

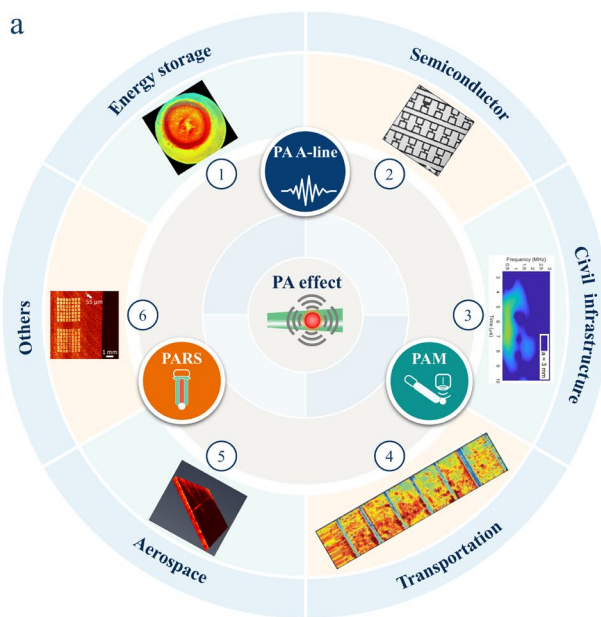
Photoacoustic nondestructive evaluation for material characterization: recent advances and future perspectives

Siqi Liang*, Myeongsu Seong and Sung-Liang Chen*

*E-mails: liangsiqi@hnust.edu.cn (S.L.); sungliang.chen@sjtu.edu.cn (S.L.C.)

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Graphical Abstract



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	Inspection target	Configuration	PA contrast / signal feature	Material information
①	Li deposits	PAM	PA signal amplitude and time-of-flight	Li height and morphology
②	Metallic microstructures	PARS	Strong contrast at the silicon-metal interface	Metal patterns and subsurface defects
③	Cracks in steel rods	PA A-line sensing	Centroid frequency	Crack depth
④	Rail surface defects	PAM	PA signal amplitude	Crack width and depth
⑤	CFRP damage	PAM	Strong optical absorption of carbon fibers	Multi-scale damage detection
⑥	Gold-coated silicon wafer	PARS	Optical absorption contrast between gold and silicon	Material differentiation

Highlights:

- PA NDE combines optical absorption contrast with acoustic information.
- PA NDE offers defect inspection, morphology monitoring and material characterization.
- Future development requires non-contact inspection and quantitative characterization.

Photoacoustic nondestructive evaluation for material characterization: recent advances and future perspectives

Siqi Liang^{1,2,*} , Myeongsu Seong^{3,4}  and Sung-Liang Chen^{5,*} 

¹ School of Information and Electrical Engineering, Hunan University of Science and Technology, Xiangtan, China

² Hunan Provincial Key Laboratory of Intelligent Control and Maintenance for Complex Systems, Hunan University of Science and Technology, Xiangtan, China

³ Academy of AI and Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou, China

⁴ Ruijin-XJTLU Intelligent Medicine Institute, Xi'an Jiaotong-Liverpool University, Suzhou, China

⁵ Global College, Shanghai Jiao Tong University, Shanghai, China

*E-mails: liangsiqi@hnust.edu.cn (S.L.); sungliang.chen@sjtu.edu.cn (S.L.C.).

Abstract: Photoacoustic (PA) nondestructive evaluation (NDE) is an emerging material characterization approach that converts optical absorption into acoustic information, enabling simultaneous access to optical absorption, structural features, and depth-dependent properties. Unlike conventional inspection techniques, PA NDE provides unique capabilities for quantitative evaluation of complex materials and structures. This Perspective summarizes recent advances in PA NDE platforms, including PA A-line sensing, PA microscopy, and all-optical PA systems such as PA remote sensing, and highlights their applications in energy storage, semiconductor manufacturing, civil infrastructure, transportation, aerospace, and other industrial fields. Representative examples demonstrate the potential of PA NDE for defect inspection, morphology monitoring, and material property characterization. Future development will require advances in non-contact inspection, wavelength-selective characterization, quantitative signal interpretation, image-based analysis, and measurement standardization. These efforts will be essential for translating PA NDE from laboratory demonstrations into reliable industrial characterization tools.

Keywords: photoacoustic nondestructive evaluation; material characterization; industrial inspection; photoacoustic microscopy; photoacoustic remote sensing; optical absorption contrast; quantitative characterization

1. Introduction

Photoacoustic (PA) nondestructive evaluation (NDE) is a hybrid approach to material characterization that converts optical absorption into acoustic information. When a material absorbs pulsed or intensity-modulated light, the deposited optical energy induces transient heating and thermoelastic expansion, which generate ultrasonic waves ^[1–5]. Through this mechanism, PA NDE combines two types of information that are typically separated in conventional inspection methods: optical absorption contrast and acoustic features, including time-of-flight and frequency-domain characteristics. These acoustic features are associated with material composition, structures (e.g., local defects), morphology, and depth distribution ^[1–3]. These capabilities extend the use of PA NDE beyond imaging to comprehensive material characterization.

In the conventional PA framework, the initial pressure is determined by the local optical fluence, optical absorption coefficient, and Grüneisen parameter ^[1]. PA signal amplitude

therefore depends on optical absorption, thermal expansion, heat capacity, and sound velocity. Acoustic arrival time and frequency spectra provide additional information about material depth and geometry ^[1,3]. These signal characteristics support the use of PA NDE in characterizing different materials. For example, lithium (Li) metal generates detectable PA signals for battery diagnostics ^[6–8]. Subsurface layers and thermal properties of semiconductor materials can be evaluated ^[9–13]. Defects in steels used for civil infrastructure can be identified through defect-induced variations in PA signals ^[14–16]. Carbon-fiber-reinforced polymers (CFRPs) used in aerospace applications can be visualized due to the strong optical absorption of carbon fibers ^[17–19].

Current PA NDE implementations can be broadly categorized into PA A-line sensing, PA microscopy (PAM), and all-optical PA systems, particularly PA remote sensing (PARS) ^[1]. All-optical PA systems can also be configured for PA A-line sensing and PAM. PA A-line sensing provides depth-resolved information and can be used for near-surface defect evaluation ^[20,21]. In comparison, PAM extends

A-line detection to spatially distributed measurements, enabling two- and three-dimensional visualization of micron-scale features [7,18,19]. All-optical non-contact PA configurations, such as PARS, enable absorption-contrast imaging without acoustic coupling media. This capability is advantageous for inspecting critical industrial materials, including semiconductor wafers and batteries [9,22], where physical contact or coupling materials may interfere with the inspection process. Recent voice-coil-based PARS systems have further demonstrated the potential of non-

contact PA inspection for centimeter-scale fields of view, depth-resolved visualization, material differentiation, and surface roughness characterization [23]. Figure 1 provides an overview of PA NDE by illustrating three widely adopted implementation strategies and six current industrial applications. PA A-line sensing emphasizes signal analysis, PAM enables spatially resolved PA imaging, and PARS provides non-contact optical detection. Their principal capabilities and representative applications are compared in Table 1.

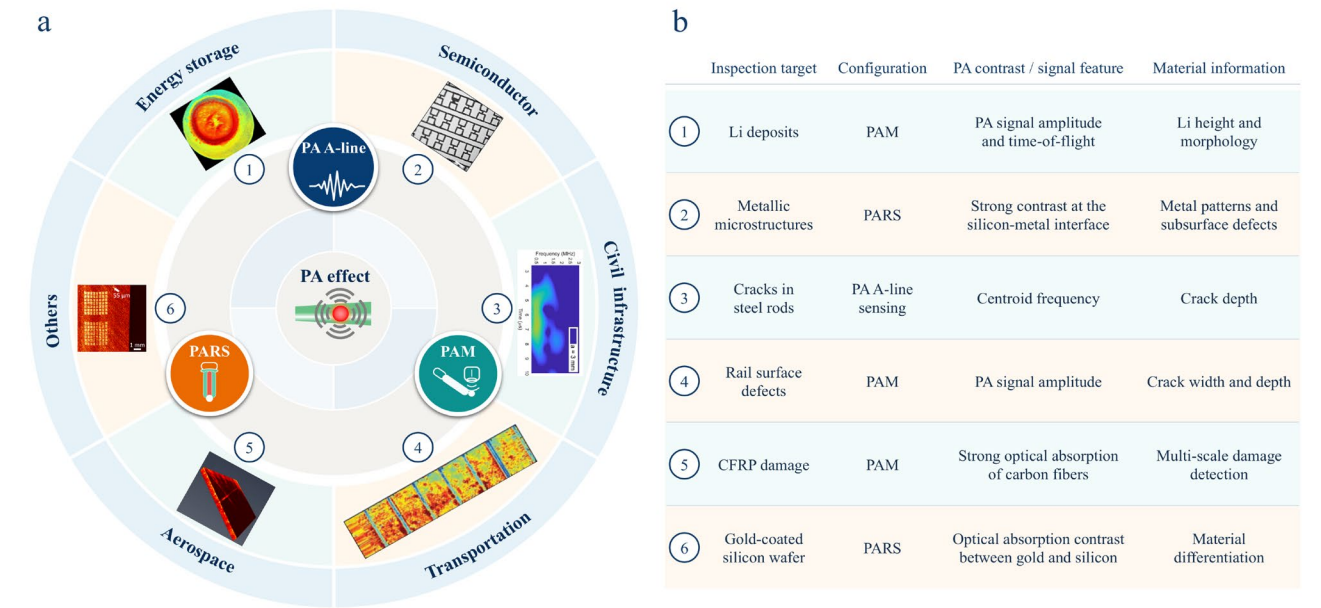


Figure 1. Overview of PA NDE for material characterization. **(a)** PA A-line sensing, PAM, and PARS provide complementary measurement strategies for applications in energy storage, semiconductors, civil infrastructure, transportation, aerospace, and other fields. The outer ring presents representative applications arranged clockwise from the upper-left sector: a height-encoded PAM image of Li deposits [8], a PARS image of metallic microstructures in silicon-based chips [9], a PA spectrogram for crack analysis in steel rods [16], a PAM image of rail surface defects [21], a three-dimensional PAM image of microscale damage in CFRP composites [19], and a PARS image of a gold-coated silicon wafer [23]; **(b)** Rows 1–6 correspond to the numbered examples in **(a)** and summarize their inspection targets, configurations, PA contrast or signal features, and material information.

Table 1. PA NDE platforms and their representative material characterization applications.

PA platform	Main capability	Representative material characterization applications
PA A-line	Thermal characterization, depth profiling, and near-surface defect detection	Semiconductor materials, transportation infrastructure
PAM	Two- and three-dimensional visualization of micron-scale features	Energy storage, transportation, and aerospace materials
PARS	Non-contact absorption-contrast imaging	Energy storage, semiconductor inspection, and surface metrology

PA NDE is unique in providing optical absorption contrast [4,24]. It also enables depth-resolved imaging of subsurface absorbers beyond the capabilities of surface-based optical inspection [7,25]. In addition, PARS, an all-optical PA system, enables non-contact detection without acoustic coupling media [9]. By combining optical absorption contrast with acoustic information, PA NDE enables the extraction of material information that may be challenging

to obtain using other measurement techniques. This Perspective focuses on the applications of PA NDE in industrial material characterization, including defect inspection, morphology monitoring, and quantitative material property evaluation, across major sectors such as energy storage, semiconductor manufacturing, civil infrastructure, transportation, aerospace, and other industrial fields.

2. Applications

2.1. Energy storage: lithium metal batteries

Li metal batteries are promising high-energy-density storage devices. However, their practical implementation is hindered by dendrite formation and capacity loss caused by nonuniform Li deposition^[26,27]. Conventional electron microscopy provides primarily two-dimensional images of Li, while demanding sample preparation can hinder nondestructive or *in situ* observation. X-ray computed tomography enables three-dimensional imaging but suffers from poor contrast for low-density Li^[6,7]. By exploiting the optical absorption of Li, PAM has demonstrated nondestructive three-dimensional imaging and operando monitoring of Li growth with high contrast^[6,7]. Subsequent studies revealed accelerated formation of electrically isolated (“dead”) Li with distinct three-dimensional morphologies during battery cycling^[8].

A representative milestone in this field is the MEMS-based operando PAM study of Li plating dynamics^[6]. This study enabled real-time monitoring of Li plating and demonstrated that Li deposition became increasingly nonuniform during cycling, ultimately resulting in heterogeneous growth. PAM provides strong contrast for Li, with the PA signal from Li being approximately three times stronger than that from the copper substrate. Moreover, its depth-resolved capability enables the conversion of time-of-flight information into Li height, allowing three-dimensional Li structures and morphologies to be reconstructed. Combined with the rapid-scanning capability of MEMS, PAM further enables repeated imaging for operando monitoring, thereby allowing Li growth dynamics to be tracked over time. In this study, 80 image frames were acquired over 60 min at 2 mA cm⁻², and Li height evolution was tracked over a 2 mm × 3.2 mm area with approximately 100,000 pixels per frame. By dividing each frame into 1000 subregions, the study revealed that Li plating initially followed diffusion-controlled growth and subsequently evolved into explosive, steady, or diminishing growth patterns. This quantitative PAM analysis provides insights into how local variations in Li growth contribute to nonuniform Li deposition and offers a pathway toward understanding and mitigating dendrite-related failures. Nevertheless, the reported operando PAM configuration required water coupling for ultrasound detection and an optically accessible battery design.

2.2. Semiconductor: porous silicon, n-type silicon, and silicon chips

Characterization of silicon nanostructures, including porous silicon and n-type silicon, and non-destructive inspection of metallic microstructures in semiconductor chips are critical for semiconductor manufacturing. PA NDE provides

unique capabilities for differentiating these structures and evaluating their properties. Beyond structural imaging, PA NDE has been used to monitor refractive index changes during porous silicon etching^[10] and to evaluate thermal conductivity, heat capacity, and thermal diffusivity of silicon nanostructures^[11,12]. Furthermore, neural-network processing of PA A-line signals has replaced conventional iterative fitting approaches, enabling simultaneous and real-time determination of the thermal and elastic properties of n-type silicon^[13].

A representative milestone for semiconductor inspection is the PA NDE of metallic microstructure in semiconductor chips^[9]. This work achieved a lateral resolution of approximately 2.3 μm and applied PARS microscopy using a 1030 nm pulsed laser to inspect internal defects in silicon-based semiconductor chips. The study demonstrated that PARS microscopy could generate strong contrast at the silicon-metal interface, compared with the silicon-air interface, enabling clear visualization of metal patterns and subsurface defects beneath a silicon layer several hundred micrometers thick (525 μm) over a large field of view, which cannot be observed using conventional optical microscopy. This contrast originates from the high optical absorption coefficient of aluminum at 1030 nm, which induces strong local heating and a large PA pressure, resulting in a greater refractive-index change at the silicon-metal interface than at the silicon-air interface. Meanwhile, the near-infrared excitation wavelength enables penetration to depths of several hundred micrometers in silicon because of its relatively weak absorption at this wavelength. Accordingly, a depth-to-resolution ratio of around 200 was achieved. More importantly, the absence of acoustic coupling and physical contact supports the potential of PARS for nondestructive industrial inspection applications. Nevertheless, galvanometer scanning in this system caused slight inhomogeneity within each PARS image.

2.3. Civil infrastructure: steel rebar and steel rods

Steel rebar and steel rods are essential components of civil infrastructure. However, hidden corrosion and cracks can compromise structural safety. Traditional fiber-based monitoring methods often rely on passive configurations, which limit their sensitivity to early-stage subsurface defects. In contrast, all-optical PA systems provide active interrogation and enable corrosion evaluation by quantifying steel rebar mass loss based on spectral variations in PA signals^[14]. Subsequent studies also demonstrated early-stage steel rebar corrosion detection using all-optical PA systems^[15].

An all-optical PA system has also been used for temperature and crack detection in steel rods^[16]. In this study, PA signals from steel rods were recorded, and short-time Fourier transform was applied to generate their spectrograms.

The time-of-flight of the spectrogram centroid was used for temperature measurement, whereas the centroid frequency was used for crack detection. Empirical equations were developed to quantify temperature changes and crack depths. These results show how PA signal features can be used to quantify temperature variations and crack depths for structural health monitoring. However, the reported configuration could monitor only a single location on a structural component.

2.4. Transportation: steel rails and sleeper rebar

Steel rails and sleeper rebar are critical railway components. Surface microcracks in these components can compromise railway safety. Conventional ultrasonic NDE has limited capability for visualizing small defects, whereas PA NDE enables defect visualization and quantitative evaluation^[20,21]. Early studies established PA imaging systems to identify rail crack morphology and depth^[20]. Subsequent work employed multiphysics simulation and time-reversal reconstruction to improve PA imaging resolution for rail defect quantification^[21].

PA NDE has also been applied to micron-scale crack detection in sleeper rebar using a gold-Polydimethylsiloxane (PDMS) nanocomposite PA transmitter^[28]. In this study, the nanocomposite transmitter was used to generate PA signals under 532 nm pulsed laser excitation. The detected PA signals were analyzed using signal amplitude, dominant frequency, and delay time as quantitative features. These features were correlated with microcrack size, enabling quantitative detection of microcracks in sleeper rebar. This work demonstrated how transmitter design and PA signal analysis can be combined for quantitative microcrack inspection in railway components. However, the quantitative relationships were established using simulated cracks in rebar.

2.5. Aerospace: CFRP composites, thermal barrier coatings, and turbine blades

CFRP composites and turbine blades are critical aerospace components that require reliable nondestructive inspection for detecting defects and impact-induced damage. Early PA imaging studies reconstructed embedded and barely visible damage in CFRP composites in three dimensions with a spatial resolution of approximately 100 μm ^[18]. Subsequent work further improved the spatial resolution to 60 μm , enabling multi-scale damage detection in CFRP composites^[19]. Beyond damage detection in CFRP composites, non-contact PA imaging has been used to visualize debonding defects in thermal barrier coatings, which protect high-temperature components in gas turbines and aeroengines^[29].

A representative milestone for aerospace inspection is the PA NDE study investigating the influence of gas

turbine blade thickness on PA signals^[30]. This study investigated the influence of blade thickness on acoustic wave propagation by introducing defects at different depths and in regions with varying blade thicknesses. The results demonstrated that material thickness affected defect detection accuracy by influencing the propagation characteristics, affecting the types, velocities, and frequencies of PA signals. This understanding was further used to guide PA imaging-based detection and characterization of defects at different depths within gas turbine blades. However, crack depth remained difficult to determine directly from PA images.

2.6. Other applications: ceramics, welded aluminum plates, flexible printed circuit boards, aluminum foils, metal-matrix composites, paintings, and silicon wafers

Several industrial materials and components, including ceramics, welded aluminum plates, flexible printed circuit boards, aluminum foils, metal-matrix composites, paintings, and silicon wafers, require high-precision nondestructive characterization. In ceramic additive manufacturing, PA imaging detected surface and subsurface defects in ceramic paste layers^[31]. In addition, PAM has been used to detect surface and internal weld defects in aluminum plates^[32]. For electronics inspection, PA imaging combined with optical coherence imaging provides complementary contrast for detecting internal delamination and defects in flexible printed circuit boards^[33]. Beyond defect detection, neural-network-assisted PA measurements enabled simultaneous quantification of the thermal diffusivity and linear thermal expansion coefficient of aluminum foils^[34]. In isotropic metal-matrix composites, PA NDE has been used to determine the local Young's modulus and quantitatively evaluate the effect of porosity on this modulus^[35]. Meanwhile, dual-wavelength PA imaging revealed hidden underdrawings and mapped paint-layer thickness in paintings^[36].

A representative milestone for industrial characterization is the wide-field PARS study of gold-coated silicon wafers^[23]. Voice-coil scanning was employed to expand the imaging field of view and achieve rapid acquisition while maintaining non-contact optical detection. The system scanned a $2 \times 2 \text{ cm}^2$ field of view in less than 6 min and obtained three-dimensional visualizations. Because gold and silicon exhibit distinct optical absorption contrasts at the 532 nm excitation wavelength, this study demonstrated that PARS microscopy can differentiate these two materials using a single wavelength based on PA amplitude. Despite these diverse applications, most demonstrations have focused on surface characterization because of the limited penetration depth of PARS.

Table 2 summarizes the corresponding materials, characterization capabilities, and references discussed above.

Table 2. PA NDE applications.

Application sector	Materials and key capabilities	References
Energy storage	Li metal: operando morphology and growth monitoring	[6–8]
	Porous silicon/n-type silicon: optical and thermal characterization	[10–12]
Semiconductor	N-type silicon: thermal and elastic characterization	[13]
	Silicon chips: subsurface defect inspection	[9]
Civil infrastructure	Steel rebar: corrosion-related parameter evaluation	[14,15]
	Steel rods: temperature and crack-depth quantification	[16]
Transportation	Steel rails: crack imaging and defect quantification	[20,21]
	Sleeper rebar: microcrack quantification	[28]
	CFRP composites: damage imaging	[18,19]
Aerospace	Thermal barrier coatings: debonding imaging	[29]
	Turbine blades: defect imaging and characterization	[30]
	Ceramics: defect monitoring	[31]
	Welded aluminum plates: weld-defect detection	[32]
	Flexible printed circuit boards: delamination and trace-defect inspection	[33]
Other applications	Aluminum foils: thermal property measurement	[34]
	Metal-matrix composites: local Young’s modulus measurement	[35]
	Paintings: stratigraphic imaging	[36]
	Silicon wafers: material differentiation	[23]

3. Perspective

PA signal amplitude generally increases with optical fluence; however, PA NDE must avoid altering component surfaces or microstructures during inspection. Excessive peak fluence or cumulative optical exposure may induce ablation, microcracking, or changes in optical, thermal, and mechanical properties. The damage threshold depends on multiple factors, including excitation wavelength, pulse duration, repetition rate, spot size, scanning speed, surface morphology, optical absorption, and thermal properties. Material-specific limits for peak fluence and cumulative optical dose should be established for clearly specified inspection conditions. Within these limits, optimized wavelength selection, sensitive detection, beam shaping, and adaptive exposure strategies could improve PA signal quality while minimizing laser-induced damage.

Conventional acoustic coupling requirements limit the range of industrial samples that PA NDE can inspect. PARS enables absorption-contrast imaging without contact receivers or acoustic coupling media, which reduces contamination and contact-induced perturbations. Demonstrated applications include imaging metallic microstructures beneath silicon layers [9], characterizing gold-coated silicon wafers [23], and imaging Li-metal batteries [22]. These studies highlight the potential of

PARS to extend PA NDE beyond contact-based inspection. Future applications may expand into semiconductor, energy-storage, and precision-manufacturing industries, particularly for inspection processes where coupling media or probe contact may interfere with fabrication or compromise product quality. However, PARS requires additional interrogation-light components with precise optical alignment, which can increase system complexity and reduce system robustness. This factor should also be considered in practical implementations.

Excitation wavelength provides PA NDE with spectrally selective material contrast. Future studies should select excitation wavelengths based on the target absorber, inspection depth, and desired material parameter. The penetration depth for inspection is limited by the optical penetration at the selected excitation wavelength in PA NDE. Visible excitation, such as 532 nm, can enhance contrast from strongly absorbing materials and defect-related structures in Li-metal and steel inspections [6,7,16]. At 808 nm, PA responses can monitor optical changes during porous silicon etching [10]. At 1030 nm, PARS enables non-contact inspection of metallic microstructures and internal defects beneath silicon layers [9]. Beyond single-wavelength excitation, multispectral or spectroscopic PA approaches can distinguish different absorbers by analyzing their wavelength-dependent PA responses [3]. Dual-wavelength PA imaging of paintings illustrates

how measurements at different wavelengths provide complementary information on hidden underdrawings and overlying paint layers [36]. Establishing quantitative relationships between excitation wavelength and extracted material parameters could enable more selective and reliable material characterization.

Interpretable PA NDE requires establishing clear relationships between measurable PA signal features and material parameters. PA amplitude and wavelength-dependent responses can provide information on material absorption and contrast [1]. In specific applications, acoustic spectral features have been correlated with crack depth [16]. Frequency-dependent PA signals have also been used to estimate thermal parameters, including thermal diffusivity, thermal conductivity, heat capacity, and thermal expansion [11–13,34]. These examples show that PA signals contain information about multiple material properties. However, measured PA frequency-domain characteristics can be influenced by both the target material, including its size, geometry, and properties, and the measurement system, including detector bandwidth and frequency response. Future work should develop quantitative models that incorporate optical absorption, structural geometry, thermal properties, and system frequency response. These models should clarify the relationships between specific PA signal features and material parameters.

PAM and PARS images contain quantitative information beyond qualitative visualization. For example, PAM images of Li deposits have been used to quantitatively analyze Li growth patterns [6], while PARS microscopy images have enabled quantitative evaluation of surface roughness [23]. For large-area inspection, however, expanding the field of view while maintaining high spatial resolution increases inspection time. Future studies should use the quantitative information in PA images to extend PA NDE from feature visualization to quantitative material characterization.

PA NDE requires measurement consistency across repeated scans, instruments, and inspection sessions. PA amplitude, arrival time, frequency features, and image intensity distributions can vary with changes in laser pulse energy, focus position, detector sensitivity, and acoustic coupling conditions. In long-term monitoring, these variations may introduce errors into extracted parameters, including crack depth, coating thickness, and surface roughness. Future work should establish calibration procedures, particularly for system sensitivity, under practical inspection conditions. Long-term PA NDE should report detected features together with the uncertainty and stability of extracted quantitative parameters.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, ChatGPT was used to assist with drafting and language editing. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, S.L. and S.L.C.; investigation, S.L.; writing—original draft preparation, S.L.; writing—review and editing, S.L., M.S. and S.L.C.; supervision, S.L.C.; funding acquisition, S.L., M.S. and S.L.C.; scientific discussions, M.S. All authors have read and approved the final version of the manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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