λ can be expressed as:

$$\lambda = 2n_{\mathrm{eff}}\Lambda \tag{3}$$

where n_{eff} is the effective refractive index of the fiber core.

The Bragg wavelength is highly sensitive to variations in both the grating period and the effective refractive index of the core mode. Consequently, FBG sensors respond sensitively to external stimuli such as mechanical loads and thermal effects. Changes in temperature and strain induce shifts in the Bragg wavelength by altering the effective refractive index and the grating spacing, enabling simultaneous or decoupled measurement of temperature and strain. In curing studies, strain signals are commonly employed to analyze thermal stress development and curing-induced deformation [59,60].

In the field of composite curing monitoring, FBG sensors have become an important tool for tracking internal stress evolution and resin

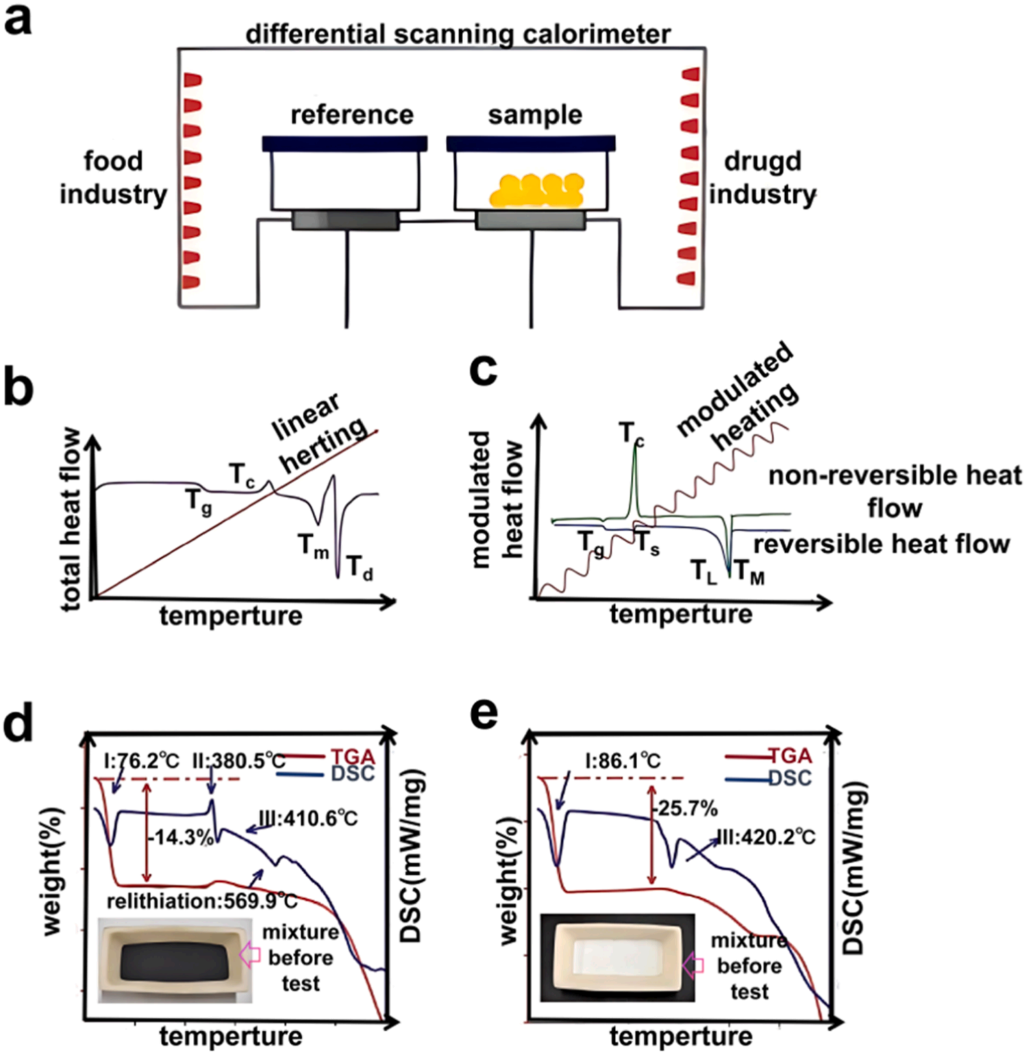

Fig. 4. DSC monitoring of composite curing processes and representative results. (a) DSC instrumentation and measurement principle. (b-c) DSC results. (d-e) DSC and TGA results [32,51].

state changes, owing to their embeddability and resistance to electromagnetic interference. By monitoring strain evolution during curing, FBG sensors can indirectly reflect key phenomena such as resin gelation, chemical shrinkage, and residual stress development.

Chailleux *et al.* [65] employed optical fiber sensors to monitor epoxy resin curing and reported good agreement with DSC measurements. Guo *et al.*[62] used embedded FBG sensors to measure curing shrinkage strain in phenolic resins and established an exponential relationship between chemical shrinkage strain and the degree of cure.

In practical applications, the interfacial coupling between the sensor and the resin matrix plays a critical role in measurement accuracy. Wang [66] pointed out that insufficient interfacial bonding strength at early curing stages may lead to inaccurate strain transfer, while monitoring reliability improves progressively as curing proceeds. Moreover, the presence of reinforcement materials may introduce additional interference. Li *et al.* [67] reported that carbon fibers can induce micro-bending in optical fibers, thereby affecting sensor sensitivity.

To achieve more comprehensive characterization of the curing process, FBG sensors are often combined with other sensing techniques. Jiang [68] integrated thermocouples with FBG sensors to simultaneously track temperature and strain evolution during autoclave curing. Tang [69] combined FBG and Fabry–Pérot sensors to capture three-dimensional resin flow fronts and key curing stages in thick composite structures.

FBG sensors have also demonstrated excellent performance in identifying critical curing transition points. Li [70] and Hu [71] successfully detected gelation and glass transition points using FBG measurements. Muule *et al.* [72], by embedding FBG sensor arrays in different laminate layers, demonstrated that the gelation stage represents a critical window for monitoring residual strain development. These findings provide direct guidance for process optimization.

Beyond conventional curing monitoring, FBG sensing technology has increasingly extended toward functionalized and intelligent monitoring applications. Zanjani *et al.* [73] employed FBG sensors to monitor structural evolution during fabrication, leading to the development of smart composite materials capable of shape response under external stimuli. Zhong [74] applied FBG sensors to monitor crosslinking degree and damage evolution in irradiation environments, expanding their applicability under extreme conditions.

Overall, FBG sensing technology has evolved from single-parameter strain monitoring to an advanced online monitoring approach capable of multi-parameter measurement, identification of key curing transitions, and even intelligent material development. This evolution provides strong technical support for precise control and optimization of composite curing processes.

However, in the context of ultraviolet (UV) in-situ cured pipe rehabilitation for municipal drainage systems, FBG-based monitoring faces notable challenges. These include relatively high system costs, complex

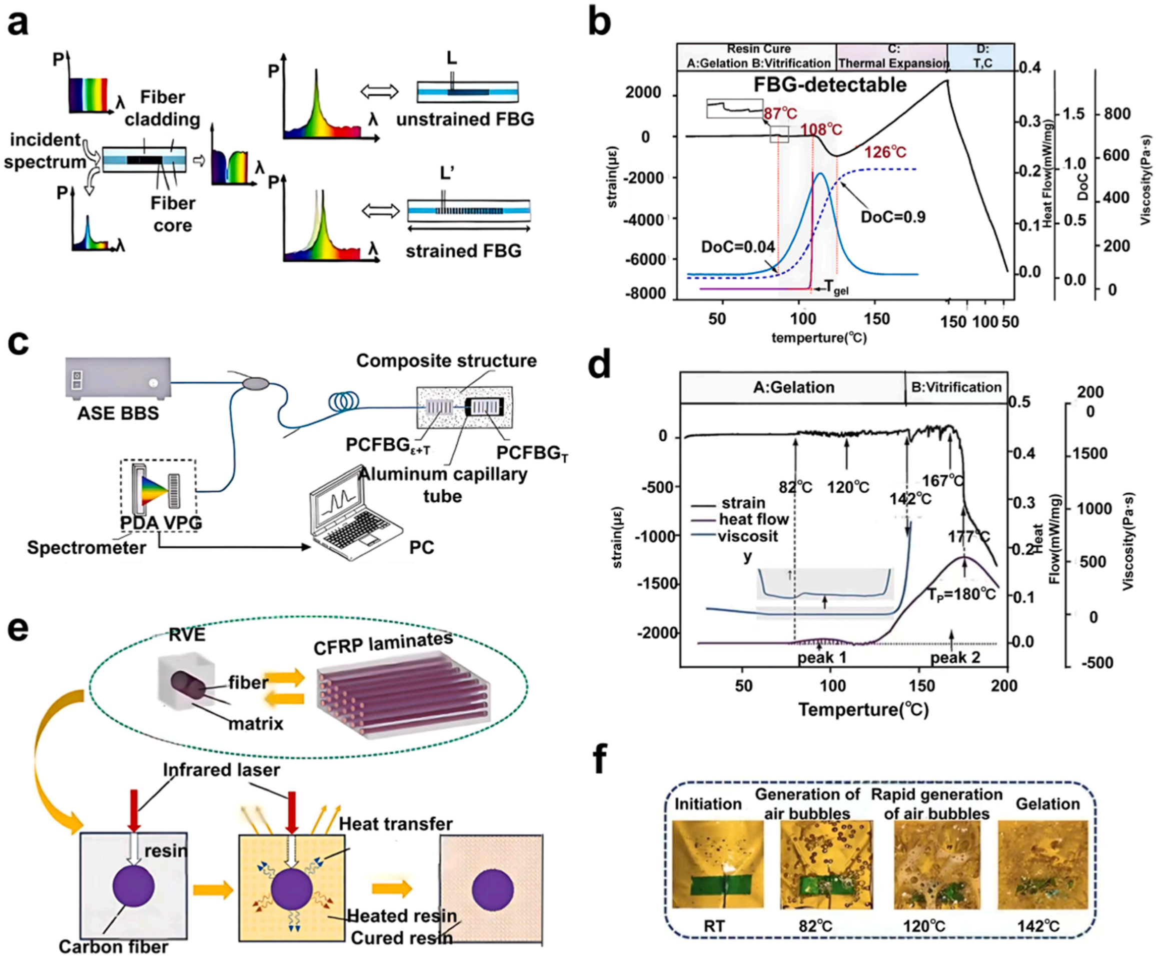

Fig. 5. Optical fiber monitoring of composite curing processes and representative measurement results. (a) Schematic diagram of spectral change of Fiber Bragg Grating (FBG). (b) Typical strain curves obtained from DSC and in-situ viscosity monitoring during the curing of phenolic resin. (c) Optical fiber monitoring system composition. (d,f) Locally enlarged regions during the heating stage and the corresponding physical states of the resin at specific temperatures. (e) Principle giagram of optical fiber monitoring in resin curing process [61–65].

installation procedures, and stringent requirements for signal demodulation. High-precision interrogators are required to convert optical signals into accurate data, while existing demodulation technologies still face limitations in terms of accuracy, speed, and long-term stability. During curing, rapid signal variations may not be captured in a timely and reliable manner. In addition, frequent fluctuations in temperature and humidity within pipelines can cause Bragg wavelength drift and affect optical transmission performance. Although compensation algorithms can be applied, they inevitably increase system complexity and overall cost. Due to its high sensitivity to temperature and strain and strong resistance to electromagnetic interference, FBG sensing shows great potential for in situ monitoring of UV-CIPP curing, although challenges remain in sensor deployment and long-distance integration.

4.2. Ultrasonic methods

Ultrasonic waves are high-frequency mechanical waves with frequencies exceeding 20 kHz, characterized by good directivity and penetration capability. Owing to their relatively simple instrumentation and nondestructive nature, ultrasonic techniques have been widely applied in the nondestructive evaluation of internal defects, thickness variation, and corrosion in materials. According to their propagation modes, ultrasonic waves can be classified into longitudinal waves, shear waves, and surface waves. Among these, longitudinal waves are most commonly employed for monitoring resin curing processes and investigating curing kinetics [75,76].

In polymer characterization, particular attention is paid to the propagation velocity, attenuation behavior, and backscattered signals of longitudinal ultrasonic waves. During the curing of thermosetting resins, monitoring is typically achieved by analyzing variations in longitudinal wave velocity and attenuation. As the resin transforms from a liquid to a solid state, its mechanical properties and internal structure evolve continuously, leading to corresponding changes in ultrasonic velocity and energy dissipation. These changes provide a basis for real-time tracking of the curing process [77,78].

Ultrasonic monitoring can be implemented in either reflection or transmission modes. In the transmission mode, the ultrasonic wave travels through a specimen of thickness d within a time interval t, and the longitudinal wave velocity c can be expressed as:

$$\mathrm{c} = \frac{\mathrm{d}}{\mathrm{t}} \tag{4}$$

The attenuation coefficient, which characterizes the energy dissipation of the ultrasonic wave as it propagates through the material, is defined based on the change in signal amplitude after transmission through a specimen of thickness d:

$$\alpha = \frac{20}{\mathrm{d}}\lg\frac{\mathrm{A}_0}{\mathrm{A}} \tag{5}$$

where A_0 and A denote the amplitudes of the incident and transmitted waves, respectively [79].

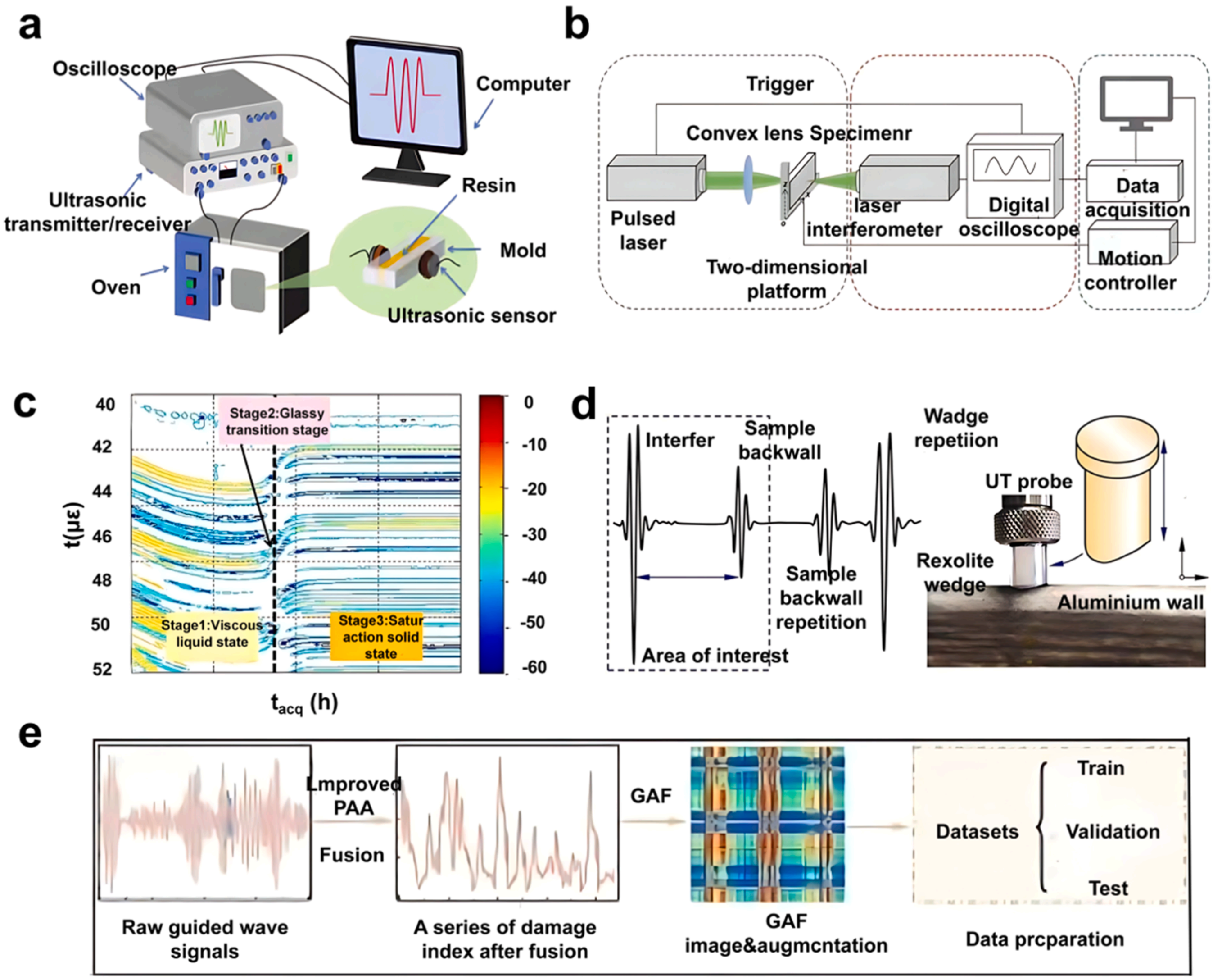

Fig. 6. Ultrasonic monitoring of composite curing processes and representative measurement results. (a,b,d) Ultrasonic testing setup and operating principle. (c) Ultrasonic monitoring of transmitted signals in a five-layer epoxy resin structure. (e) Ultrasonic monitoring and localization of defects and damage during the curing process [80–83].

The core advantage of ultrasonic monitoring lies in the strong correlation between acoustic parameters and the mechanical state of the material. The longitudinal wave velocity (or the corresponding longitudinal modulus derived from it) is highly sensitive to stiffness evolution and thus serves as a key indicator for tracking curing progression [78]. Ultrasonic attenuation, on the other hand, is associated with internal energy dissipation and scattering mechanisms and can reflect phase transitions within the resin system.

Maffezzoli *et al.* [84] demonstrated that longitudinal wave velocity exhibits even higher sensitivity to the glass transition during the late curing stage than DSC, highlighting its effectiveness for curing monitoring.Early studies primarily focused on establishing linear relationships between ultrasonic parameters—such as wave velocity and attenuation—and the degree of cure. Guo [85] and Huang [86] monitored various resin systems and verified the correspondence between ultrasonic signal evolution and curing behavior, enabling the extraction of kinetic parameters.

To enhance sensitivity, Koissin *et al.* [87] employed non-collinear wave mixing techniques to monitor nonlinear elastic constants, achieving precise detection of gelation and glass transition points and demonstrating superior sensitivity to rheological changes compared with linear ultrasonic methods. Studies by Tao [88] and Hu [89] further confirmed that ultrasonic techniques can effectively characterize and quantify curing behavior in fiber-reinforced resin systems, accurately capturing the influence of fibers on gelation behavior. Zhao [79] reported that ultrasonic monitoring enables reasonable prediction of mechanical behavior parameters during curing, allowing real-time feedback for process control. Zhang [90] combined online ultrasonic monitoring with a model-free analytical approach to investigate epoxy resin curing kinetics. By analyzing variations in ultrasonic amplitude, energy, and attenuation, distinct curing stages were successfully identified. The study further revealed the existence of an optimal curing temperature for the resin system and showed that slower heating rates lead to improved mechanical properties of the resulting composites.

More advanced ultrasonic configurations have also been developed. Zhang [91] established a fiber-optic laser ultrasonic detection system based on dual-wave mixing interferometry, optimizing coupling efficiency for both single-mode and multimode optical fibers. By constructing a degree-of-cure model based on dispersion characteristics, precise identification of gelation, glass transition, and saturation curing stages during epoxy curing was achieved, demonstrating the advantages of laser ultrasonics in terms of non-contact operation and broadband response. Francesca Lionetto *et al.* [81] compared contact-based and air-coupled ultrasonic systems, concluding that the latter, which does

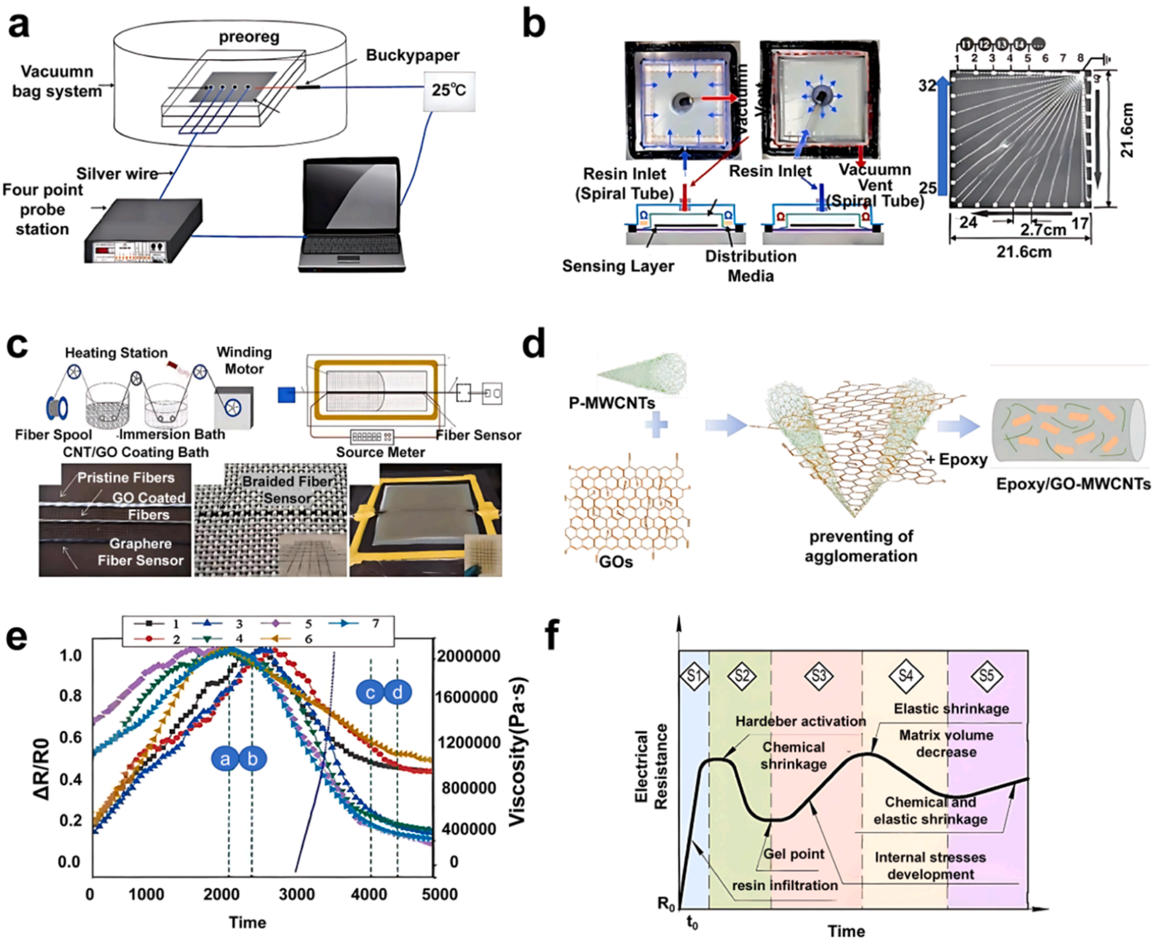

Fig. 7. CNT-based monitoring of composite curing processes and representative resistance responses. (a) Monitoring principle of carbon nanotube sensors. (b,d) Integration process of carbon nanotubes. (c) Experimental setup for the VARTM process with carbon nanotube sensors and composite materials integrated with multilinear sensors. (e) Relative resistance change of MWCNT-Coated glass fiber sensors (the blue solid line represents the viscosity variation). (f) Resistance changes of SWCNT films induced by different polymerization steps [94–96].

not require physical contact with the resin, is more suitable for online monitoring of composite curing. Maréchal *et al.* [83] employed high-temperature ultrasonic transducers equipped with delay lines to successfully identify multiple stages of high-temperature epoxy polymerization, establishing a robust methodology for correlating curing evolution with material performance.

In summary, ultrasonic monitoring techniques have evolved from basic linear parameter measurements to advanced nonlinear characterization and online monitoring approaches suitable for high-temperature and non-contact conditions. These methods not only enable accurate identification of key curing transitions but also provide quantitative characterization of curing kinetics and final mechanical properties, offering effective tools for process optimization and closed-loop control in composite manufacturing. Nevertheless, their application remains challenged by sensitivity to complex service environments—such as pipeline geometry, temperature gradients, and surrounding media—as well as high requirements for sensor deployment and signal interpretation. Furthermore, quantitative models linking ultrasonic parameters to the degree of cure require further refinement to accommodate process variability and material diversity. Ultrasonic testing provides a non-destructive approach for evaluating curing progress and structural integrity; however, signal attenuation and complex interpretation may limit its effectiveness in heterogeneous composite systems.

4.3. Electrical resistance–based strain sensing methods

4.3.1. Carbon nanotube-based sensing approaches

The sensing mechanism of carbon nanotube (CNT)-based sensors primarily relies on the tunneling effect and piezoresistive behavior. When CNTs are incorporated into a composite material, they form a percolated conductive network, and the overall electrical resistance consists of two main contributions: the intrinsic resistance of individual CNTs and the contact (or tunneling) resistance at CNT-CNT junctions [92]. During resin curing, processes such as resin flow, gelation, crosslinking, and volumetric shrinkage continuously modify the relative spacing and contact state between CNTs, leading to distinct resistance evolution patterns.

Specifically, during the resin flow stage, polymer molecules infiltrate the interstitial spaces between CNTs, increasing the tunneling barrier and resulting in a rise in electrical resistance. As gelation and crosslinking proceed, the crosslink density increases and the viscosity of the system rises, progressively immobilizing the CNT network, causing the resistance to gradually stabilize as curing advances. In the subsequent cooling stage, resin shrinkage further adjusts CNT contact configurations, producing resistance fluctuations that correlate with temperature variations [8,93]. By continuously monitoring resistance changes, key curing parameters—such as gelation onset and degree of cure—can be inferred in real time, enabling online monitoring of the composite curing process.

Based on this principle, CNT-based materials have been extensively

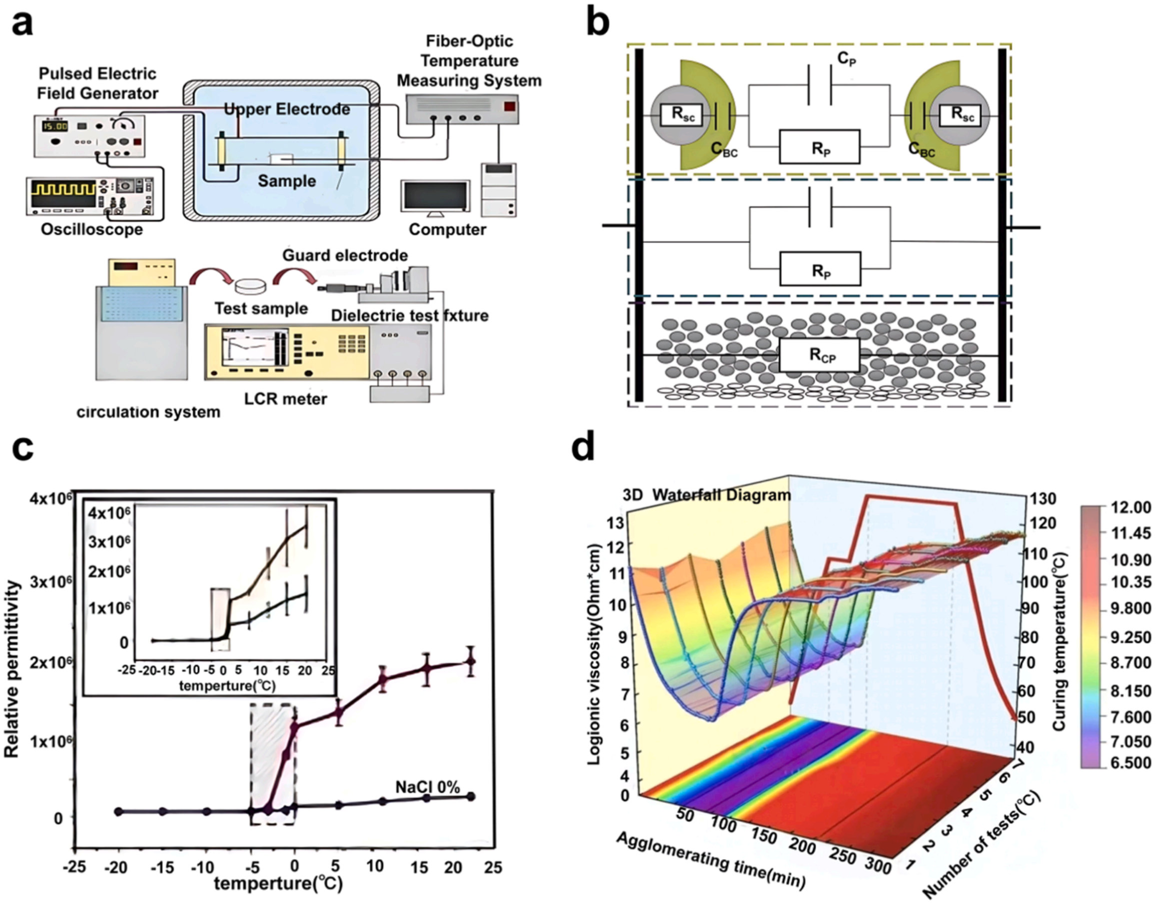

Fig. 8. Dielectric monitoring of composite curing processes and representative dielectric responses. (a,b) Dielectric measurement setup and operating principle. (c-d) Dielectric measurement results [108,109].

investigated as embedded or integrated sensors for resin flow and curing monitoring. Yang *et al.* [96] developed a novel CNT paper sensor for real-time monitoring of resin flow during vacuum infusion processes. The CNT paper was embedded within composite preforms, enabling in situ tracking of resin flow behavior. Their results demonstrated that the sensor could effectively capture dynamic resin movement, providing a new approach for defect prevention, process parameter optimization, and manufacturing quality improvement.

Lu and co-workers from Shenyang Aerospace University [8,97,98] successfully developed a fabric-based paper composed of monodispersed multi-walled CNTs. By exploiting the piezoresistive effect of CNTs, this sensor was used to monitor the curing process of glass fiber/epoxy composites in real time, offering an innovative solution for curing process surveillance. Zhao *et al.* [99] fabricated highly flexible graphene/CNT conductive network sensors using a spray-assisted vacuum filtration process and successfully integrated them into complex-curvature composite structures. The resistance response of the sensor enabled low-cost, in situ, and accurate identification of critical curing stages. Furthermore, by analyzing the temperature coefficient of resistance (TCR), a critical threshold value of -7.18×10^{-4} °C^{-1} was identified: when the TCR exceeded this value, the resin network was considered stabilized and in a glassy state, indicating near-complete curing. This criterion was shown to be consistent with DSC measurements. Dai *et al.* [94] investigated CNT-based textile sensors as distributed sensing elements for monitoring resin flow and curing during vacuum infusion processes. By integrating electrical impedance tomography (EIT), two-dimensional resin flow mapping was achieved. Experimental results confirmed that the sensor system could accurately capture flow front position, geometry, and dry spot defects, with resistance responses directly correlated to resin viscosity evolution and gelation behavior. Li *et al.* [100] systematically studied the influence of CNTs on composite manufacturing processes, mechanical properties, and structural health monitoring performance. Their results indicated that CNTs significantly enhance the mechanical performance of fiber-reinforced polymers (FRPs) through mechanisms such as crack bridging and interfacial reinforcement, while their intrinsic self-sensing capability enables effective damage detection and localization.

M. S. Irfan *et al.* [101] explored piezoresistive fiber sensors coated with carbon nanomaterials for both process monitoring and structural health monitoring of composites. The sensors demonstrated sensitivity to fiber compaction, resin flow, degree of cure, and damage under tensile, bending, and impact loading, enabling full life-cycle monitoring of composite structures. Rahinul Hasan Mazumder *et al.*[102] further extended CNT-based sensing to the digitalization of vacuum-assisted resin transfer molding processes. By designing point-, line-, and area-type sensors and integrating machine learning algorithms with digital twin frameworks, defects and process parameters throughout vacuum compaction, resin infusion, and curing stages were successfully monitored, highlighting the potential of CNT-based sensors as a core enabling technology for digital composite manufacturing. Wen et al. [103] investigated UV/thermal dual-cured MWCNT-reinforced composites for pipeline rehabilitation and analyzed their mechanical performance and damage evolution characteristics. By introducing MWCNTs into the resin matrix, a conductive network was formed, enabling the composite to exhibit electrical responses sensitive to structural damage. Zhang *et al.* [104,105] developed a highly sensitive and flexible MXene/CNT composite film sensor that can be embedded within fiber-reinforced composites for real-time monitoring of the resin

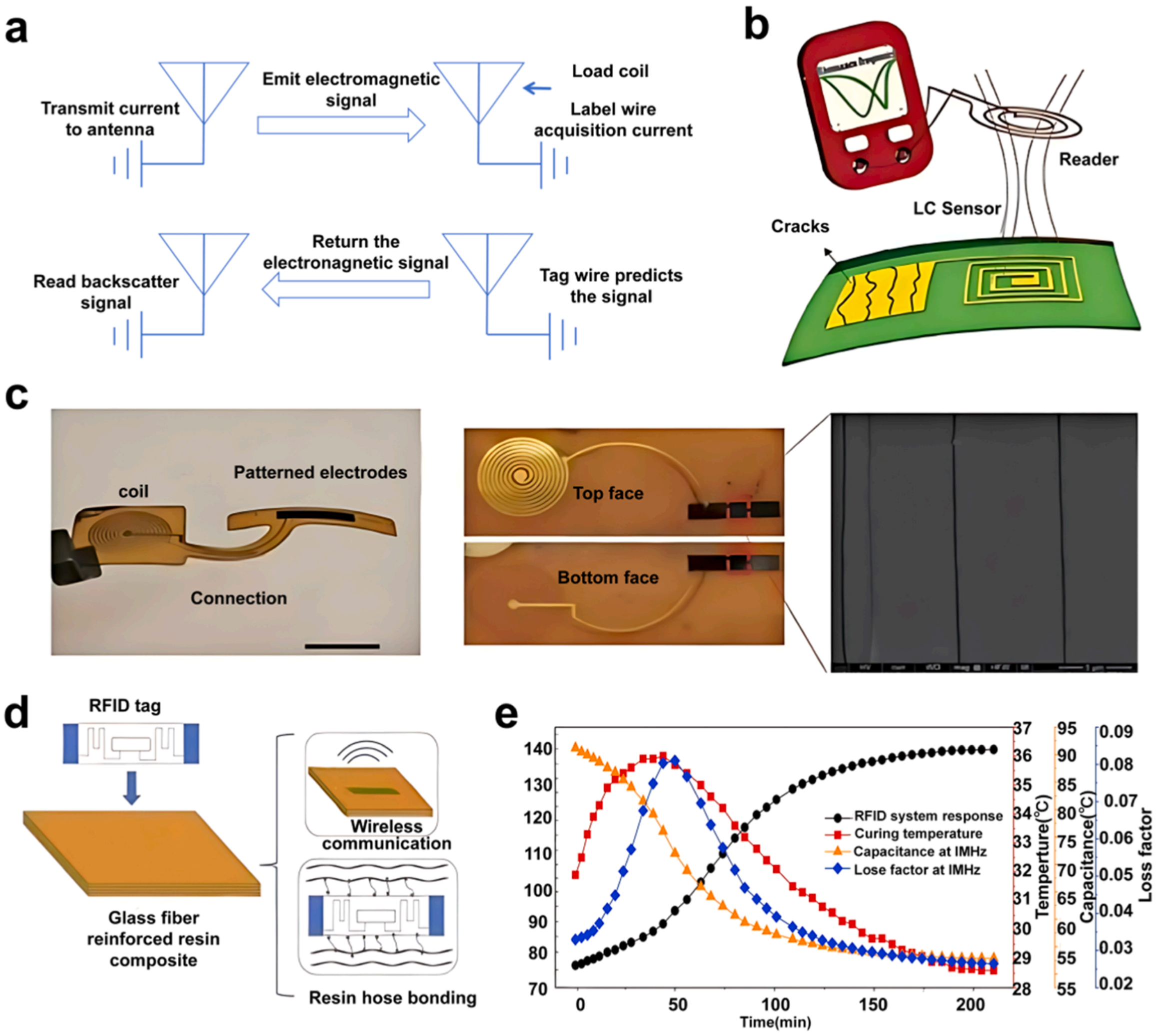

Fig. 9. RFID-based monitoring of composite curing processes and representative RSSI responses. (a) RFID system configuration and signal transmission principle. (b) Signal transmission principle of RFID reader and tag. (c) Principle and distribution diagram of reader and tag connection in material. (d) Schematic diagram of RFID tag integration in glass fiber reinforced resin composite. (e) Evolution of RSSI, temperature, and dielectric constant during resin curing [117–119].

curing process. The results demonstrated that the sensor was capable of accurately identifying the gel point during curing, and the monitoring results showed good agreement with those obtained from dynamic mechanical analysis (DMA). After curing, the sensor can continue to function as a structural health monitoring element, enabling lifecycle monitoring of composite materials from manufacturing to service. Furthermore, the MXene/CNT composite film sensor was employed for in situ real-time monitoring of the liquid composite molding (LCM) process in sandwich composite structures, where it was able to precisely capture the resin flow front and impregnation state. These studies provide valuable insights for the online monitoring and deformation control of UV-CIPP liner curing processes.

From an engineering perspective, CNTs possess nanoscale dimensions (typically 10–30 nm in diameter), allowing uniform dispersion within UV-curable resins without significantly degrading the mechanical performance of repair materials, such as strength and flexibility. Resistance-based sensing enables real-time tracking of gelation and crosslinking progression during UV curing, ensuring that pipeline rehabilitation achieves the designed degree of cure and mitigating the risk of premature failure caused by insufficient curing. Moreover, the percolated CNT conductive network facilitates spatially distributed monitoring rather than point-wise sensing, allowing detection of curing heterogeneity across different regions of the pipeline, which is particularly advantageous for complex geometries encountered in UV-CIPP applications. Given the rapid curing kinetics of UV-induced systems—often on the order of minutes—the fast electrical response of CNT sensors is well suited for real-time monitoring requirements.

Nevertheless, several challenges remain for large-scale implementation in pipeline rehabilitation projects. The cost of CNT materials and sensor integration processes is relatively high, which may limit economic feasibility for widespread deployment. Additionally, achieving uniform dispersion and stable long-term performance under harsh underground environments requires further optimization. Addressing these issues will be critical for translating CNT-based resistance sensing from laboratory demonstrations to practical, large-scale UV-CIPP engineering applications.

4.3.2. Dielectric analysis–based methods

Dielectric analysis (DEA) enables indirect monitoring of the curing state of resin-based composites by tracking variations in ionic mobility, which are closely associated with resin viscosity and molecular mobility. In uncured resins, ions can move freely under an alternating electric field, contributing significantly to the dielectric response. As curing proceeds, polymer chain growth and crosslinking progressively restrict ion transport [106]. By exploiting the evolution of dielectric properties during curing, DEA provides a powerful means for real-time monitoring of the curing process.

During the curing reaction, changes in molecular structure, viscosity,

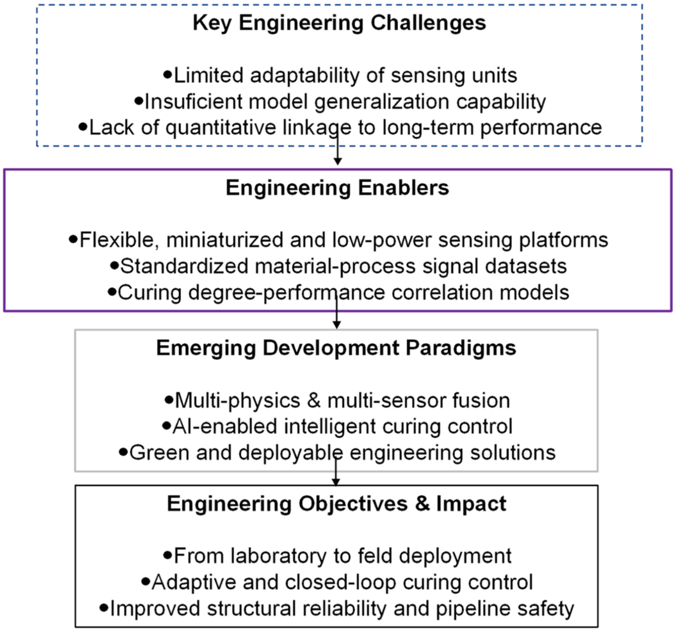

Fig. 10. Conceptual framework illustrating the key challenges, enabling technologies, emerging paradigms, and engineering objectives for intelligent monitoring and control of curing processes in advanced composite manufacturing.

and crosslink density lead to an increase in resistance to ionic motion, commonly described as ionic viscosity. Using capacitive or interdigitated dielectric sensors, dielectric parameters such as ionic conductivity and dielectric loss can be measured in situ. By establishing functional relationships between these dielectric parameters and the degree of cure, continuous online monitoring of curing progression can be achieved. Among these parameters, the dipolar response is often characterized by the dielectric loss factor D, expressed as [107]:

$$D = 1/\left(W \cdot C \cdot R \right) \tag{6}$$

where ω is the angular frequency of the applied alternating electric field, C is the dielectric capacitance, and R denotes the loss resistance.

The key dielectric parameters monitored by DEA—such as ionic conductivity and dielectric loss—are directly related to the polarity and flowability of the resin system. As early as the 1980s, NASA research groups [110] systematically established the foundational framework for using dielectric methods to characterize the curing behavior of thermosetting resins, laying the groundwork for subsequent studies. In the 1990s, further investigations deepened the understanding of the underlying mechanisms, with Kim *et al.* [111] demonstrating a clear correspondence between dielectric loss factors and degree of cure, validated through DSC measurements.

Since the early 21st century, dielectric monitoring has increasingly shifted toward engineering-oriented applications. On the one hand, research efforts have focused on enhancing monitoring reliability through multi-technique integration. For example, Nitin *et al.* [112] combined DEA with DSC to improve the prediction accuracy of curing progression. On the other hand, advances in sensor design and deployment strategies have significantly expanded application scenarios. Yenilmez *et al.* [113] arranged dielectric sensors sequentially within RTM molds to form a sensor network, enabling real-time online monitoring of resin flow paths and room-temperature curing behavior during the RTM process. Yang *et al.* [114,115] fabricated dielectric sensors on flexible substrates using printed circuit board (PCB) technology and successfully employed them for real-time monitoring of resin curing processes.

Dielectric monitoring offers several notable advantages for curing characterization. First, it is highly sensitive to curing reactions, particularly during the early stages, allowing timely detection of reaction onset and progression, which is critical for process adjustment and control. Second, dielectric sensors are typically non-contact or embedded capacitive devices, minimizing damage to the material and making them suitable for monitoring complex structures or inaccessible regions. Third, by establishing quantitative models linking dielectric parameters (e.g., ionic conductivity) to the degree of cure, DEA enables accurate prediction and continuous tracking of curing evolution.

Nevertheless, several limitations constrain the broader application of dielectric methods. The measured dielectric response is sensitive to impurities, moisture content, and environmental conditions, all of which can alter the dielectric properties of the material and interfere with accurate assessment of curing state. [106,116] Measurement accuracy is also highly dependent on sensor performance, necessitating high-precision sensing elements and stable signal acquisition systems. Moreover, due to variations in resin formulations, fiber surface insulation layers, and excitation frequencies, the relationship between dielectric parameters and degree of cure must often be calibrated for each specific material system and processing condition, resulting in limited generality of the models.

Overall, dielectric analysis represents a mature and industrially relevant technique for online monitoring of resin curing, particularly when combined with complementary sensing methods. Addressing issues related to environmental sensitivity, calibration robustness, and system adaptability will be essential for its effective application in complex engineering scenarios such as UV-CIPP composite pipeline rehabilitation.

4.3.3. *Radio frequency identification (RFID)–based methods*

During the transition of resin from the liquid to the solid state, its internal structure and physicochemical properties undergo substantial changes, accompanied by pronounced variations in dielectric permittivity. Dielectric permittivity characterizes the polarization capability of a dielectric material and reflects its ability to store electric energy. As curing progresses, molecular chain crosslinking and polymerization alter the distribution of polar groups and intermolecular interactions, leading to measurable changes in dielectric properties. These variations directly affect the electromagnetic coupling efficiency, signal attenuation, and propagation characteristics between embedded RFID tags and external readers, which are commonly manifested as changes in the received signal strength indicator (RSSI) [117].

By continuously monitoring the evolution of RFID signal parameters and establishing correlations between electromagnetic responses and curing behavior, online monitoring of the degree of cure can be achieved. This approach leverages the non-contact, wireless, and interference-resistant characteristics of RFID technology, effectively transforming microscale material evolution during curing into macroscopic electrical signals, thereby providing a novel pathway for monitoring the curing process of composite materials.

The application of RFID technology for curing monitoring in UV-CIPP systems primarily relies on the interaction between RFID tags and the surrounding composite material. Yuan *et al.* [120] investigated an RFID-based curing control strategy for UV-CIPP liners, enabling real-time monitoring of the curing process and reducing the risk of insufficient curing during pipeline rehabilitation. In addition, their study addressed the dimming control of ultraviolet mercury lamps to mitigate the effects of voltage fluctuations and temperature rise on light intensity stability. This integrated approach not only improved the curing quality of CIPP liners but also reduced unnecessary energy consumption, thereby enhancing the efficiency and reliability of trenchless pipeline rehabilitation.Veigt *et al.* [121] explored the integration of RFID tags into glass fiber–reinforced composites for curing monitoring applications. Through experimental investigations, a relationship between the RSSI of RFID transponders and the curing state of composite components was established. Comparative analysis with dielectric analysis methods demonstrated that such “curing transponders” are capable of effectively tracking the curing process.

Overall, RFID technology offers a wireless, passive, and easily integrable solution for online monitoring of the curing process in UV-CIPP resin-based composites. Its primary advantages lie in the ability of passive RFID tags to be embedded within composite structures, enabling non-contact, remote, and multi-point monitoring of curing states. However, several challenges currently limit its broader application. First, RFID-based monitoring is inherently indirect, requiring complex inverse models to translate electromagnetic signal variations into engineering parameters such as degree of cure or elastic modulus. These calibration procedures are often material- and process-specific, limiting model generality. Second, metallic pipeline structures, complex geometries, and moisture-rich environments can induce severe electromagnetic shielding and signal interference, significantly compromising signal transmission reliability and interpretation accuracy. Consequently, the robustness and repeatability of RFID-based curing monitoring under realistic and harsh field conditions remain to be further validated.

5. Engineering applicability analysis

Various techniques have been developed to monitor the curing behavior of composite materials, each with distinct advantages and limitations. Optical spectroscopy methods such as FTIR enable direct characterization of chemical bond conversion, while thermal analysis techniques like DSC provide accurate evaluation of curing kinetics; however, both methods are generally limited to laboratory environments due to their offline operation and instrumentation requirements. In contrast, sensing technologies including fiber Bragg grating (FBG), dielectric analysis (DEA), carbon nanotube (CNT) sensors, ultrasonic testing (UT), and RFID-based sensing offer greater potential for in situ monitoring. Among them, FBG and DEA exhibit high sensitivity to temperature, strain, and dielectric property evolution during curing, whereas CNT-based sensors provide distributed monitoring through conductive networks. RFID sensors further offer advantages in wireless monitoring and ease of integration, making them suitable for confined environments such as pipeline rehabilitation. In practical UV-CIPP engineering, distributed optical fiber sensing and embedded thermocouples have already been applied for field monitoring due to their reliability and relatively simple installation, enabling real-time tracking of temperature evolution during curing. By contrast, several emerging approaches, including dielectric analysis, infrared spectroscopy, and nanomaterial-based resistance sensing, remain primarily at the laboratory stage because of challenges related to sensor integration, durability, and maintenance in harsh environments. A comparative summary of these monitoring techniques is presented in Table 2.

Therefore, when selecting monitoring technologies for UV-CIPP rehabilitation projects, practical factors such as installation feasibility, long-term stability, and economic cost must be carefully considered. In general, temperature-based sensing methods are currently closer to engineering deployment, whereas multifunctional intelligent sensing systems integrating multiple monitoring principles remain at the research and development stage.

6. Outlook and future perspectives

The degree of cure monitoring of UV-CIPP resin-based composites constitutes a critical technical foundation for ensuring the structural integrity and long-term service performance of rehabilitated pipelines. This field has evolved from high-precision offline characterization to in-situ real-time monitoring and is currently advancing toward intelligent, closed-loop process control. Nevertheless, several core challenges remain to be addressed in this area.

First, most existing sensing units are based on rigid or quasi-rigid structures, which limits their adaptability to the confined, curved, and geometrically complex environments typical of municipal pipelines. Future efforts should therefore focus on the development of flexible, miniaturized, and low-power sensors, such as stretchable fiber Bragg gratings, ultra-thin RFID tags (<50 μm), and self-powered sensing units, to enable seamless integration into UV-CIPP liners. Second, current data-driven or physics-based models are often trained or calibrated for specific resin systems and curing conditions, resulting in limited generalizability across different materials and engineering scenarios. To overcome this limitation, large-scale, cross-material and cross-process datasets should be established, and advanced machine learning

Table 2
Comparison of typical monitoring techniques for curing processes in composite materials.

Method	Sensing principle	Monitoring target	Sensitivity	Spatial resolution	Cost	Operational complexity	Robustness	Engineering applicability
FTIR	Infrared absorption of chemical bonds	Functional group conversion / degree of cure	High (direct chemical characterization)	Local (surface or point measurement)	Medium	Moderate (requires optical instrumentation)	Moderate (affected by humidity and contaminants)	Low (mainly laboratory use)
DSC	Measurement of exothermic heat during curing	Reaction heat / degree of cure	High (laboratory reference technique)	Sample-averaged (no spatial distribution)	High	Low (offline and destructive)	High (controlled laboratory conditions)	Low
FBG	Wavelength shift caused by strain/ temperature variation	Temperature / strain evolution	High (high precision)	Distributed multi-point sensing	High	Moderate (sensor installation and calibration required)	High (immune to electromagnetic interference)	Medium
UT	Propagation of ultrasonic waves in materials	Elastic modulus / curing state	Medium	Local to near-surface	Medium	Moderate (requires coupling and signal interpretation)	Moderate (affected by geometry and medium)	Medium
CNT	Electrical resistance variation in conductive networks	Strain / curing-induced deformation	Medium	Distributed sensing network	Medium	Moderate (requires controlled dispersion and fabrication)	Moderate	Medium
DEA	Variation of dielectric properties during polymerization	Molecular mobility / curing kinetics	High (sensitive to early-stage curing)	Local to distributed	Medium	Relatively high (requires calibration and instrumentation)	Moderate (affected by humidity)	High
RFID	Wireless electromagnetic signal modulation	Temperature / strain / curing state (depending on sensor design)	Medium	Distributed multi-point sensing	Low	High (wireless, easy embedding)	Moderate (susceptible to shielding and interference)	High (suitable for confined pipeline environments)

strategies, including transfer learning and self-supervised learning, should be incorporated to enhance model robustness and adaptability. Third, most existing studies focus primarily on degree of cure as an isolated indicator, while the quantitative relationship between degree of cure and long-term performance, such as corrosion resistance, fatigue durability, and creep behavior, remains insufficiently understood. Addressing this gap requires systematic accelerated aging experiments and the development of predictive models linking degree of cure to long-term service performance.

Looking forward, the future development of UV-CIPP curing monitoring technologies can be broadly categorized into three synergistic directions.

(1) Multi-technology integration, where complementary sensing techniques—such as optical fiber sensing combined with RFID, or ultrasonic monitoring coupled with dielectric analysis—are jointly employed to balance local sensitivity and global coverage, thereby improving spatial completeness and monitoring reliability. For example, Tsamasphyros *et al.* [122] investigated the combined application of fiber Bragg grating and dielectric sensors for monitoring the curing process of bonded composite repairs. Kalkanis *et al.* [123] further studied the integration of dielectric sensors and FBG sensors to control the curing cycle of composite patch repairs. Sampath *et al.* [124] developed a fiber-optic monitoring system combining FBG sensors with Fresnel reflection measurements to improve cure-state identification. In addition, ultrasonic guided waves coupled with phase-shifted FBG sensors have also been explored for simultaneous monitoring of strain evolution and ultrasonic responses during composite curing [125].

(2) AI-driven and digital-twin-enabled intelligent monitoring, in which self-learning algorithms are integrated with real-time sensing data to establish closed-loop frameworks encompassing real-time monitoring, dynamic process optimization, and early-stage defect warning, ultimately reducing reliance on empirical operator experience.For example, Fernández et al. [126]developed a digital-twin framework for resin transfer molding processes to enable real-time monitoring and defect prediction. Xu et al. [127] further proposed a deep-learning-enhanced digital twin for complex composite structures, enabling real-time interaction between physical and virtual systems. Kamath *et al.* [128] established a machine-learning-based digital twin to predict curing evolution and optimize multizone heating during wind turbine blade manufacturing. In addition, Chai *et al.* [129] proposed an AI-enabled industrial IoT framework integrating multi-sensor data and machine learning models for intelligent monitoring and process prediction in composite manufacturing. Xia *et al.* [130] employed machine-learning algorithms to predict the bending strength of methacrylate-based UV-CIPP rehabilitation materials. Zhang *et al.* [131] further proposed an Archimedes optimization algorithm-based extreme gradient boosting model to improve the prediction accuracy of the bending strength of UV-cured GFRP composites. In addition, Wu *et al.* [132] developed a data-driven framework for predicting curing curves of thermoset composites, enabling more accurate characterization of curing kinetics. Meanwhile, Xia *et al.* [17] also investigated the bending damage behavior of UV-CGFR composites for pipeline rehabilitation through experimental and numerical approaches, providing important data support for intelligent modeling of material performance.

(3) Engineering-oriented implementation, emphasizing the translation of laboratory-scale sensing principles into robust, portable, and cost-effective engineering products, such as integrated sensing liners and handheld monitoring terminals, while also considering low-energy consumption, recyclability, and environmental sustainability in alignment with carbon-neutral development goals. For example, Glombitza *et al.* [133] developed a distributed fiber-optic temperature monitoring technique for verifying the curing state of CIPP liners in field installations. In addition, engineering monitoring systems based on distributed optical fiber sensing have been implemented to continuously record temperature profiles during liner curing, enabling data-driven verification of curing completeness. Konstantopoulos *et al.* [134] further studied in-situ monitoring of composite curing using integrated fiber optic and dielectric sensors, highlighting the feasibility of real-time monitoring during industrial composite production. Zhang *et al.* [135] developed an intelligent multifunctional composite material with integrated deformation and temperature sensing capabilities, enabling real-time monitoring of drainage pipelines and demonstrating the potential of embedding sensing functions directly into structural materials.

By addressing these challenges and advancing along the above directions, degree of cure monitoring technologies are expected to play a pivotal role in enabling intelligent, visualized, and large-scale controllable UV-CIPP rehabilitation, particularly for critical urban trunk pipelines, thereby providing a solid technical foundation for the safe and sustainable operation of underground pipeline networks.

7. Conclusion

This review examines the current technological landscape for monitoring the cure state of UV-CIPP composites, offering a critical assessment of methods spanning from fundamental principles to practical constraints. Traditional characterization techniques, such as FTIR and DSC, provide high accuracy in evaluating the degree of cure of resin-based composites; however, their inherent offline nature prevents real-time feedback, confining their application mainly to laboratory studies and post-process quality inspection. In contrast, emerging monitoring approaches—including fiber-optic sensing, ultrasonic techniques, electrical methods, and RFID—enable in-situ and real-time tracking of the curing process, yet each technique exhibits distinct limitations. FBG sensors offer high sensitivity and reliability but are associated with relatively high cost and complex deployment; ultrasonic methods are simple and non-destructive but are susceptible to environmental disturbances; dielectric analysis shows high sensitivity during the early curing stage but requires careful calibration across different material systems; RFID-based approaches enable regional or distributed monitoring but suffer from limited signal penetration and electromagnetic interference in complex pipeline environments.

In this context, the integration of artificial intelligence and digital twin technologies, supported by multi-source data fusion and virtual–-physical mapping, offers a promising strategy to overcome the constraints of individual sensing techniques. Such data-driven and model-assisted frameworks are expected to facilitate intelligent, adaptive, and closed-loop control of the UV-CIPP curing process, thereby enhancing process reliability, quality assurance, and long-term performance of rehabilitated pipelines.

CRediT authorship contribution statement

Peijie Wang: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Conceptualization. **Hengjing YU**: Writing – original draft, Visualization, Conceptualization. **Wenlin Jing:** Writing – original draft. **Wu Zhang:** Writing – review & editing, Writing – original draft. **Jingguo Cao:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Conceptualization. **Chunyan Gao:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Conceptualization.

Statement

During the preparation of this manuscript, the authors used ChatGPT to improve language clarity and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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