

Article

Multi-Feature Characterization and Numerical Simulation of Interfacial Damage in Thermal Barrier Coatings Using Immersion Ultrasonics

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Highlights

What are the main findings?

- Immersion ultrasonics from the substrate side gives high-SNR echoes for tracking TBC delamination.
- FFT, CWT and WPEE together outperform single time-domain amplitude for early TBC damage detection.
- Four-layer FE model reproduces wave propagation, matching experiments and validating the NDE method.

What is the implication of the main finding?

- The proposed NDE approach enables detect ability of interfacial spallation in aero engine hot sections.
- Multi domain feature fusion reduces noise interference and improves damage stage identification reliability.
- The validated FE simulation provides a theoretical basis for optimizing inspection parameters.

Abstract

Owing to their exceptional thermal insulation and protective capabilities, thermal barrier coatings (TBCs) are widely applied to critical hot-section components of aero-engines. However, under increasingly harsh service environments, internal defects such as delamination tend to form within the coatings, posing a severe threat to engine operational safety and service life. To effectively evaluate delamination defects in TBCs, this study employs the immersion ultrasonic pulse-echo technique to inspect specimens subjected to various thermal cycling treatments. Four specimens, subjected respectively to 21, 32, 43, and 54 thermal cycles at 1200 °C, were tested. Ultrasonic response data were systematically acquired via normal incidence scanning from both the superalloy substrate side and the ceramic top coat side. Combining Fast Fourier Transform (FFT), Continuous Wavelet Transform (CWT) based on the generalized Morse wavelet, Wavelet Packet Energy Entropy (WPEE), and peak-to-peak amplitude variations of the second echo, multi-dimensional features were extracted from ultrasonic signals across the frequency domain, joint time-frequency domain, and energy distribution profiles. Through comparative analysis, ultrasonic waveform and



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time-frequency characteristics representing defect evolution were obtained. A significant monotonically decreasing trend of WPEE with the aggravation of interfacial delamination was established, characterizing the acoustic energy confinement process induced by interfacial damage. Furthermore, a multilayer finite element (FE) model reasonably reproduced dynamic acoustic wave propagation; numerical results are in agreement with experimental data, validating the feasibility of the proposed detection method. The detection and evaluation framework established in this study provides a reference for safety monitoring and lifespan prediction of aero-engine TBCs.

Keywords: thermal barrier coatings; immersion ultrasonic testing; defect detection; wavelet packet energy entropy; finite element simulation

1. Introduction

Research on thermal barrier coatings originated in the late 1940s, and NASA pioneered their application to aero-engine turbine blades in the 1970s. TBCs significantly reduce the substrate temperature of hot-section components, delivering critical benefits including high-temperature oxidation and corrosion resistance, prolonged component service life, and enhanced engine performance [1–5]. With the growing demand for higher performance metrics such as thrust-to-weight ratio in the aviation industry, turbine blades operate under increasingly harsh service conditions. This renders TBCs susceptible to internal defects and premature spallation, which drastically shortens the coating service life and poses a severe threat to the safe and reliable operation of aero-engines [6–8]. Accordingly, developing reliable non-destructive testing methods for early TBC delamination is of critical engineering significance.

Bilayer thermal barrier coatings are the mainstream configuration in the aviation industry, consisting of a yttria-stabilized zirconia (YSZ) ceramic top coat and an MCrAlY (M = Ni, Co, or NiCo) bond coat deposited on a superalloy substrate [9]. Owing to the thermal expansion coefficient mismatch between the two constituent layers and harsh high-temperature service conditions, a thermally grown oxide (TGO) layer typically forms at the ceramic–bond coat interface, which subsequently initiates internal cracks in the coating system. Progressive crack propagation to the coating surface ultimately triggers spallation, a failure mode that severely compromises aero-engine service life [10–12]. Accordingly, deploying effective non-destructive testing (NDT) techniques for TBCs is critical, as it enables real-time monitoring of internal interfacial delamination and provides key data to support timely repair, thus guaranteeing the long-term safe and stable operation of aero-engine systems [13].

To date, a wide spectrum of non-destructive testing techniques has been established for thermal barrier coatings, among which ultrasonic testing, digital imaging, microwave sensing, terahertz technology, and eddy current testing are the most widely adopted. For ultrasonic detection, Wei et al. evaluated the anisotropic mechanical properties of thermally exposed coatings [14], and Dou et al. developed an immersion ultrasonic testing approach to resolve TBC thickness measurement challenges [15]. For characterization-based methods, Zhang et al. applied digital imaging to analyze the interfacial failure behavior of TBCs under thermal shock [16]. For thickness-oriented measurement, Rahman achieved high-precision coating thickness detection using microwave resonant sensors [17], while Cao et al. demonstrated terahertz-based thickness measurement for constrained TBC specimens [18]. For interfacial defect identification, Kim et al. utilized eddy current resonance to detect coating delamination defects [19]. Notably, accurate thickness measurement is inevitably

affected by internal defects including delamination and porosity, and conversely, internal defect detection in TBCs can be intrinsically framed as the identification and quantification of thickness parameters. While existing NDT methods have delivered substantial progress in thickness measurement, porosity assessment, and surface defect characterization, gaps remain for sensitive detection of early interfacial delamination in TBCs: (1) Conventional contact ultrasonic testing [20] can suffer from unstable coupling conditions, including probe pressure fluctuations and non-uniform couplant thickness. These variations introduce additional signal noise, making it more difficult to resolve weak echoes from early micro-delamination. (2) Existing immersion ultrasonic C-scan studies for TBCs [21,22] predominantly use time-domain echo amplitude as the imaging feature. While effective for identifying macroscopic, fully developed delamination, this single-parameter approach often has limited sensitivity to track progressive microcrack growth prior to spallation. (3) WPEE has been demonstrated as a sensitive feature for defect detection in welds [23] and concrete structures [24], as it quantifies ultrasonic energy redistribution during damage evolution. However, this method has rarely been applied to immersion ultrasonic evaluation of TBC delamination, and its capability for early micro-damage characterization in coating systems remains largely unvalidated.

To address these challenges, the immersion ultrasonic pulse-echo technique is employed in this study. By virtue of its inherent non-contact nature, this technique eliminates coupling-related interferences, delivering a high signal-to-noise ratio and stable signal output. This makes it well-suited for capturing the faint acoustic responses induced by early-stage micro-delamination [25].

In this work, the immersion ultrasonic pulse-echo technique is adopted to systematically investigate the internal delamination behavior of TBCs after isothermal thermal cycling with varying cycle numbers, combined with numerical simulations to visually reproduce the ultrasonic propagation process in specimens with different delamination degrees. For TBCs applied to aero-engine turbine blades, ultrasonic waves are introduced at normal incidence from both the superalloy substrate and ceramic top coat sides, and their echo responses are collected and analyzed to achieve effective characterization of internal defects and interfacial delamination under high-temperature service conditions.

The main contributions of this work are threefold: (1) WPEE is introduced to immersion ultrasonic testing of TBCs, combined with generalized Morse wavelet-based CWT for multi-domain feature extraction. This framework enables sensitive characterization of early interfacial damage, improving sensitivity over conventional single time-domain amplitude analysis for tracking progressive microcrack growth. (2) The physical mechanism of “acoustic energy trapping” associated with TBC delamination is investigated: the air gap from delamination blocks nearly all ultrasonic transmission into the ceramic top coat, traps energy in the bond coat and substrate, and is consistent with the observed monotonic WPEE reduction, second echo amplitude increase, and main frequency shift. The coupled evolution of these multi-parameter features shows promise as indicators for damage stage identification. (3) A four-layer finite element model is developed to simulate transient ultrasonic propagation in both intact and delaminated TBCs. The numerical results are in reasonable agreement with experimental measurements, providing supporting numerical evidence for the acoustic reflection and reverberation mechanisms during delamination.

The rest of this paper is structured as follows. Section 1 elaborates the research background and objectives. Section 2 covers the theoretical fundamentals of ultrasonic signal processing and analysis. Section 3 details the implementation of the immersion ultrasonic pulse-echo experiment, and analyzes the evolution of ultrasonic signal features with thermal cycle counts from a multidimensional perspective. Section 4 constructs a finite element model to simulate the dynamic propagation of acoustic waves in the multilayer

coating structure and extract simulated echo signals. Section 5 conducts an integrated discussion of experimental and simulation results. Section 6 concludes the work and summarizes the core findings.

2. Theoretical Fundamentals

2.1. Theoretical Model of Ultrasonic Propagation and Reflection

Drawing upon the established elastodynamic theory of longitudinal wave propagation in multilayered media [26]. Immersion ultrasound in a homogeneous isotropic elastic medium propagates predominantly in the form of longitudinal waves. The propagation along the thickness direction (denoted as the z -axis) is governed by the one-dimensional wave equation:

$$\frac{\partial^2 u(z, t)}{\partial t^2} = c^2 \frac{\partial^2 u(z, t)}{\partial z^2} \quad (1)$$

where $u(z, t)$ is the particle displacement, c is the acoustic wave velocity in the medium, and t is time.

When ultrasonic waves propagate through a multilayered structure or encounter delamination within the coating, they undergo reflection and transmission at each interface due to the mismatch in acoustic impedance Z between different media.

If the ultrasonic testing system is regarded as a linear time-invariant system, the time-domain signal $x(t)$ received by the ultrasonic transducer can be expressed as the convolution of the incident pressure pulse $p(t)$ and the impulse response $h(t)$ of the test specimen, plus additive environmental noise. Mathematically, the model is given by:

$$x(t) = p(t) * h(t) + n(t) \quad (2)$$

where $*$ is convolution, $n(t)$ is additive noise from the DAQ system and environment, and $h(t)$ captures the specimen's multi-interface reflection behavior, approximated as an impulse train with varying amplitudes and time delays:

$$h(t) = \sum_{i=1}^N R_i \delta(t - \tau_i) \quad (3)$$

where R_i is the acoustic pressure reflection coefficient and τ_i the round-trip time for the i -th interface, and $\delta(t)$ is the Dirac delta function. Coating delamination evolution alters the acoustic impedance profile, which is reflected in corresponding changes to R_i and τ_i in the received echo.

2.2. Time-Frequency Feature Characterization Based on Continuous Wavelet Transform

From the physical model established above, the noise component $n(t)$ in the raw signal $x(t)$ received by the ultrasonic transducer in practical measurements typically consists of high-frequency Gaussian white noise and low-frequency baseline drift. Since weak echoes from delamination interfaces are easily masked by noise, we first preprocess the raw signal $x(t)$ to accurately extract informative features from the impulse response $h(t)$. Given that ultrasonic echoes are inherently non-stationary, we perform 5-level wavelet decomposition using the sym4 wavelet. This wavelet basis closely matches ultrasonic pulse waveforms. Coupled with hard-threshold denoising, the decomposition effectively suppresses high-frequency Gaussian white noise while maximally preserving echo peaks and temporal features. After denoising, a 6th-order high-pass Butterworth filter with a 10 MHz cutoff frequency is applied to suppress low-frequency baseline drift caused by

water column fluctuations or instrumental thermal drift. After this combined filtering step, we finally obtain a clean analytical signal $x_f(t)$.

We perform time-frequency analysis on the preprocessed signal $x_f(t)$ using the CWT. By translating and scaling the mother wavelet $\psi(t)$, CWT achieves multiresolution time-frequency localization and is mathematically defined as:

$$W_x(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x_f(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (4)$$

where $W_x(a, b)$ denotes the wavelet coefficients, a denotes the scale parameter, b denotes the translation parameter, and $\psi^*(t)$ denotes the complex conjugate of the mother wavelet.

In this work, we adopt the generalized Morse wavelet (GMW) as the mother wavelet for the CWT, supported by its established applications in non-stationary fault diagnosis and structural anomaly detection [27,28]. The GMW constitutes a family of strictly analytic superwavelets that eliminates the ambiguity arising from negative frequency components. Compared with conventional wavelets, the GMW achieves superior time-frequency localization and resolution, as well as better feature aggregation, for processing high-frequency, non-stationary, attenuated ultrasonic signals [29]. Its frequency-domain expression is given by:

$$\Psi(\omega) = U(\omega) \cdot a_{\beta, \gamma} \cdot \omega^{\beta} \cdot e^{-\omega^{\gamma}} \quad (5)$$

where $U(\omega)$ is the unit step function, γ is the time-domain symmetry parameter, and β the parameter controlling frequency-domain decay.

To visualize the dynamic evolution of ultrasonic signal features with the number of thermal cycles, we extract the magnitudes of the CWT-derived wavelet coefficients to generate time-frequency amplitude maps. The amplitude at a given time b and scale a is given by:

$$A(a, b) = |W_x(a, b)| \quad (6)$$

Subsequently, we convert the dimensionless scale parameter a to the physical frequency f via the center-frequency method. The resulting 2D time-frequency maps use color mapping to encode the instantaneous amplitude across different frequency bands, revealing the evolution of the material's internal structure under thermal cycling.

2.3. Wavelet Packet Energy Entropy

During thermal cycling, the evolution of microscopic pores and incipient interfacial delamination in thermal barrier coatings produces only subtle changes in the amplitude and temporal characteristics of ultrasonic echoes. Limited by the resolution of conventional time- and frequency-domain analyses, these subtle nonlinear features are barely detectable. It is therefore critical to adopt an information entropy perspective: as internal micro-defects evolve into macroscopic delamination, the severe acoustic impedance mismatch introduced by the air gap dominates acoustic reflection, driving the rapid concentration of received signal energy within the primary reflection band and reducing the uncertainty of the system acoustic response. Consequently, this entropy shift serves as a highly sensitive indicator for detecting early-stage delamination and microstructural degradation.

The conventional discrete wavelet transform (DWT) iteratively decomposes only the low-frequency components of a signal, limiting its time-frequency resolution when processing non-stationary ultrasonic signals rich in high-frequency transient components. In contrast, the wavelet packet transform (WPT) orthogonally decomposes both low- and high-frequency subbands, delivering finer time-frequency localization across the full frequency band.

Owing to the multi-scale coupled non-stationary behavior of ultrasonic signals caused by delamination, the WPT-based information entropy method (WPEE) achieves superior time-frequency localization, simultaneously capturing transient reflection pulses in the time domain and energy dispersion in the frequency domain. This enables clear characterization of the evolution of ultrasonic energy distribution from disorder to order throughout delamination progression, providing an effective approach for early damage identification.

Considering the characteristics of the received ultrasonic testing signals, we select the WPEE derived from a 4-level wavelet packet decomposition as the key feature metric. Let $x(t)$ denote the original ultrasonic signal. The wavelet packet basis is generated by the scaling function $\phi(t)$ and the wavelet function $\psi(t)$. Let $u_0(t) = \phi(t)$ and $u_1(t) = \psi(t)$. The recursive relations for wavelet packet decomposition are then given by the two-scale difference equations:

$$\begin{cases} u_{2n}(t) = \sqrt{2} \sum_k h(k) u_n(2t - k) \\ u_{2n+1}(t) = \sqrt{2} \sum_k g(k) u_n(2t - k) \end{cases} \quad (7)$$

where $h(k)$ denotes the low-pass filter coefficients corresponding to the scaling function, $g(k)$ the high-pass filter coefficients corresponding to the wavelet function, and n the node index.

In the discrete domain, for decomposition at the j -th level, the wavelet packet coefficients $d_{j,n}$ of the n -th node are obtained by further decomposing the parent-node coefficients $d_{j-1,n}$ from the previous level:

$$\begin{cases} d_{j,2n}[k] = \sum_m h[m - 2k] d_{j-1,n}[m] \\ d_{j,2n+1}[k] = \sum_m g[m - 2k] d_{j-1,n}[m] \end{cases} \quad (8)$$

where k denotes the discrete sampling index.

At each decomposition level, the WPT decomposes every subband node into low- and high-frequency child nodes, forming a full binary tree, as shown in Figure 1. For a given ultrasonic testing signal $x(t)$, 4-level ($j = 4$) WPT produces $2^4 = 16$ contiguous, non-overlapping subbands of equal bandwidth. This achieves full coverage and high discrimination of the signal's spectral features, enabling accurate evaluation of internal delamination severity.

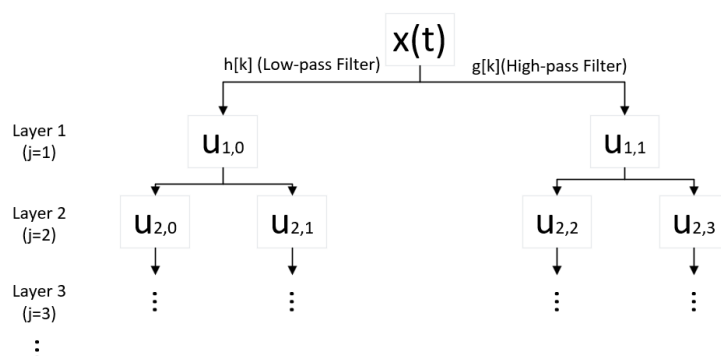


Figure 1. Schematic of multi-level wavelet packet decomposition.

By Parseval's theorem, the total energy of a signal in the time domain equals the sum of its subband energies in the wavelet domain. The subband energy $E_{j,n}$ for the n -th node at decomposition level j is given by the sum of the squares of the reconstructed signal coefficients for this node:

$$E_{j,n} = \sum_{k=1}^N |d_{j,n}(k)|^2 \quad (9)$$

where N denotes the length of the sampled signal.

The total energy E_{total} across this decomposition level is the sum of the energies of all terminal nodes:

$$E_{\text{total}} = \sum_{n=0}^{2^j-1} E_{j,n} \quad (10)$$

To apply the concept of information entropy from probability theory, we first normalize the subband energies to obtain a probability distribution sequence. The normalized energy p_n for the n -th subband is defined as:

$$p_n = \frac{E_{j,n}}{E_{\text{total}}} \quad (11)$$

Thus, p_n satisfies the axioms of a valid probability distribution: $0 \leq p_n \leq 1$ and $\sum_n p_n = 1$.

According to the definition of Shannon information entropy, for a discrete system with a finite set of possible states, where the n -th state occurs with probability p_n , the system entropy is defined as the expected information content across all states. Following recent state-of-the-art applications of entropy-based non-destructive evaluation methodologies [23,24,30], the WPEE in this work is adopted to quantify the acoustic energy concentration and is calculated as:

$$WPEE = - \sum_{n=0}^{2^j-1} p_n \ln(p_n) \quad (12)$$

where, by convention, $0 \ln 0 = 0$.

In this study, the raw ultrasonic signals were acquired at a sampling frequency of 100 MHz. A discrete time window of 10 μ s encompassing the interface echoes was extracted for analysis. A four-level wavelet packet decomposition was performed using the sym4 mother wavelet. Given the Nyquist frequency of 50 MHz, the four-level decomposition yields $2^4 = 16$ terminal subbands, each with a uniform bandwidth of 3.125 MHz. The normalized energy p_n denotes the fractional energy of the n -th subband relative to the total energy within the analyzed window ($\sum p_n = 1$). The WPEE in Equation (12) is the raw Shannon entropy without maximum-entropy normalization.

3. Experimental Setup and Analysis of Ultrasonic Testing Results

3.1. Specimen Preparation

A conventional thermal barrier coating system generally consists of a ceramic top coat (200–600 μ m thick) deposited on a superalloy substrate, with a modified metallic bond coat sandwiched between the two layers. Serving as a transition layer, the bond coat is conventionally deposited via low-pressure plasma spraying. It not only effectively improves the interfacial bonding strength between the ceramic top coat and metallic substrate but also significantly mitigates thermal stresses induced by the coefficient of thermal expansion (CTE) mismatch between the two dissimilar layers.

For this study, a set of identical coin-shaped TBC specimens was fabricated under uniform deposition conditions. Each specimen featured a 3-mm-thick nickel-based superalloy substrate with 25 mm diameter. Prior to coating, the substrate surface was grit-blasted to enhance mechanical interlocking. A 200 μ m-thick NiCoCrAlY bond coat was first deposited onto the substrate via low-pressure plasma spraying (LPPS), followed by a 350 μ m-thick 7–8 wt.% yttria-stabilized zirconia (YSZ) top coat deposited by atmospheric plasma spraying (APS), giving a total coating thickness of 550 μ m. Photographs of the as-fabricated specimens are provided in Figure 2. To replicate progressive interfacial delamination at

different aging stages, four specimens were respectively subjected to 21, 32, 43, and 54 full isothermal thermal cycles at a standard TBC cycling temperature of 1200 °C, producing varying degrees of interfacial damage for subsequent ultrasonic characterization. Thermal cycling was conducted using a vertical tube furnace in ambient air. One complete cycle consisted of 15 min heating at 1200 °C, followed by 5 min cooling at room temperature.



Figure 2. Photographs of the as-fabricated specimens.

3.2. Immersion Ultrasonic Testing System

A high-precision immersion ultrasonic testing system was developed in-house for this work, with a system schematic provided in Figure 3 and a photograph of the hardware platform shown in Figure 4. The focused immersion ultrasonic transducer (Olympus, Tokyo, Japan) (5 mm element diameter) was mounted on a precision motorized XY scanner (Shenzhen Dynamikwell Technology Co., Ltd., Shenzhen, China) through a rigid support and suspended vertically inside the water tank. The transducer was connected to a DPR300 pulser-receiver (JSR Ultrasonics, Pittsford, NY, USA) for pulse excitation and signal amplification, and the received interface echoes were digitized by a WaveRunner 6100A digital oscilloscope (Teledyne LeCroy, Chestnut Ridge, NY, USA) for storage and post-processing. Hardware synchronization across the full raster scan ensured consistent pulse excitation, echo acquisition, and data transmission.

A 20 MHz center frequency was chosen for the transducer because this high frequency provides a sufficiently short acoustic wavelength to resolve the closely spaced layer boundaries, while avoiding the excessive attenuation in the superalloy substrate that would occur at even higher frequencies. A separate Z-axis stage was used to precisely adjust the water path, positioning the focal spot directly at the target coating interfaces to maximize the signal-to-noise ratio of the weak interfacial echoes.

Prior to scanning, each coin-shaped specimen was fixed on the sample holder at the tank bottom, and its position was adjusted to align the central axes of the transducer and specimen. The incidence angle was carefully calibrated to be strictly normal (90°) to the specimen surface, ensuring pure longitudinal-wave propagation and minimizing mode-conversion losses at the water/specimen interface. For C-scan imaging, the scan area was sampled on a 60 × 60 grid with a 0.5 mm scan interval, covering a 30 mm × 30 mm region that fully enclosed the 25-mm-diameter specimen. This step size provides an optimal balance: it offers sufficient spatial resolution to capture the morphology and coalescence of localized micro-delamination clusters, while keeping the acquisition time and data volume manageable. At each grid point,

a full A-scan waveform was acquired through the transducer–DPR300–oscilloscope signal chain described above.

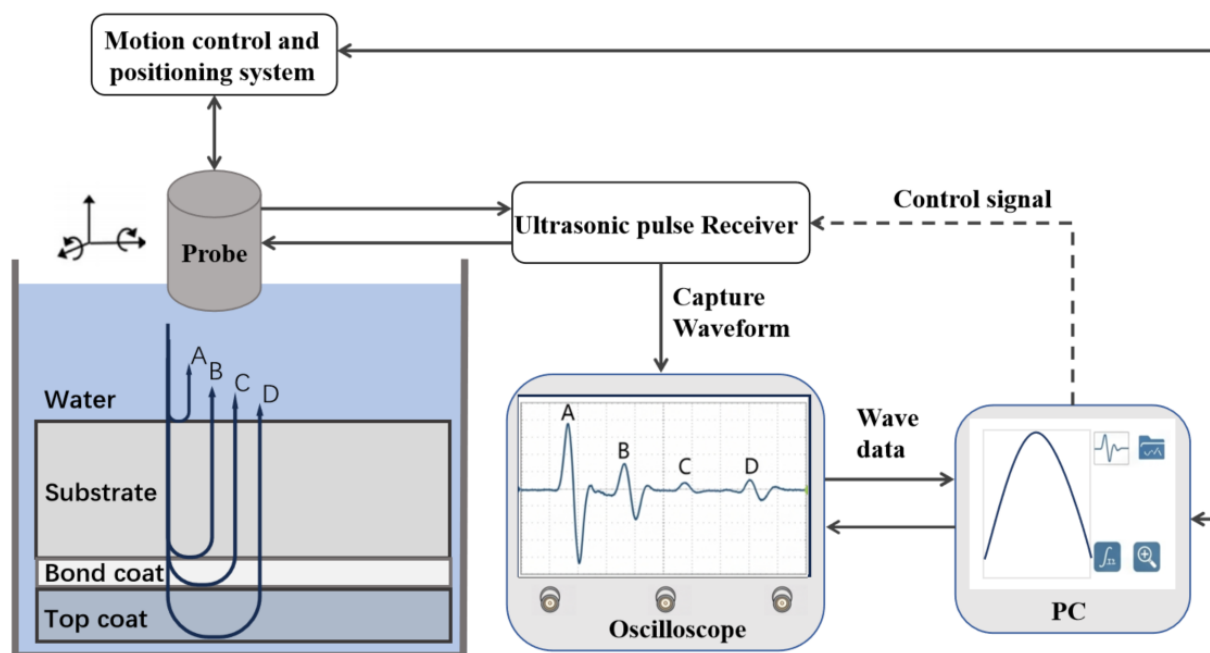


Figure 3. Schematic of the immersion ultrasonic testing system.

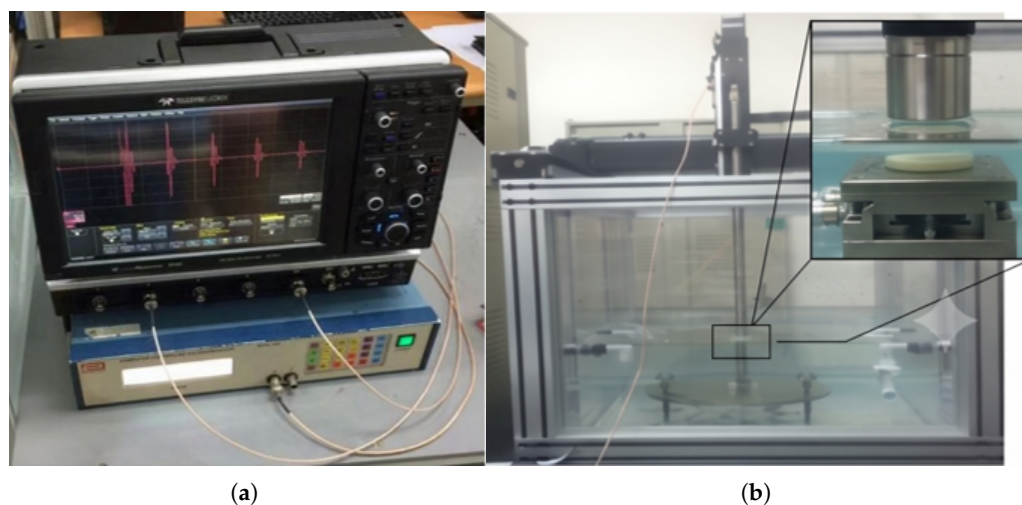


Figure 4. (a) Digital oscilloscope and pulser-receiver. (b) Immersion scanning setup with the precision multi-axis stage, with a close-up view of the ultrasonic transducer.

Beyond conventional A-scan time-domain features (echo amplitude and time-of-flight (ToF)), we further applied FFT and generalized Morse wavelet-based CWT for time-frequency analysis. WPEE was extracted to quantify energy redistribution caused by cumulative damage. Combined with ultrasonic C-scan imaging, this multi-dimensional feature framework enabled cross-validation of results, supporting comprehensive evaluation of delamination growth and spatial distribution within the coating. We initially compared inspection performance for normal incidence from both the substrate and ceramic top coat sides. High ultrasonic attenuation and strong scattering in the porous top coat significantly degraded transmitted signal-to-noise ratio (SNR) for top-coat incidence. To ensure data reliability, all subsequent analyses use ultrasonic data acquired from the substrate incidence path.

3.3. Ultrasonic Characteristics of Substrate-Side Incidence

Ultrasonic pulses centered at 20 MHz were generated by the transducer and normally incident on the specimen from the superalloy substrate side, as schematized in Figure 5. To establish a reference baseline for defect inversion, ultrasonic responses were first acquired from a pristine, uncycled TBC specimen. The results in Figure 6 show clear reflection and transmission of ultrasonic energy at each layer interface, driven by acoustic impedance mismatch across the multilayer system. The first dominant echo arises when the longitudinal wave reaches the bond coat/top coat interface after propagating through the substrate. Owing to strong interfacial bonding in the as-fabricated state, most acoustic energy propagates into the top coat, where it travels to the ceramic-water interface and reflects back to the transducer, forming the second dominant echo immediately after the first echo. The time separation $\Delta t = 0.193 \mu\text{s}$ between these two echoes equals the round-trip ToF of ultrasound in the ceramic top coat. A low-amplitude second echo from multiple internal reflections is also visible at $27.2 \mu\text{s}$, strongly attenuated by scattering in the porous ceramic. These clear, well-characterized echoes confirm that 20 MHz ultrasound effectively penetrates the intact TBC structure, and provide a reliable baseline for tracking interfacial degradation and delamination growth during subsequent thermal cycling.

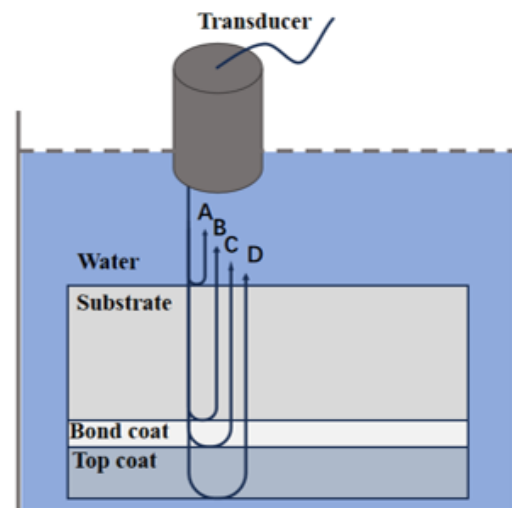


Figure 5. Schematic diagram of ultrasonic incidence from the metallic substrate side.

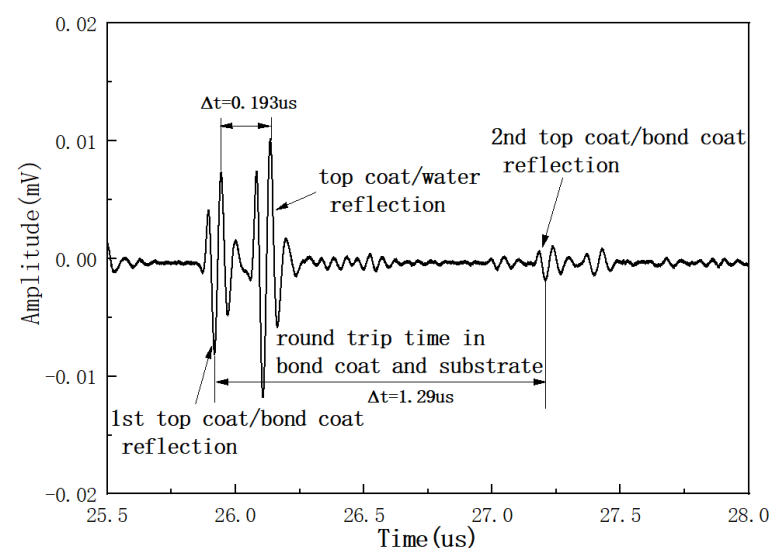


Figure 6. Ultrasonic response of the pristine uncycled TBC specimen.

With the baseline acoustic response of pristine TBCs established, we systematically tracked time-domain waveform evolution as a function of thermal cycle number to characterize microscale interfacial degradation during high-temperature exposure. As presented in Figure 7a,b, after 21 and 32 thermal cycles, the first bond coat/top coat interface echo shows clear overlap of multiple scattered signals, preventing clear resolution of the pure interfacial reflection. Notably, the amplitude of the second ceramic-water interface echo remains extremely low at this stage. This suggests that despite initial TGO growth, the interface retains good bonding integrity; the acoustic impedance mismatch across the interface remains small, so most ultrasonic energy transmits through the bond coat/top coat interface and continues propagating into the top coat.

At 43 thermal cycles (Figure 7c), the second echo amplitude shows a clear increase relative to lower cycle counts. Interfacial microcracks have propagated laterally along the boundary but have not coalesced into a continuous delamination, so partial ultrasonic transmission across the interface remains possible. At 54 thermal cycles (Figure 7d), the time-domain pulse-echo response exhibits a sharp amplitude jump and significant waveform distortion. A second echo with amplitude matching the primary interface reflection appears immediately after the first return from the top coat/TGO interface, with almost no attenuation relative to the primary echo. This indicates the interface has formed a nearly continuous air gap from delamination. The extreme acoustic impedance mismatch at this air gap prevents almost all ultrasonic transmission, producing near-total reflection of the incident wave. This response is in stark contrast to the high transmission observed in as-fabricated, uncycled TBCs (Figure 6), and captures the full progression of TBC interfacial degradation under thermal cycling: from initial localized TGO growth and microcracking to large-area delamination failure.

To characterize frequency-dependent scattering and attenuation at defective interfaces, FFT was applied to A-scan signals across all thermal cycle counts, with the resulting frequency spectra shown in Figure 8. The primary echo spectrum from the top coat/TGO interface exhibits both amplitude growth with increasing thermal damage, and a pronounced upward shift of the center frequency. At 21 and 32 cycles, the spectral peak is centered at 16–17 MHz. This is attributed to the rough scattering interface formed by uneven TGO growth and early-stage microcracks, which strongly scatters high-frequency ultrasound and causes significant high-frequency roll-off in the reflected signal. At 54 cycles, when large-area delamination forms, the dominant spectral peak shifts abruptly to ~22 MHz. This frequency shift arises because microcracks have coalesced into a continuous, thin air gap at the interface, replacing the rough solid-solid boundary with a high-reflectivity planar interface of near-zero acoustic transmission. With transmission into the top coat blocked, high-frequency components (preferentially lost to transmission and scattering at rough interfaces) are strongly reflected, producing a marked recovery of high-frequency content in the primary echo spectrum.

The second echo spectra in Figure 8b provide direct physical evidence for interfacial transmission loss. For specimens with 21–43 thermal cycles, even with progressive interfacial damage, a large portion of acoustic energy transmits through the interface and dissipates in the porous top coat. This strong transmission leaves negligible energy in the superalloy substrate to form the second echo, leading to very low FFT magnitudes. For the 54-cycle specimen with full delamination, by contrast, interfacial transmittance is reduced to near zero, and the transmission path into the top coat is fully blocked. Most incident acoustic energy is trapped between the substrate backwall and the delamination air gap, forming low-loss multiple internal reverberations that produce a sharp rise in second echo spectral amplitude.

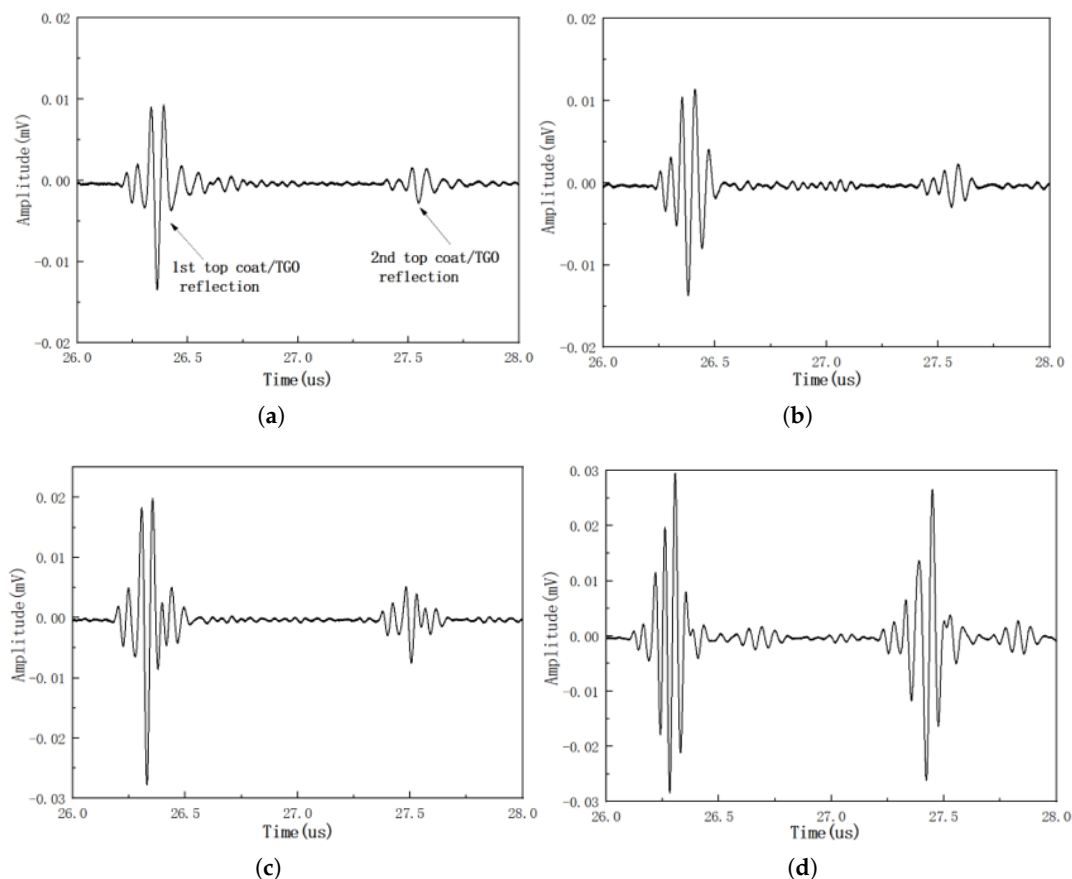


Figure 7. Pulse-echo waveforms reflected from the top coat/TGO interface after different thermal cycles: (a) 21. (b) 32. (c) 43. (d) 54 thermal cycles.

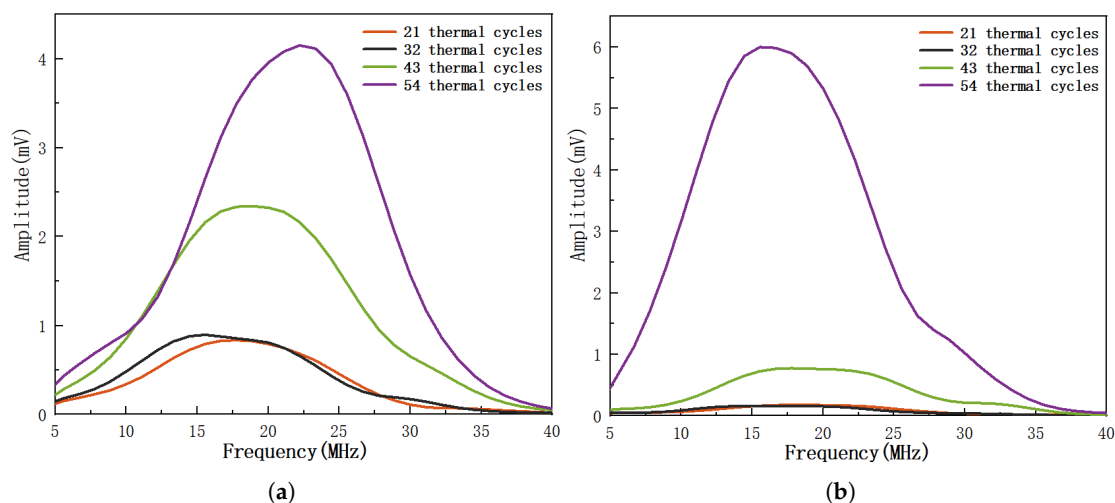


Figure 8. FFT magnitude spectra of A-scan echoes for TBC specimens under varying thermal cycles: (a) Primary interface echo. (b) Secondary multiple echo.

To characterize time-frequency energy evolution of top coat/TGO interface echoes under different thermal cycles, generalized Morse wavelet-based CWT was used for time-frequency feature extraction from A-scan signals, with the resulting 2D time-frequency magnitude scalograms shown in Figure 9. The scalograms clearly resolve ultrasonic pulse energy distribution in the time-frequency plane. A strong vertical energy cluster is visible at 26.3 μ s for all specimens, corresponding to the primary echo from the top coat/TGO

interface. With increasing thermal cycles from 21 to 54, this high-energy region shifts and narrows toward higher frequencies, consistent with reduced diffuse scattering as the rough microcracked interface evolves into a smooth delamination reflector, producing strong specular reflection of high-frequency ultrasound.

The most prominent change appears at 27.5 μ s. For 21-cycle specimens, this region shows near-zero energy (dark blue), indicating high transmission into the ceramic top coat. For 54-cycle specimens, a broad, high-intensity energy core spanning 12–28 MHz emerges at this time, growing from negligible amplitude to match the primary echo intensity. These features confirm that the delamination air gap blocks transmission into the top coat, trapping acoustic energy in the substrate and bond coat to produce low-loss multiple internal reflections.

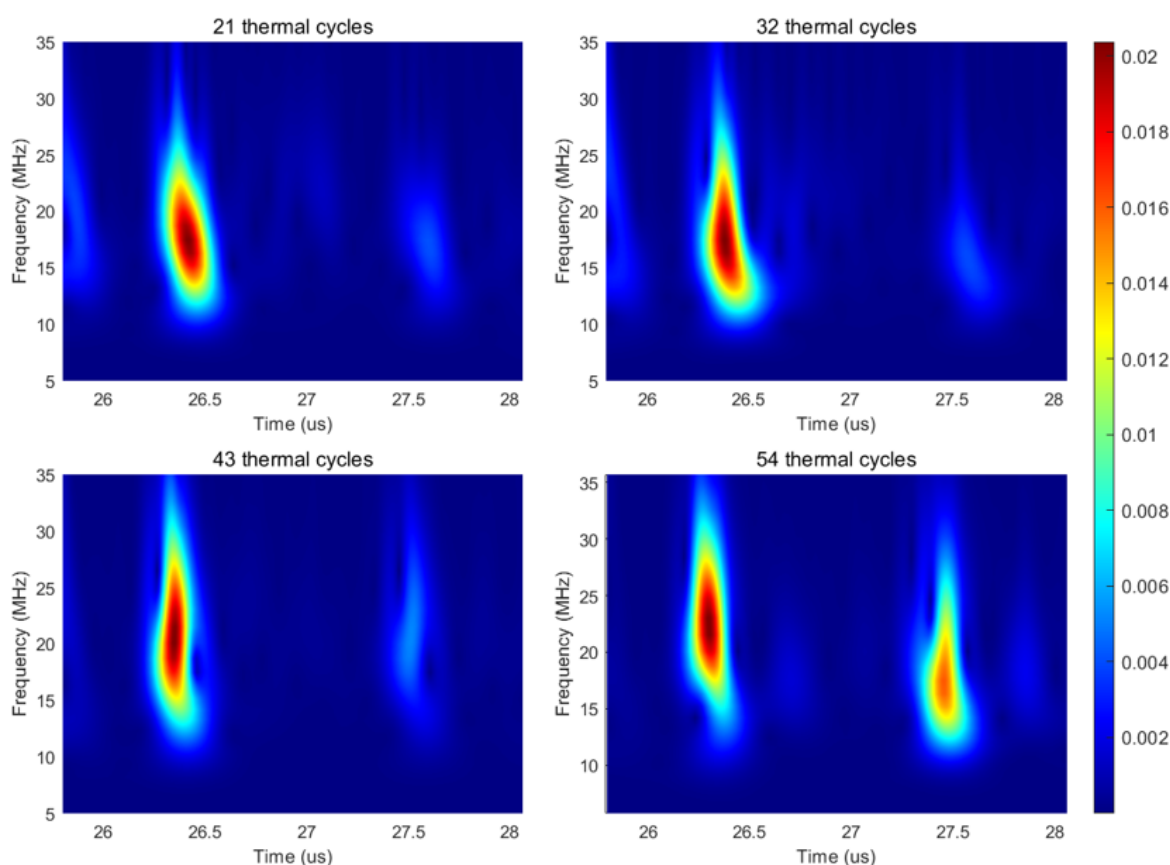


Figure 9. Generalized Morse wavelet-based time-frequency scalograms.

In this study, WPEE was extracted from ultrasonic signals, and its evolution as a function of thermal cycle number is shown in Figure 10. The mean WPEE values calculated from Equation (12) for specimens after 21, 32, 43, and 54 thermal cycles are 0.0067, 0.0059, 0.0025, and 0.0009, respectively, exhibiting a clear monotonically decreasing trend with increasing delamination severity. From 21 to 32 cycles, WPEE shows a slow decrease of 11.9%, corresponding to initial TGO growth. From 32 to 43 cycles, WPEE drops by 57.6%, corresponding to lateral microcrack propagation and partial coalescence. Most notably, from 43 to 54 cycles, WPEE decreases sharply by 64.0% to nearly zero, corresponding to the formation of a continuous air gap and full delamination. Overall, WPEE decreases by 86.6% from the earliest measured damage stage to full delamination.

The absolute WPEE values are low (0.0009–0.0067) because the ultrasonic energy is strongly concentrated around the 20 MHz center frequency, so that one dominant subband carries most of the energy ($p_n \rightarrow 1$), driving the raw Shannon entropy toward zero. As the identical processing procedure was applied to all four specimens, the diagnostically

meaningful quantity is not the absolute magnitude, but the relative monotonic trend across cycling stages.

Fundamentally, based on information entropy theory, WPEE quantifies the uniformity of energy distribution across frequency subbands. A higher WPEE value indicates energy spread across multiple subbands, corresponding to complex broadband signal composition; conversely, a lower WPEE value indicates energy concentrated in a small number of subbands, corresponding to a narrowband, spectrally concentrated signal. The near-zero WPEE at 54 cycles supports that almost all acoustic energy is trapped in the narrow resonant frequency band of the superalloy substrate, with minimal energy scattered into the broadband frequency range.

To explain this monotonic WPEE decrease and link signal evolution to coating microstructural degradation, we propose the following physical mechanism. Microdefect evolution at the TGO interface alters the coating system's acoustic response via two coupled effects: (1) The continuous air gap from delamination blocks ultrasonic transmission into the ceramic top coat, strongly suppressing diffuse scattering and attenuation of high-frequency ultrasound in the porous ceramic top coat. (2) The large solid-air acoustic impedance mismatch produces near-total reflection at the interface, trapping most acoustic energy in the resonant cavity formed between the superalloy substrate backwall and the delamination interface, leading to low-loss local resonance.

The combined effect of these two mechanisms drives ultrasonic echo energy to redistribute from a broadband, dispersed state to a narrow distribution concentrated around the substrate's resonant frequency. This energy reconfiguration leads to the observed WPEE reduction. The monotonic WPEE decrease thus provides a quantitative indicator of delamination-induced acoustic confinement and spectral concentration.

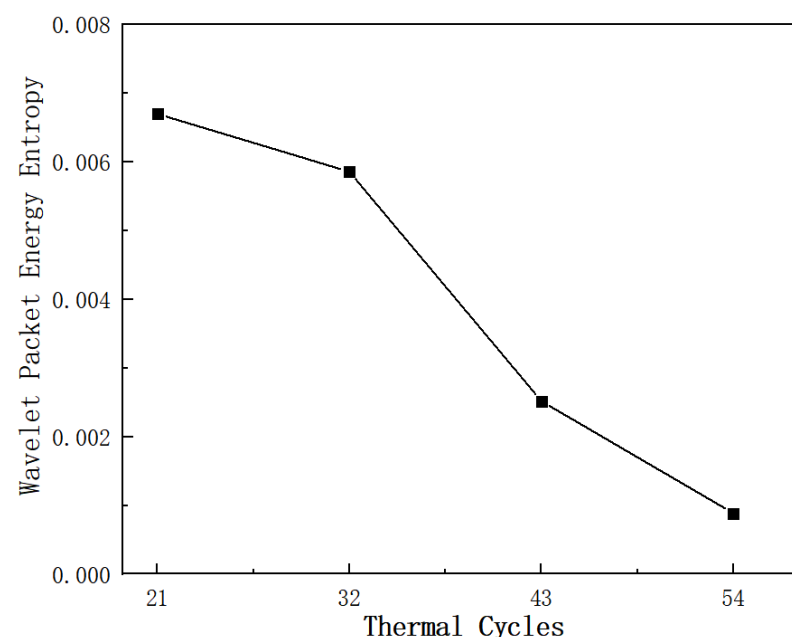


Figure 10. Evolution of WPEE for the top coat/TGO interface echoes vs. thermal cycles.

To characterize the pulse-echo response of fully delaminated TBCs, Figure 11 presents the full time-domain ultrasonic waveform for the specimen subjected to 54 thermal cycles. A clear train of multiple reflection echoes, separated by a constant time interval of $\Delta t = 1.145 \mu\text{s}$, is clearly resolved. These echoes exhibit high phase coherence across their envelopes, with amplitudes showing progressive exponential decay from intrinsic material attenuation during successive round trips. This observation supports that upon full delamination at the top coat/TGO interface, the air gap creates an extreme acoustic impedance

mismatch, producing near-total reflection that blocks further transmission into the ceramic top coat. As a result, ultrasonic pulses are acoustically trapped in the resonant cavity bounded by the delamination interface and superalloy substrate backwall, generating the equally spaced multiple echoes observed in the waveform. This distinct multiple-echo signature serves as a clear diagnostic indicator for identifying full TBC delamination.

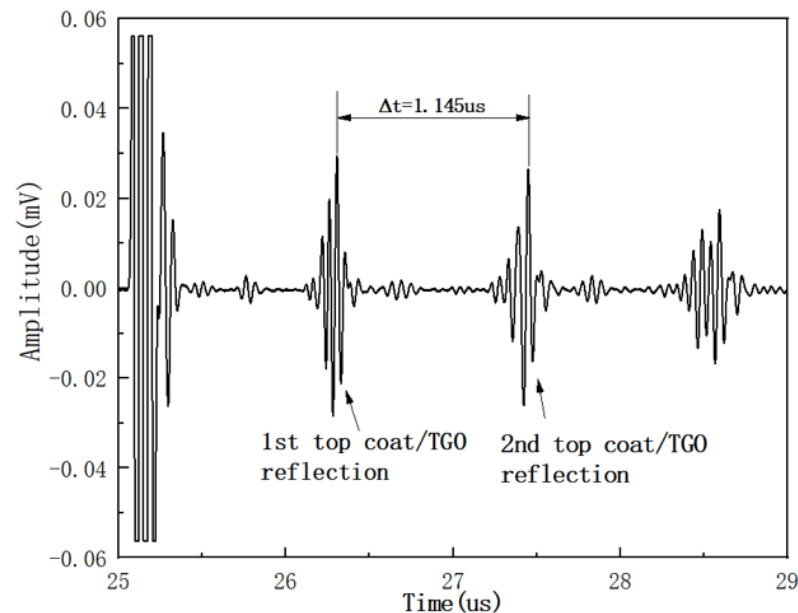


Figure 11. Multiple-echo train of the fully delaminated specimen after 54 thermal cycles.

In this study, the peak-to-peak amplitude of the second echo from the top coat/TGO interface was extracted, and its dynamic evolution with thermal cycle number is plotted in Figure 12. The measured peak-to-peak amplitudes for specimens after 21, 32, 43, and 54 thermal cycles are 0.00163, 0.00236, 0.00509, and 0.02656, respectively, showing a monotonically increasing trend opposite to the WPEE evolution. From 21 to 32 cycles, the amplitude shows a slow increase of 44.8%, corresponding to initial TGO growth and weak acoustic impedance mismatch at the interface. From 32 to 43 cycles, the amplitude increases by 115.7% as microcracks propagate laterally and partial delamination forms. Most notably, from 43 to 54 cycles, the amplitude surges by 421.8% to 16.3 times the value measured at 21 cycles, supporting formation of a continuous air gap and full delamination.

This exponential amplitude growth supports the acoustic trapping mechanism: when a continuous delamination air gap forms, almost no ultrasonic energy transmits into the ceramic top coat, and most energy is reflected back to form high-amplitude second echoes. The opposite monotonically evolving trends of WPEE decrease and second echo amplitude increase provide cross-validated quantitative evidence for delamination evolution [31].

To complement the ultrasonic figures, the macroscopic surface appearance of specimens at different thermal cycling stages was recorded and compared. As shown in Figure 13, the visible surface discoloration and progressive spalled area increase systematically with cycle number, a macroscopic trend that is consistent with the interfacial degradation revealed by the ultrasonic measurements. With increasing thermal cycles, thermal mismatch stresses accumulate owing to the CTE difference between coating layers, while continuous TGO thickening introduces volumetric growth stress. Their synergistic effect raises interfacial shear and peel stresses, which are recognized as the primary driving forces for interfacial micro-crack initiation, propagation, and coalescence, eventually leading to macroscopic spallation [32,33]. Direct cross-sectional microscopy to verify these mechanisms at each stage is identified as future work.

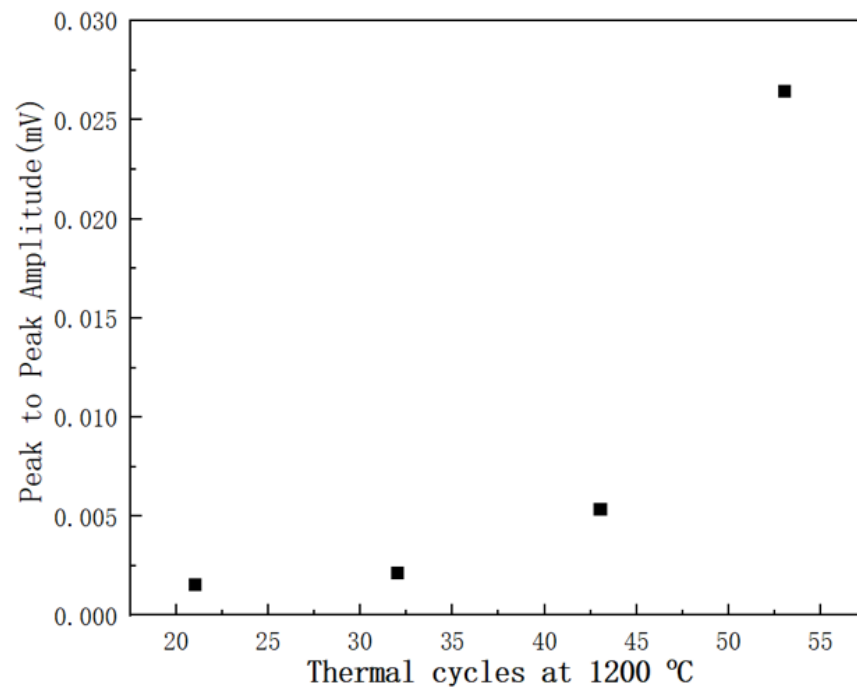


Figure 12. Evolution of the peak-to-peak amplitude for the second echo from the top coat/TGO interface across varying thermal cycles.



Figure 13. Interfacial delamination morphologies of the specimens subjected to varying thermal cycles.

3.4. Ultrasonic Characteristics of Ceramic-Side Incidence

To compare acoustic responses under different inspection paths and better replicate practical in-service NDT conditions for TBC aero-engine blades, we reversed the ultrasound incidence direction for this set of tests. All other experimental hardware parameters were kept strictly consistent, with ultrasonic pulses normally incident directly from the ceramic top coat side of the specimen. A schematic of this inspection configuration is provided in Figure 14.

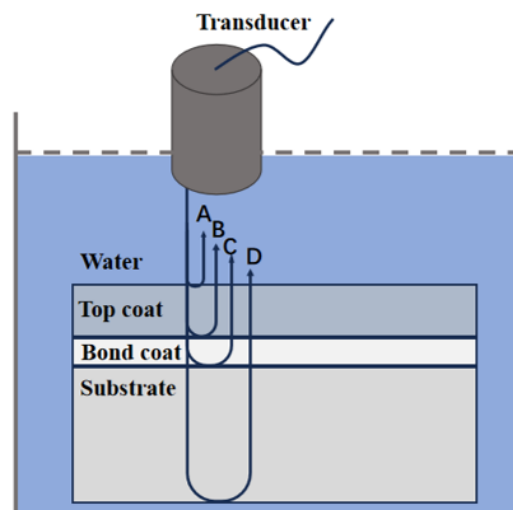


Figure 14. Schematic diagram of ultrasonic incidence from the ceramic top coat side.

A typical time-domain A-scan waveform acquired under top coat-side incidence is presented in Figure 15. In stark contrast to the clear responses obtained from substrate-side incidence, this waveform exhibits severe distortion and strong energy attenuation. Only the top coat/TGO interface echo and an extremely faint superalloy backwall echo are discernible. The waveform shows a severely degraded signal-to-noise ratio, primarily attributed to the inherently porous microstructure of the top coat, which acts as a strongly scattering and absorbing medium for high-frequency ultrasound. Compared to propagation through the superalloy substrate, high-frequency components of the incident pulse undergo intense diffuse scattering at numerous micropore interfaces in the ceramic, generating persistent, disordered structural noise between the two reflection peaks. This strong scattering not only causes significant acoustic energy dissipation but also severely distorts coherent target signals, making key diagnostic features difficult to identify. From a methodological perspective, this observation strongly supports the rationality of our core inspection strategy: for internal non-destructive evaluation of complex coating systems with a high-porosity ceramic top coat, substrate-side ultrasonic excitation is the optimal configuration. This approach effectively avoids strong microstructural scattering interference from the top coat, enabling the acquisition of high-fidelity, high-resolution, and dynamically stable interfacial echo features.

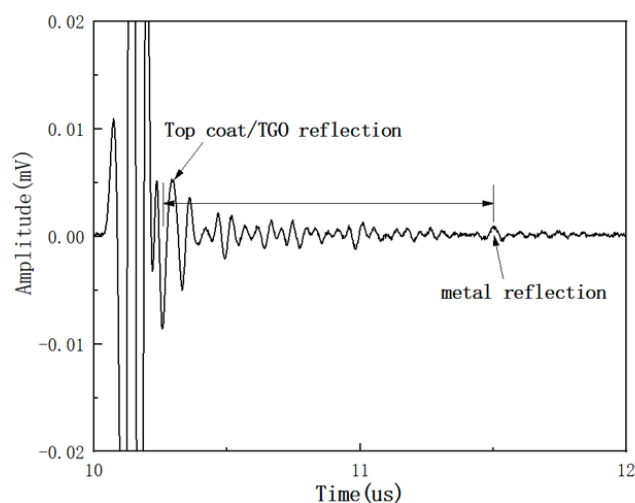


Figure 15. Ultrasonic pulse-echo waveform of the specimen subjected to 21 thermal cycles under top coat-side incidence.

3.5. Ultrasonic C-Scan Imaging

To map the spatial distribution and growth of interfacial delamination in TBCs on a macroscopic 2D scale, ultrasonic C-scan images were reconstructed from raster scan data collected by a precision multi-axis scanning stage, with 3600 spatial measurement points across the 30 mm × 30 mm scan area. The displayed quantity is the peak-to-peak amplitude, A_{pp} , of the top coat/TGO interface echo extracted point-by-point. Figure 16 presents C-scan maps showing the 2D damage of specimens after different numbers of thermal cycles. For quantitative comparison, the same amplitude limits of 0–0.03 mV were applied to all four C-scan maps. In this adopted color scale, dark blue corresponds to low-amplitude regions, indicating good interfacial bonding and high acoustic transmission; yellow, red, and magenta correspond to high-amplitude regions, associated with strong reflection from interfacial delamination zones.

Because interfacial delamination produces a strong acoustic-impedance mismatch and consequently enhances the reflected amplitude, a common amplitude threshold of $A_{th} = 0.015$ mV was adopted as the operational criterion for identifying delamination-affected regions. Spatial points satisfying $A_{pp} \geq A_{th}$ were classified as delamination-affected regions, whereas points below this threshold were regarded as bonded or weakly damaged regions. At 21 cycles, the scan field is predominantly dark blue with only scattered yellow-green points, suggesting damage is limited to sparse local microdefects. After 32 cycles, high-amplitude points increase noticeably in density and spread diffusely across the specimen, consistent with the progressive initiation of lateral microcrack growth. At 43 cycles, distinct high-amplitude red regions emerge and begin to coalesce into clusters. In contrast, at 54 cycles, large contiguous high-amplitude regions dominate the scan field, visually confirming the pronounced increase. This indicates the formation of an extensive, interconnected delamination network. This spatial evolution from isolated point defects to connected macroscopic damage regions provides supporting evidence that is consistent with the point-measurement results: the monotonically decreasing WPEE and the corresponding increase in second echo amplitude derived from the central region follow the same overall damage trend observed across the scanned field.

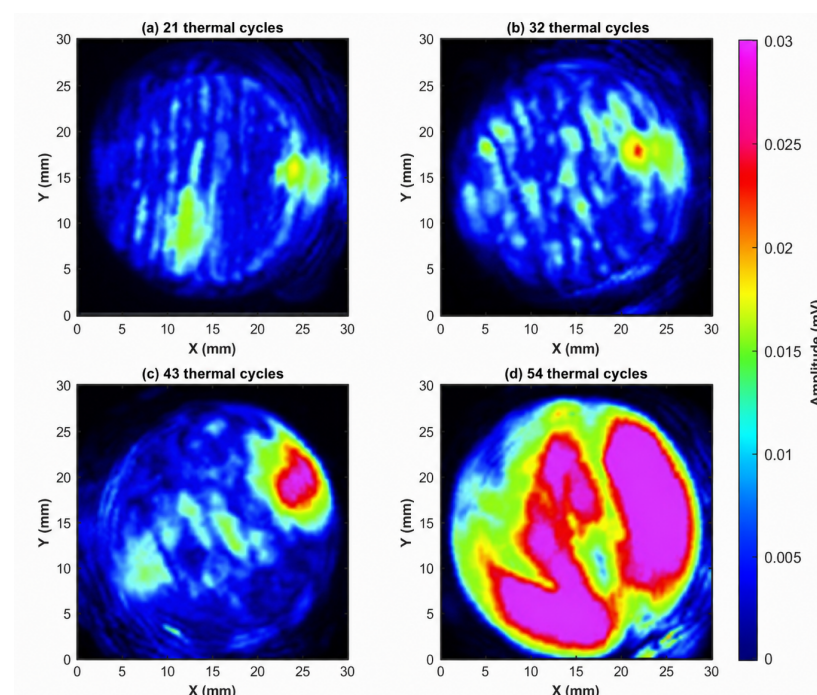


Figure 16. Ultrasonic C-scan results of specimens after different thermal cycles: (a) 21. (b) 32. (c) 43. (d) 54 thermal cycles.

4. Finite Element Simulation

4.1. Multilayer Finite Element Model Development

To provide a physical insight into the ultrasonic pulse-echo measurement results, a finite element model for ultrasonic pulse propagation in TBC systems is developed in this section, based on elastic wave propagation principles and finite element theory. The model simulates transient ultrasonic wave propagation across the multilayer TBC stack, and is validated against experimental data to ensure accuracy. The validated model provides a theoretical foundation for accurate defect identification and state assessment of internal coating damage. An outline of this section is provided in Figure 17.

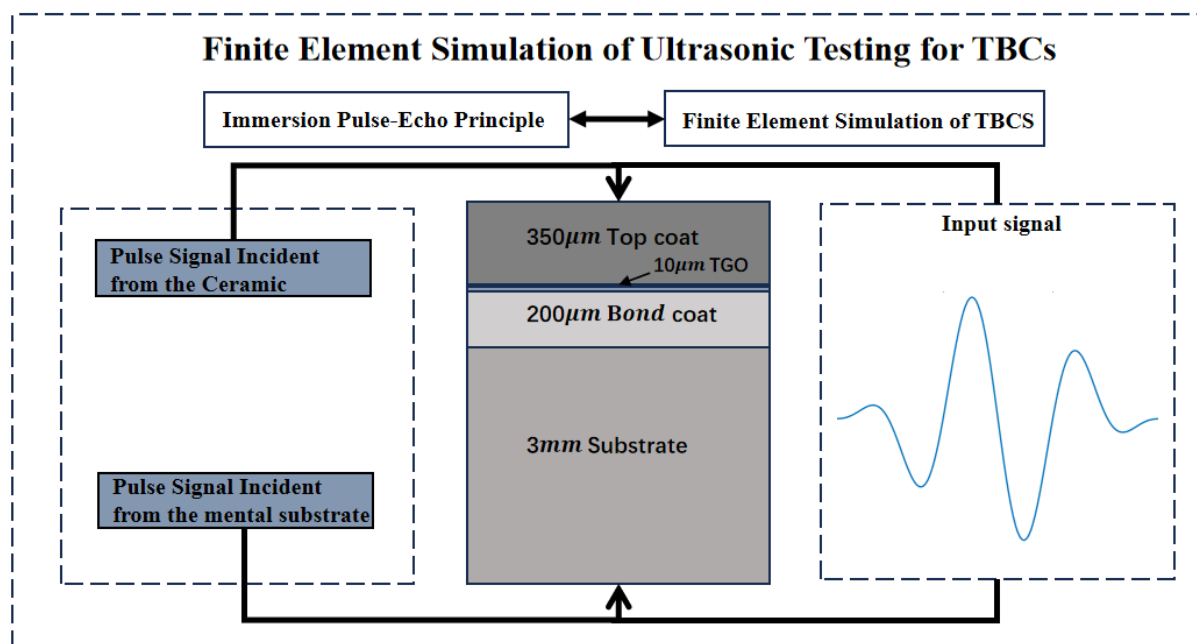


Figure 17. Overall framework of the finite element simulation.

A simplified four-layer FE model including the top coat, TGO, NiCoCrAlY bond coat, and superalloy substrate was built in Abaqus/Explicit version 2025 (Dassault Systèmes SIMULIA, Vélizy-Villacoublay, France) for this work. The model is designed to compare ultrasonic propagation characteristics for normal incidence from both the top coat surface and substrate back surface.

(1) A 2D dynamic FE model was constructed per the experimental parameters described above. As illustrated in Figure 18, the model comprises four vertically stacked layers: top coat, TGO, bond coat, and superalloy substrate. To suppress numerical dispersion from spatial discretization and accurately resolve transient high-frequency ultrasonic waveforms, meshing strictly follows the standard wavelength convergence criterion for wave propagation simulations: a minimum of 8 elements per shortest wavelength is required to avoid numerical artifacts. The element size is calculated as:

$$L_e \leq \frac{\lambda_{\min}}{8} = \frac{C_{\min}}{8f} \quad (13)$$

where L_e is the maximum allowable mesh element size (in mm), $\lambda_{\min}$ is the minimum ultrasonic wavelength propagating in each layer, $C_{\min}$ is the minimum longitudinal wave velocity across all model layers, and f is the center frequency of the incident ultrasonic pulse. Four-node bilinear plane strain quadrilateral elements with reduced integration (CPE4R) were used for all layers, with enhanced hourglass control enabled to suppress

spurious zero-energy deformation modes. All elements had an aspect ratio close to 1 to ensure numerical accuracy for high-frequency wave propagation.



Figure 18. Schematic of the finite element simulation model for TBC ultrasonic propagation.

(2) Material properties were specified to match experimental measurements, with YSZ as the ceramic top coat. To replicate the 20 MHz transducer excitation used in experiments, a Hanning-windowed sinusoidal toneburst with a central frequency of 20 MHz was applied as a uniform dynamic surface pressure load across the excitation boundary, generating ideal normal-incidence longitudinal plane waves. It should be noted that while this linear elastic FE model captures ToF and interfacial reflection physics driven by acoustic impedance mismatch, it does not explicitly include the frequency-dependent attenuation caused by random 3D porosity in the air-plasma-sprayed YSZ top coat. Therefore, numerical validation in this work focuses primarily on temporal characteristics and relative amplitude trends between echoes, rather than absolute amplitude values.

For the isotropic materials within the TBC system, the longitudinal wave velocity is expressed as:

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (14)$$

By substituting the corresponding material properties into the equation, the longitudinal wave velocities for each constituent layer are obtained. The comprehensive simulation parameters for the TBC system are summarized in Table 1.

Table 1. Simulation properties of the TBC system.

Layer	Young's Modulus E (GPa)	Density ρ (kg/m ³)	Poisson's Ratio ν	Longitudinal Velocity c_L (m/s)
Top coat	35	5355	0.20	2695
TGO	390	3960	0.25	10,871
Bond coat	195	7176	0.30	6048
Substrate	201	8630	0.25	5287

Based on layer thicknesses and corresponding longitudinal wave velocities from Table 1, the round-trip ToF of the ultrasonic pulse in each layer was calculated as:

- Top coat: $t_1 = \frac{2H_1}{c_1} = 0.26 \mu\text{s}$
- TGO: $t_2 = \frac{2H_2}{c_2} = 0.0018 \mu\text{s}$
- Bond coat: $t_3 = \frac{2H_3}{c_3} = 0.066 \mu\text{s}$
- Substrate: $t_4 = \frac{2H_4}{c_4} = 1.135 \mu\text{s}$

where H_1, H_2, H_3, H_4 denote the thicknesses of the top coat, TGO, bond coat, and substrate, respectively; c_1 to c_4 are the longitudinal wave velocities of each layer.

The theoretical arrival time of the substrate backwall echo for top coat-side incidence (total round-trip ToF through the full coating stack) is therefore:

$$t = t_1 + t_2 + t_3 + t_4 = 1.4628 \mu\text{s} \quad (15)$$

(3) Boundary conditions: symmetry boundary conditions were applied to both lateral edges to exploit the 2D symmetric configuration. This reduces the computational domain and the associated cost, while suppressing spurious wave reflections from the lateral edges that would otherwise contaminate the transient wave field.

For the fully delaminated model, a thin air layer was inserted between the top coat and TGO to simulate a continuous air-gap delamination. The acoustic impedance of air is 400 Rayl, which is five orders of magnitude lower than that of the solid coating materials. This extreme impedance mismatch produces a near-total reflection of ultrasonic energy at the interface, consistent with the actual physical delamination behavior.

4.2. Ultrasonic Incidence from the Top Coat Surface

In the established 2D FE model, a unit-amplitude pulse load was applied across the entire top surface of the ceramic top coat to simulate normal plane wave incidence. The pulse shape and bandwidth were calibrated against measured reflection signals to match the transducer response. Figure 19 presents the dynamic ultrasonic propagation process: the initial pulse propagates downward through the top coat at a longitudinal velocity of 2695 m/s. As the wave sequentially passes through the top coat/TGO and bond coat/substrate interfaces, ultrasonic energy undergoes partial reflection and transmission at each boundary, driven by acoustic impedance mismatch between adjacent heterogeneous layers.

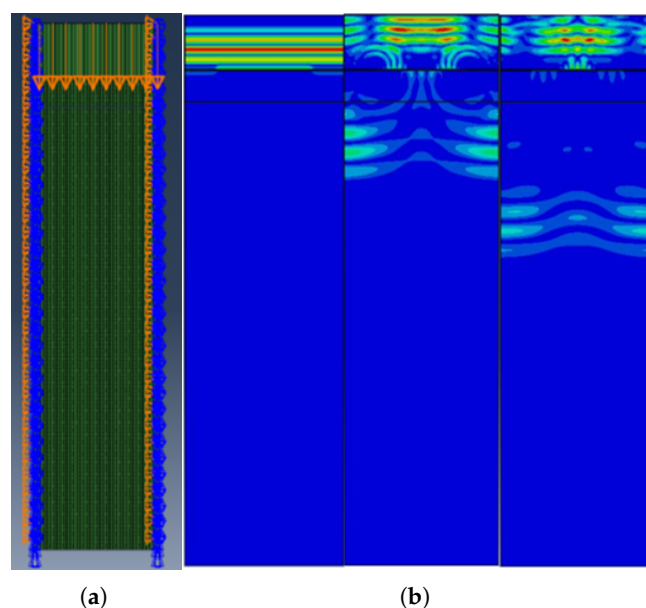


Figure 19. (a) Incidence of the stress wave from the ceramic top coat surface. (b) Snapshots of the transient wave propagation process at different time instances.

Figure 20a presents the simulated time-domain waveform for normal incidence from the ceramic top coat. The first wave packet corresponds to the front-surface reflection at the specimen/water interface, followed by the primary partial reflection from the top coat/TGO interface. The first backwall echo from the superalloy substrate/air interface arrives at 1.473 μs , matching the total round-trip ToF through the full multilayer TBC system. This close agreement with theoretical ToF values calculated from layer acoustic properties confirms the baseline accuracy of the explicit dynamics FE model.

To characterize the ultrasonic response of fully delaminated interfaces, a comparative model with a fully delaminated top coat/TGO interface was built, with results shown in Figure 20b. The numerical results show that the extreme acoustic impedance mismatch at the interlayer air gap blocks nearly all ultrasonic transmission into the superalloy substrate, leading to the complete disappearance of the substrate backwall echo. Instead, ultrasonic energy is trapped within the ceramic top coat, producing a series of evenly spaced multiple echoes. This response is distinct from intact TBCs, where a portion of acoustic energy transmits through the interfaces into the substrate and gradually dissipates.

Crucially, while this linear elastic model demonstrates energy trapping within the top coat, it also provides a clear theoretical contrast to experimental reality. As shown in Section 3.4 (Figure 15), air-plasma-sprayed YSZ top coats contain significant 3D random porosity. The high-frequency multiple reverberations predicted here would be strongly attenuated and masked by microstructural scattering noise in practice. Therefore, this simulation indirectly but clearly validates the core methodological choice of this study: for reliable delamination detection, ultrasonic inspection must be performed from the metallic substrate side to bypass the highly scattering ceramic layer.

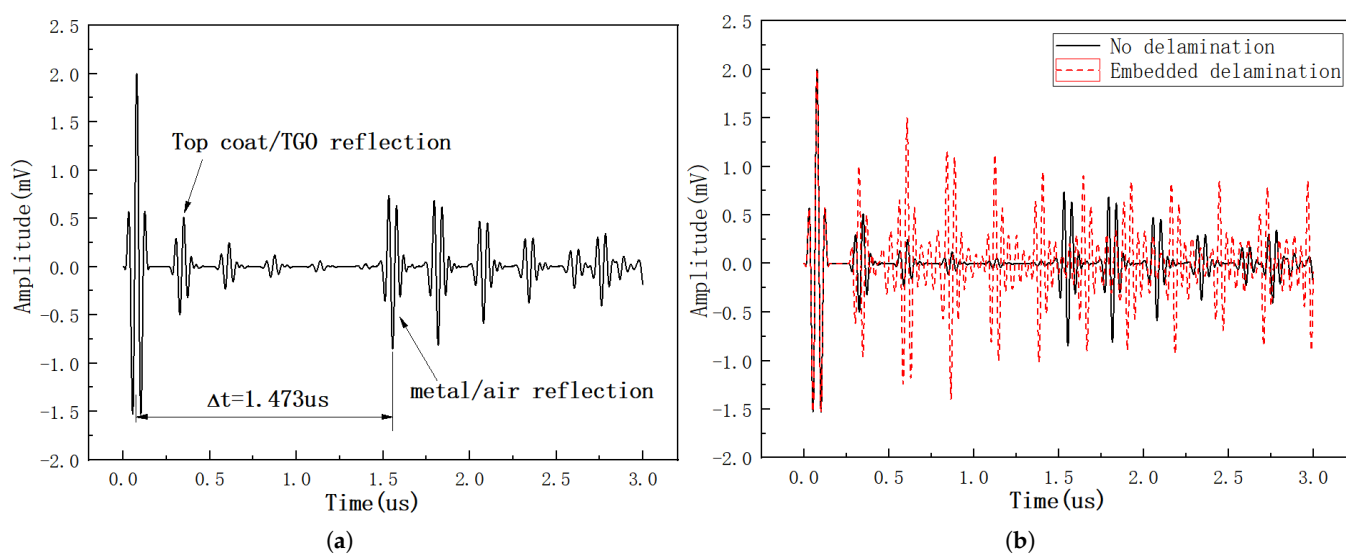


Figure 20. Simulated time-domain waveforms under normal incidence from the ceramic top coat: (a) time-domain waveform of the intact state. (b) comparison between the delaminated and intact waveforms.

4.3. Ultrasonic Incidence from the Metallic Substrate Surface

Using the same simulation framework as described in Section 4.2, all model parameters were kept unchanged, and only the unit-amplitude plane wave load direction was reversed to simulate normal incidence from the superalloy substrate side, as shown in Figure 21. The simulated transient ultrasonic propagation follows this sequence: the excitation pulse first propagates through the superalloy substrate at a longitudinal velocity of 5287 m/s. As the wave reaches the substrate/bond coat and bond coat/TGO interfaces sequentially, partial reflection and transmission occur due to acoustic impedance mismatch between adjacent

layers. Finally, the transmitted wave penetrates the top coat and reaches the outermost top coat/air interface, where it undergoes total reflection and propagates back toward the excitation source.

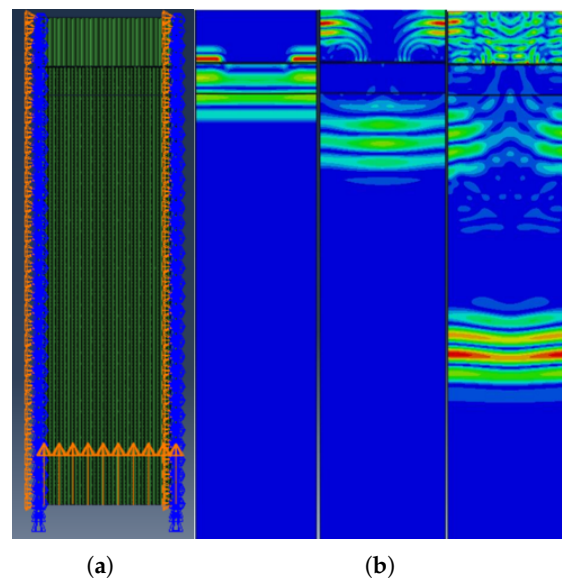


Figure 21. (a) Incidence of the stress wave from the metallic substrate surface. (b) Snapshots of the transient wave propagation process at different time instances.

To further verify ultrasonic propagation behavior in the coating, the simulated time-domain waveform received on the substrate side for the intact state is first presented in Figure 22a. In this baseline configuration, the waveform clearly resolves the front-surface reflection, followed by the primary echo from the top coat/TGO interface. Because the interface is well-bonded, a portion of the acoustic energy transmits into the ceramic layer and reflects off the outermost top coat/air boundary. This produces a distinct top coat/air reflection separated from the primary interface echo by $0.198\ \mu\text{s}$, matching the theoretical round-trip ToF in the YSZ top coat. A secondary reflection from the top coat/TGO interface is also clearly observed. The time interval between the primary and secondary top coat/TGO reflections is $1.22\ \mu\text{s}$, corresponding to the round-trip propagation time through the bond coat and superalloy substrate. Overall, acoustic energy effectively penetrates the full multilayer stack and gradually dissipates, leaving only weak residual reflections at later times.

To validate the physical mechanism of interfacial damage, the transient responses for intact and fully delaminated states are compared in Figure 22b. Distinct from the intact state, the introduction of a continuous air-gap delamination produces a clear change in waveform morphology. The large acoustic impedance mismatch at the air gap effectively acts as an acoustic mirror, blocking nearly all energy transmission into the top coat. Consequently, ultrasonic energy is trapped in the acoustic cavity formed by the well-bonded superalloy substrate and bond coat, producing a long train of equally spaced multiple echoes as the wave repeatedly reflects between the delaminated interface and the substrate backwall. The time interval between adjacent echoes corresponds to the round-trip ToF in the bond coat and superalloy stack, measured as $1.22\ \mu\text{s}$. This value agrees well with the theoretical ToF calculated from layer acoustic properties, supporting the proposed ultrasonic propagation mechanism.

Most importantly, this simulated transient response closely matches the experimental multiple-echo signature measured from the 54-cycle fully delaminated specimen (Figure 11).

The FE simulation results show reasonable agreement with experimental measurements both qualitatively and quantitatively.

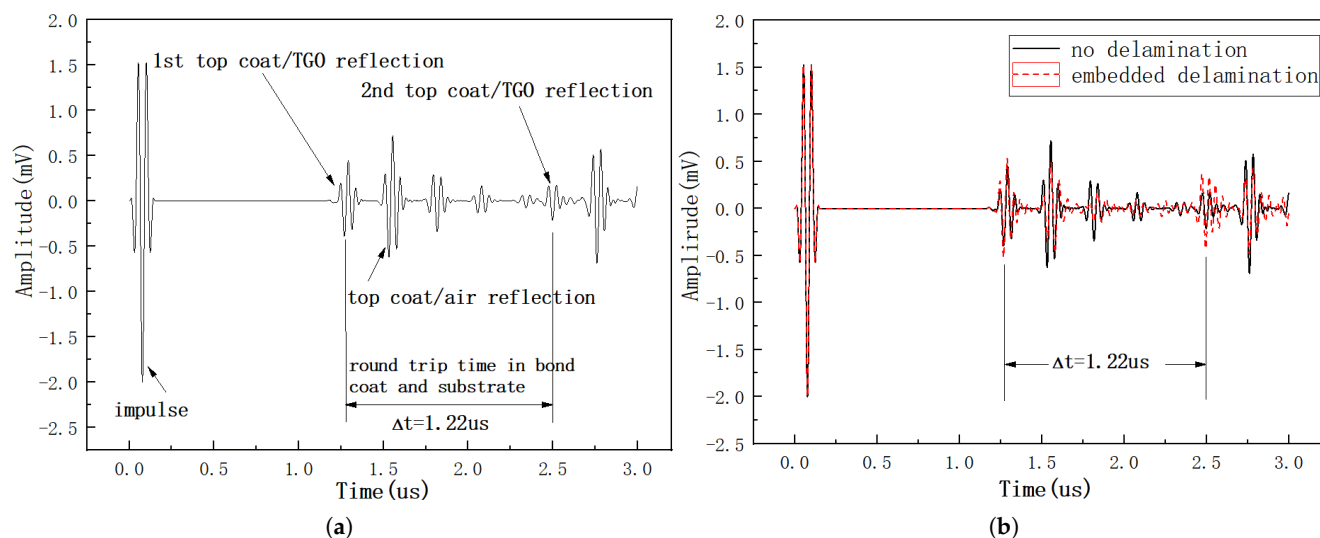


Figure 22. Simulated time-domain waveforms under normal incidence from the superalloy substrate: (a) time-domain waveform of the intact state. (b) comparison between the delaminated and intact waveforms.

5. Discussion

Through multi-dimensional ultrasonic feature extraction and finite element simulation, this study investigates interfacial delamination evolution and ultrasonic propagation mechanisms in thermal barrier coatings during high-temperature thermal cycling. Results show that TGO thickening and thermal mismatch stress drive microcrack growth with increasing thermal cycles, eventually forming a continuous air gap at the interface and full delamination. The large solid-gas acoustic impedance mismatch at the air gap produces near-total reflection, and the resulting acoustic trapping in the bond coat and superalloy is consistent with the observed monotonic WPEE decrease, second echo amplitude increase, FFT main frequency shift, and local high-energy features in CWT scalograms across all tested specimens.

For inspection methodology, results indicate that normal incidence from the superalloy substrate side reduces strong scattering and structural noise from the porous YSZ top coat. Combining multiple features including FFT frequency shift, CWT time-frequency energy distribution, and WPEE variation complements conventional single time-domain amplitude analysis, and shows potential for identifying coating degradation from early microdamage to macroscopic delamination. The developed multilayer FE model reasonably reproduces the observed ultrasonic response. To quantify model accuracy for both intact and fully delaminated states, Table 2 compares round-trip ToF values from theoretical calculation, experimental measurement, and simulation.

Table 2. Comparison of round-trip ToF values for substrate-side incidence.

Layer	Theoretical ToF (μ s)	Experimental ToF (μ s)	Simulated ToF (μ s)	Error 1	Error 2
Bond coat and substrate (intact)	1.20	1.29	1.22	7.5%	1.7%
Bond coat and substrate (fully delaminated)	1.20	1.145	1.22	4.6%	1.7%

Note: Error 1 is the relative deviation between experimental and theoretical values, calculated as $|\text{Experimental} - \text{Theoretical}| / \text{Theoretical} \times 100\%$. Error 2 is the relative deviation between simulated and theoretical values, calculated as $|\text{Simulated} - \text{Theoretical}| / \text{Theoretical} \times 100\%$.

For intact specimens, the measured and simulated ToF through the bond coat and substrate deviate from the theoretical baseline by 7.5% and 1.7%, respectively. For fully delaminated specimens, however, the measured 1.145 μs interval is noticeably lower than the theoretical 1.201 μs calculated for the substrate together with the as-sprayed 200- μm bond coat, and lies closer to the substrate-only value of 1.135 μs . This should not be regarded as a simple measurement deviation, nor does it indicate a misassignment of the reflecting interfaces. Rather, it physically reflects the continuous oxidation and microstructural degradation of the bond coat throughout the thermal cycling process. During repeated 1200 °C exposure, aluminum continuously diffuses outward from the NiCoCrAlY bond coat to sustain TGO growth, accompanied by progressive β -phase depletion, internal oxidation, and interdiffusion with the substrate [34]. Consequently, the effective metallic bond coat thickness is reduced well below its nominal value, shifting the actual acoustic round-trip time closer to the substrate-dominated baseline. Despite these microstructure-induced deviations, the multiple echoes themselves support the acoustic-trapping mechanism. When a continuous air gap forms at the top coat/TGO interface, most incident energy is reflected rather than transmitted into the ceramic top coat, giving the equally spaced reverberations observed in the waveform. The remaining small ToF discrepancies, including the 7.5% deviation for the intact specimen, are attributed to non-uniform TGO growth, interfacial roughness, and minor deviations between nominal and actual material properties.

The proposed non-destructive evaluation (NDE) method shows good feasibility for TBC delamination detection, but the current 2D FE model has inherent limitations. It assumes perfectly flat interfaces and treats the coating layers as homogeneous elastic media, and it does not explicitly incorporate frequency-dependent attenuation or the measured transducer waveform, thereby not fully representing the complex ultrasonic scattering induced by 3D random porosity and microcracks in real coatings. Consequently, to reproduce the ultrasonic response of TBCs with defects that are not solely caused by thermal cycling, the numerical model requires further improvement. Additionally, recognizing that isothermal cycling at 1200 °C does not fully replicate the complex thermal-shock conditions experienced by real aero-engine components, future experimental studies will explore in situ high-temperature ultrasonic monitoring. These improvements may broaden the applicability of the simulation framework and support application of this NDE method to inspect hot-section components.

Although this study emphasizes non-destructive acoustic evaluation, the dynamic evolution of the extracted ultrasonic features is fundamentally driven by the microstructural degradation of the TBCs at various thermal cycling stages. The correlation between the acoustic features and the coating microstructure can be delineated into three main stages.

Early Stage (21–32 cycles): the microstructure is characterized by initial TGO growth and the nucleation of isolated microcracks at the top coat/TGO interface, with interfacial bonding largely intact [35]. This state is consistent with the acoustic observations, namely relatively high ultrasonic transmission into the top coat, a gradual decrease in WPEE, and a minimal second-echo amplitude.

Intermediate Stage (43 cycles): As thermal cycling progresses, accumulated thermal mismatch stresses drive the lateral propagation and partial coalescence of interfacial microcracks, while the bond strength gradually decreases with expanding delamination area [36]. Acoustically, this transition corresponds to the 57.6% drop in WPEE and the distinct rise in second echo amplitude. The emerging partial air gaps begin to impede ultrasonic transmission.

Late Stage (54 cycles): In the final stage, the microstructure approaches a continuous macroscopic delamination along the interface, accompanied by progressive bond coat oxidation and Al depletion [37]. This physical state reveals the ultrasonic phenomenon, that is the near-zero WPEE and the sharp increase in second echo amplitude. The continuous air gap acts as a

strong acoustic reflector, reducing wave transmission into the top coat and confining acoustic energy within the substrate, giving rise to the observed multiple-echo reverberations.

Future studies will incorporate post-test cross-sectional SEM analyses to correlate the ultrasonic features with TGO thickness and micro-crack morphology, providing further microstructural validation of the proposed non-destructive methodology.

6. Conclusions

In this study, a NDE method based on immersion ultrasonic pulse-echo testing and multi-parameter feature extraction is proposed to evaluate interfacial delamination evolution of thermal barrier coatings during high-temperature thermal cycling, combined with finite element simulation to analyze the underlying ultrasonic response mechanisms. The main conclusions are summarized as follows:

(1) Ultrasonic signals were analyzed across multiple domains (frequency domain, time-frequency domain, and energy distribution) by integrating FFT, CWT, and WPEE methods. Results show that delamination-associated energy redistribution appears as a main frequency shift in FFT spectra and local energy concentration in CWT time-frequency scalograms. WPEE decreases monotonically with increasing thermal cycles, while the peak-to-peak amplitude of the second echo from the top coat/TGO interface increases monotonically. Compared with conventional single time-domain amplitude analysis, this multi-parameter feature extraction method reduces noise influence, and shows potential for identifying coating degradation progression from early microdamage to macroscopic delamination.

(2) Ultrasonic C-scan imaging provides spatial visualization of defect distribution, showing progression from initial distributed microdefects to macroscopic delamination. In addition, the FE model reasonably reproduces dynamic ultrasonic propagation in the multilayer coating, with numerical results in agreement with experimental data, providing a physical explanation for interfacial near-total reflection and multiple round-trip reverberation.

Overall, the proposed NDE method shows good feasibility for TBC delamination detection, and may serve as a technical reference for damage evaluation in aero-engine hot-section components.

Author Contributions: Conceptualization and supervision, Z.T. and S.-J.S.; methodology, X.Z. and Z.T.; formal analysis, X.Z. and D.J.; validation, D.J. and Y.H.; Investigation, Y.H. and Y.T.; data curation and result analysis, X.Z. and Z.T.; resources, H.Q. and T.L.; testing, Y.H.; writing (draft manuscript preparation), X.Z. and Z.T.; writing (review and editing), W.-H.K., Y.H., Y.T., X.Z., H.Q. and T.L. All authors have read and agreed to the published version of the manuscript.

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