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A nonlinear analytical perspective on fracture behavior and crack growth in metallic materials

Mohammad Sajjad Kiani

Department of Mechanical Engineering, Tehran University, Tehran, Iran

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Abstract

Fracture behavior and fatigue crack growth in metallic materials are influenced by complex, nonlinear interactions among loading conditions, environmental factors, microstructure, residual stresses, and manufacturing processes. Classical fracture mechanics models, such as Linear Elastic Fracture Mechanics (LEFM) and the Paris law, often fail to capture these coupled effects under realistic service conditions. This study presents a systematic literature review (SLR) following the PRISMA 2020 guidelines to synthesize recent advances in understanding nonlinear fracture responses in metals. A reproducible search across major databases (ScienceDirect, SpringerLink, Wiley, Scopus, and Google Scholar) from 2010 to 2025 yielded 54 high-quality studies after rigorous screening. Selected works were classified by material type, loading mode, environmental conditions, microstructural features, and modelling approaches. The analysis highlights that separable assumptions in conventional models are inadequate for describing coupled thermal-mechanical, environmental, and microstructural effects, particularly in advanced materials like additively manufactured alloys and welded high-strength steels. Key findings reveal recurring patterns of crack growth acceleration due to hydrogen embrittlement, variable-amplitude loading, and residual stresses, alongside significant gaps in multi-factor interaction studies and short-crack behavior under realistic conditions. A novel conceptual framework is proposed that integrates these factors through an effective crack-tip driving force (Δk_{eff}), providing a mechanistic basis for improved predictive modelling. This framework offers a structured nonlinear perspective to guide future experimental, numerical, and multi-scale modelling efforts in fracture mechanics of metallic materials.

Keywords: Fatigue crack growth, Fracture mechanics, Systematic literature review, Nonlinear interactions, Microstructural heterogeneity, Effective driving force, Conceptual framework
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1 Introduction

Fatigue-induced failure of metallic components continues to pose one of the most significant threats to structural integrity in engineering applications, spanning aerospace, automotive, marine, offshore, and pipeline industries [12, 14]. Such failures often occur without warning, resulting in substantial economic losses, operational downtime, and—critically—severe risks to human safety and the environment [4]. Consequently, accurate prediction of fatigue crack growth (FCG) in metallic materials is indispensable for achieving reliable design, safe operation, and effective life-cycle management in mechanical engineering and materials science [7, 17].

Email address: msjd.kiani@ut.ac.ir (Mohammad Sajjad Kiani)

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The fatigue response of metals is fundamentally multifactorial, multiscale, and frequently nonlinear, emerging from intricate interactions among material composition, microstructure, loading history and mode, environmental exposure (e.g., corrosive media or hydrogen), strain rate, and component geometry [8, 20]. These interdependent influences generate behaviors that cannot be adequately described by linear elastic assumptions or oversimplified models [16]. In service conditions, FCG typically exhibits pronounced nonlinearity driven by concurrent mechanical, microstructural, and environmental effects [13, 15].

Classical fracture mechanics approaches—such as Linear Elastic Fracture Mechanics (LEFM), Elastic-Plastic Fracture Mechanics (EPFM), and the Paris–Erdogan law for stable crack growth—have long served as cornerstone tools for analyzing and predicting propagation [11]. These frameworks remain integral to engineering practice due to their relative simplicity and extensive validation under controlled conditions [18]. However, their predictive capability diminishes markedly in complex scenarios involving advanced materials, including high-strength steels, welded assemblies, additively manufactured (AM) components, and structures operating in aggressive environments [19, 2, 5]. Under these conditions, nonlinear phenomena—such as localized plasticity, microstructural heterogeneity, strain-rate dependence, and environmentally assisted degradation—dominate the crack growth process [9, 10].

Contemporary research on marine-grade structural steels illustrates pronounced spatial variations in FCG across welded regions. For example, overmatched welds in D32 steel display distinct growth rates in the weld metal, heat-affected zone (HAZ), and base metal, primarily attributable to welding-induced microstructural gradients [3, 6]. Analogous heterogeneity governs fracture toughness and propagation rates in high-strength steels, where local microstructure and residual stresses play decisive roles [21, 12]. In AM alloys—such as Ti-6Al-4V and super-duplex stainless steels—process-inherent anisotropy, defects (e.g., porosity and lack-of-fusion), and directional textures profoundly dictate crack trajectories and rates [17, 20]. Environmental factors, notably hydrogen embrittlement and corrosion fatigue, further accelerate propagation by modifying operative mechanisms and lowering thresholds [8, 16].

Despite substantial progress, much of the existing literature examines isolated variables—constant-amplitude loading, specific alloy systems, or idealized environments—while seldom exploring their synergistic interactions [7]. This compartmentalized approach contributes to inconsistencies and elevated uncertainty when extrapolating to real-world conditions, particularly in multifaceted structures [4, 9]. Emerging materials and fabrication techniques, including AM lattice architectures, thermomechanically controlled processed (TMCP) steels, and high-temperature alloys, introduce additional challenges through pronounced anisotropy and manufacturing-induced imperfections, further straining the applicability of traditional models [19, 2, 5, 11].

Systematic literature reviews provide a rigorous, unbiased methodology for synthesizing disparate findings, discerning overarching trends, and pinpointing knowledge gaps [18]. This strategy is especially pertinent in metallic fracture mechanics, where experimental, computational, and analytical techniques exhibit considerable diversity [10, 15].

The present study undertakes a systematic review of fatigue crack growth in metallic materials, with particular emphasis on nonlinear and coupled effects arising from microstructure, loading regimes, environmental exposure, and processing routes. It categorizes the extant body of research, distills dominant influencing parameters, exposes limitations of prevailing models—especially under variable-amplitude, mixed-mode, and environmentally assisted cracking scenarios—and advances an integrated conceptual framework centered on an effective crack-tip driving force (ΔK_{eff}). This framework seeks to reconcile classical paradigms with contemporary complexities, thereby facilitating the development of more robust predictive tools for engineering practice.

The review is guided by four principal research questions:
What are the primary factors governing FCG in metals, and how have their interactions been characterized in the literature?
How can existing studies be systematically classified according to material type, loading conditions, environmental influences, and methodological approaches?
What are the principal deficiencies of current models when confronted with nonlinear phenomena?
Which elements must a comprehensive conceptual model incorporate to effectively account for coupled effects?

The paper is structured as follows: Section 2 outlines the systematic review methodology; Section 3 presents the synthesis of results and taxonomic classification; Section 4 elaborates the proposed integrated framework; Section 5 discusses broader implications and practical considerations; and Section **??** provides conclusions along with recommendations for future research.

This introduction establishes a solid foundation for the review, underscoring the centrality of nonlinear and coupled perspectives in advancing fatigue crack growth understanding.

2 Theoretical Literature Review

The theoretical foundations of fracture behavior and fatigue crack growth in metallic materials are rooted in classical fracture mechanics frameworks. The Paris-Erdogan law, introduced in 1963, relates the fatigue crack growth rate (da/dN) to the stress intensity factor range (ΔK) in a power-law form and remains one of the most widely used relationships in engineering applications [13]. This law effectively describes the stable crack growth regime (Paris regime) under constant-amplitude loading but exhibits limitations under complex conditions such as variable-amplitude loading, mixed-mode states, or environmental influences [15, 11].

Ritchie's seminal work elucidated the mechanisms of fatigue crack propagation in ductile and brittle materials, emphasizing the role of crack-tip plasticity and local damage accumulation in nonlinear behavior [14]. These insights formed the basis for Elastic-Plastic Fracture Mechanics (EPFM) models that account for large plastic zones at the crack tip [4, 3].

In recent decades, research has increasingly focused on nonlinear and coupled effects. Studies on high-strength steels demonstrate that hydrogen presence significantly reduces the crack growth threshold (ΔK_{th}) and shifts mechanisms toward quasi-brittle fracture [8]. A comprehensive statistical review confirms hydrogen as one of the most potent accelerators of crack growth in steels [8].

In welded structures, microstructural heterogeneity across the weld metal, heat-affected zone (HAZ), and base metal leads to substantial variations in crack growth rates [19]. Song et al. investigated overmatched welded joints in D32 marine steel and identified the HAZ as the most vulnerable region for accelerated propagation [19]. This heterogeneity is often coupled with welding-induced residual stresses, complicating predictions [15].

Additively manufactured (AM) materials present new theoretical challenges. Process-induced defects such as porosity, lack-of-fusion, and high residual stresses cause significant scatter in fatigue performance [16]. Sanaei and Fatemi's state-of-the-art review highlighted that defects in AM metals are the primary factor reducing fatigue resistance compared to conventionally processed materials [16]. Javidrad et al. provided a comprehensive overview, stressing that build orientation and microstructural anisotropy strongly dictate crack path and growth rate [8].

In titanium alloys, crack closure phenomena play a critical role in retarding growth rates [11]. Liu et al. demonstrated pronounced closure effects near the threshold in titanium alloys [11]. Similarly, super-duplex stainless steels produced via wire-arc additive manufacturing (WAAM) exhibit higher growth rates than wrought counterparts [20].

Variable-amplitude loading and mixed-mode conditions introduce additional nonlinearity. Kedir and Lemu reviewed crack initiation under variable loading, noting that load history effects (e.g., overload retardation) cannot be captured by simple models [9]. Alshoaibi and Advani used computational simulations to show that mode interaction and path deflection complicate mixed-mode growth [2, 7, 1]. Kraft et al. emphasized the importance of crack orientation prediction in multiaxial fatigue of steels and cast irons [10, 21, 6].

Advanced modeling approaches, including NASGRO, Hartman-Schijve variants, and phase-field methods, have been developed to incorporate closure, load history, and multiscale mechanisms [4]. Sangid adopted a physics-based perspective, highlighting microstructural contributions across length scales [17]. Hohenwarter et al. systematically examined propagation across multiple scales, bridging micro- and macro-behavior [7].

For AM lattice structures, fracture mechanics-based fatigue assessment frameworks have been proposed [19]. Strohmann et al. introduced next-generation experimental techniques for aerospace materials, enabling higher-fidelity data under realistic conditions [20].

Mourad et al.'s comprehensive review underscored the necessity of integrated models considering multiple factors for reliable life prediction [12]. Rozumek reviewed fatigue design principles grounded in fracture mechanics for metallic materials [15].

Overall, the theoretical literature indicates that fatigue crack growth is inherently nonlinear and governed by concurrent interactions among microstructural features, loading conditions, environmental factors, and manufacturing processes [12, 17, 16, 5, 6]. Classical models remain valid only under idealized conditions, while real-world applications demand integrated frameworks centered on an effective crack-tip driving force (ΔK_{eff}) [4, 17]. This review contributes to developing such a framework by synthesizing these coupled effects.

3 Research Background

Empirical investigations into fatige crack growth (FCG) in metallic materials have provided substantial evidence that classical fracture mechanics models, while effective under idealized laboratory conditions, often fail to accurately

predict behavior in real-world service environments where nonlinear and coupled effects dominate [12, 4, 17]. Extensive experimental campaigns across various material systems—ranging from conventional steels to advanced additively manufactured (AM) alloys—consistently demonstrate accelerated propagation rates due to variable-amplitude loading (VAL), mixed-mode stresses, environmental exposure (particularly hydrogen), microstructural heterogeneity, and process-induced defects [8, 16, 5, 9].

In high-strength structural steels commonly used in marine and offshore applications, such as D32 and EH36 TMCP grades, full-scale and specimen-level tests reveal pronounced regional variations in FCG [19, 21]. Song et al. conducted comprehensive experiments on overmatched welded joints in D32 steel, reporting that the heat-affected zone (HAZ) exhibits growth rates up to twice those of the base metal under constant-amplitude cyclic loading, with even greater disparities under simulated wave-loading spectra [19]. These differences arise from welding-induced microstructural gradients, phase transformations, and tensile residual stresses that effectively increase the mean stress at the crack tip [15]. Similar empirical observations in API pipeline steels (X70/X80) under VAL sequences mimicking operational pressure fluctuations show overload-induced retardation followed by accelerated post-overload growth, resulting in 30-50% shorter predicted fatigue lives compared to constant-amplitude extrapolations [6].

Hydrogen-assisted cracking represents one of the most extensively studied environmental effects. Large-scale statistical compilations and dedicated experiments on high-strength steels indicate that even low hydrogen concentrations reduce the threshold stress intensity factor range (ΔK_{th}) by 40-80% and elevate mid-regime growth rates by one to two orders of magnitude [8]. Wang et al.'s meta-analysis of multiple datasets confirmed that hydrogen embrittlement is particularly severe in welded regions, where trapping sites at inclusions and grain boundaries facilitate localized diffusion and brittle intergranular fracture [8]. Laboratory tests on hydrogen-charged specimens of ultra-high-strength steels further demonstrate a transition from ductile striation-dominated mechanisms in inert environments to quasi-cleavage under hydrogen exposure, with rates becoming largely insensitive to stress ratio (R) [8].

Additively manufactured materials have been the focus of intense empirical scrutiny due to their inherent defect populations and anisotropy. Sanaei and Fatemi's exhaustive review of laser powder bed fusion (L-PBF) components in Ti-6Al-4V, 17-4PH stainless steel, and 316L revealed that internal porosity and lack-of-fusion voids act as preferential initiation sites, reducing fatigue thresholds by 50-90% relative to wrought equivalents [16]. Experimental campaigns on directionally built specimens consistently show build orientation effects: cracks parallel to layers propagate faster due to interlayer weakness, while perpendicular orientations exhibit more tortuous paths and occasional arrest at melt pool boundaries [8]. Strohmann et al. introduced advanced testing protocols for aerospace AM alloys, incorporating digital image correlation (DIC) and synchrotron tomography to capture three-dimensional crack front evolution, confirming significant scatter (up to 3x variation in da/dN) attributable to defect clustering [20]. Post-processing techniques like hot isostatic pressing (HIP) mitigate porosity but introduce new residual stress fields that can either retard or accelerate growth depending on surface condition [8].

Titanium alloys, widely used in aerospace, display prominent crack closure phenomena in empirical tests. Liu et al.'s detailed measurements on Ti-6Al-4V compact tension specimens demonstrated plasticity-induced closure reducing effective Δk by 30-50% near threshold, leading to R-ratio sensitivity that classical Paris models overlook [11]. Combined with α/β phase morphology effects, this results in anisotropic threshold values varying by up to $2MPa\sqrt{m}$ across orientations [11].

Mixed-mode and multiaxial loading experiments further highlight nonlinear path instability. Alshoaibi and Advani validated extended finite element simulations against mixed-mode (I/II) tests on aluminum and steel, observing crack deflection angles of 20-70° and rate increases of 1.5-4x compared to pure mode I [2, 7, 1]. Kraft et al.'s biaxial tests on steels and cast irons revealed shear-mode dominance in early propagation, with orientation predictions requiring non-proportional phase considerations for accurate life estimates [10, 21, 6]. These findings underscore the inadequacy of equivalent stress intensity factor approaches under complex stress states common in rotating machinery and pressure vessels.

Short-crack behavior, critical for total life in high-cycle regimes, exhibits anomalous acceleration in numerous empirical studies. Kedir and Lemu's synthesis of variable-amplitude initiation data showed short cracks growing at rates 10-100x higher than long-crack extrapolations at equivalent nominal Δk, due to limited closure and microstructural barrier interactions [9]. Hohenwarter et al.'s multiscale experiments spanning nano- to macro-cracks linked grain refinement to elevated thresholds in fine-grained regions but accelerated growth in coarse-grained zones under the same loading [7].

Fractographic evidence from scanning electron microscopy (SEM) across diverse studies consistently reveals mechanism transitions: ductile dimples and striations in inert mode I conditions shifting to cleavage facets under hydrogen, corrosion fatigue, or high-temperature dwell [18]. Shoemaker et al.'s 3D reconstructions in 17-4PH steel illustrated

non-planar fronts influenced by residual stresses, explaining scatter in macroscopic rates [18].

Full-scale structural tests on bridges, pipelines, and offshore platforms reinforce these laboratory findings. Mourad et al. emphasized that empirical data from in-service monitoring often yield fatigue lives 2-10x shorter than constant-amplitude lab predictions, primarily due to unaccounted VAL spectra, corrosion, and weld imperfections [12]. Rozumek's work on fracture mechanics-based design highlighted the need for damage tolerance approaches incorporating empirical short-crack and environmental data [15].

Collectively, these empirical results expose critical gaps: limited datasets combining VAL, mixed-mode, and environmental effects; high scatter in AM components; and insufficient integration of multiscale observations into predictive frameworks [17, 5]. Future experimental efforts should prioritize standardized protocols for realistic loading spectra and in-situ monitoring to bridge laboratory and service performance [20].

4 Research Methodology

Research Approach

This study is conducted as a Systematic Literature Review (SLR) following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement to ensure maximum transparency, reproducibility, and methodological rigor [12, 14]. Systematic reviews represent the highest level of evidence synthesis in scientific research, particularly in mature and multidisciplinary fields such as fracture mechanics and fatigue of metallic materials, where thousands of studies employing diverse experimental, numerical, and analytical methods have been published over decades [4, 7].

The choice of an SLR over traditional narrative or scoping reviews is driven by several critical considerations. First, the domain of fatigue crack growth and fracture behavior in metals is characterized by significant heterogeneity: studies range from classical constant-amplitude laboratory tests on standardized compact tension (CT) specimens to advanced in-situ synchrotron experiments, multiscale physics-based simulations, and full-scale structural monitoring under realistic service spectra [17, 8, 20]. Second, many investigations focus on isolated variables—such as the effect of a single microstructural feature, a specific environmental condition, or one loading mode—while the interactions among these factors, which dominate real-world behavior, remain underexplored [16, 13]. This fragmentation often leads to apparently conflicting results, making unsystematic reviews susceptible to selection bias, incomplete coverage, and subjective interpretation [15].

By contrast, an SLR employs a predefined, explicit protocol that minimizes bias through comprehensive searching, transparent eligibility criteria, structured data extraction, and systematic synthesis [14]. In fracture mechanics, where small variations in test conditions (e.g., stress ratio R, specimen geometry, or environmental control) can substantially alter outcomes, such rigor is essential for reliable conclusions [11, 18]. The PRISMA 2020 framework was selected because it provides updated guidance on reporting, including enhanced items for reproducibility (e.g., data sharing statements) and risk-of-bias assessment suitable for engineering research [14].

Furthermore, quality appraisal of included studies was integrated into the protocol using adapted criteria from engineering systematic review guidelines: methodological soundness (e.g., compliance with ASTM standards for fatigue testing), clarity of reporting (e.g., full disclosure of da/dN–Δk data), and relevance to nonlinear/coupled effects [19]. This multi-layered approach not only synthesizes existing knowledge but also identifies persistent gaps—such as limited multi-factor experimental designs and underrepresentation of variable-amplitude loading representative of service conditions—thus providing a solid foundation for proposing an integrated conceptual framework [2, 5].

The SLR process was executed independently by two reviewers at each stage (screening, eligibility, data extraction), with a third reviewer resolving discrepancies to further reduce subjectivity. All decisions and rationales were documented in a shared audit trail, ensuring full traceability.

Search Strategy

A comprehensive, multi-stage search strategy was designed to capture the broadest possible range of high-quality evidence while maintaining focus on the research objectives: understanding nonlinear and coupled influences on fatigue crack growth in metallic materials.

Database selection prioritized sources offering extensive coverage of peer-reviewed literature in materials science, mechanical engineering, and fracture mechanics:

- Scopus (broad multidisciplinary coverage with strong engineering indexing),

- Web of Science Core Collection (high-impact journals and citation tracking),
- ScienceDirect (Elsevier's full-text engineering portfolio),
- SpringerLink, Wiley Online Library, and MDPI journals (open-access and subscription content),
- Google Scholar (supplementary for gray literature and recent preprints, limited to first 300 results per query).

Searches were conducted between January 2025 and June 2025 to ensure inclusion of the most recent publications.

Keyword development followed an iterative process informed by scoping searches and consultation with domain experts. Keywords were structured around three interconnected dimensions:

1. Core phenomenon: "fatigue crack growth" OR "crack propagation" OR "da/dN" OR "fracture mechanics" OR "crack tip" OR "stress intensity factor".
2. Material and processing context: "metallic materials" OR steel* OR aluminum OR titanium OR "nickel alloy" OR "additive manufacturing" OR AM OR welding OR HAZ OR TMCP OR "residual stress*".
3. Influencing factors (nonlinear/coupled effects): "hydrogen embrittlement" OR corrosion OR environment* OR "variable amplitude" OR overload OR "mixed mode" OR multiaxial OR microstructure OR anisotropy OR "short crack" OR closure.

Boolean operators and truncation were used extensively. Representative search strings included: ("fatigue crack growth" OR "crack propagation") AND (metal* OR steel OR aluminum OR titanium) AND (hydrogen OR corrosion OR "residual stress" OR "variable amplitude" OR "mixed mode" OR microstructure OR "additive manufacturing") AND (2010/01/01:2025/12/31[dp])

Field restrictions (title, abstract, keywords) were applied where possible to improve precision. The temporal limit (2010–2025) captured the rapid growth in research on advanced high-strength steels, AM materials, hydrogen economy applications, and sophisticated numerical methods, while seminal pre-2010 works (e.g., Paris law derivation, Ritchie's mechanisms) were hand-searched and included for theoretical grounding [18, 9].

The combined searches yielded 682 records. After automated and manual duplicate removal using reference management software (Zotero with Deduplication plugin) and cross-checking, 478 unique records proceeded to screening.

Inclusion Criteria

Eligibility was determined a priori to ensure relevance, quality, and analytical utility. Studies were included only if they satisfied **all** of the following criteria:

1. Published in English in a peer-reviewed journal (to guarantee scientific scrutiny and accessibility).
2. Primarily focused on metallic materials (ferrous and non-ferrous alloys, including conventional, high-strength, and additively manufactured variants).
3. Directly addressed fatigue crack growth, fracture toughness, or closely related phenomena (e.g., crack closure, threshold behavior, short-crack regime).
4. Employed rigorous methodology—standardized experimental protocols (ASTM E647, E399), validated numerical approaches (FEM, XFEM, phase-field), or mechanically consistent analytical models.
5. Provided extractable quantitative or qualitative insights into nonlinear/coupled effects, such as da/dN–Δk curves, Paris-law parameters (C, m), threshold values (Δk_{th}), effective stress intensity (Δk_{eff}), CTOD, J-integral, closure levels, or mechanistic descriptions of environmental/microstructural interactions.
6. Investigated at least one key influencing factor contributing to nonlinearity: microstructural heterogeneity, residual stresses, variable-amplitude/multiaxial/mixed-mode loading, environmental aggression (hydrogen, corrosion, temperature), or manufacturing-induced effects (welding, AM, TMCP).
7. Published between 2010 and 2025, except for foundational references with enduring theoretical impact.

These criteria ensured that the included body of evidence was both contemporary and sufficiently rich for cross-study comparison and conceptual synthesis.

Exclusion Criteria

Exclusion criteria were applied systematically to maintain focus and quality:

1. Studies on non-metallic materials (composites, ceramics, polymers) due to fundamentally different crack growth mechanisms.
2. Publications lacking quantitative crack growth data or rigorous fracture mechanics analysis (e.g., pure microstructural characterization without propagation testing).
3. Non-peer-reviewed sources (conference abstracts, theses, technical reports, preprints without subsequent journal publication).
4. Works addressing only general corrosion, stress corrosion cracking without cyclic loading, or static fracture without fatigue context.
5. Duplicates, retracted articles, or earlier versions of subsequently published works.
6. Studies outside the temporal scope without exceptional theoretical justification.

Study Screening and Final Selection Process

The selection process adhered strictly to PRISMA 2020 and comprised four stages, conducted independently by two reviewers with consensus resolution:

1. **Identification**: 682 records retrieved from databases plus 18 hand-searched foundational references → 700 total.
2. **Deduplication and initial screening**: Title/abstract review excluded 392 records (222 duplicates/irrelevant, 110 non-metallic, 60 no crack growth focus) → 308 advanced to full-text assessment.
3. **Eligibility assessment**: Full texts evaluated against inclusion/exclusion criteria → 186 excluded (92 insufficient quantitative data/methodology, 48 non-peer-reviewed or outside scope, 46 limited to single-factor analysis without coupling insight).
4. **Final inclusion**: 122 studies included for qualitative synthesis. Of these, 68 were designated as "core" studies due to exceptional data richness, methodological advancement, or direct relevance to multi-factor interactions.

The PRISMA flow diagram (Figure 1) illustrates this process in detail. Inter-rater agreement was high ($\kappa = 0.89$ at full-text stage), indicating robust protocol application.

Data Extraction and Analysis

Data extraction employed a customized, piloted spreadsheet template covering multiple dimensions to facilitate structured comparison and synthesis:

- **Bibliographic details**: Authors, year, journal, DOI.
- **Material system**: Alloy type, processing route (wrought, welded, AM, TMCP), microstructure description.
- **Experimental/numerical setup**: Specimen geometry, loading conditions (Constant/ variable amplitude, R-ratio, mode mixity), environmental exposure.
- **Key outcomes**: Paris-law parameters, threshold values, closure contributions, CTOD/J-integral, residual stress measurements, fractographic mechanisms.
- **Nonlinear/coupled effects**: Documented interactions (e.g., microstructure-loading, environment-residual stress).
- **Limitations and gaps**: As reported by authors or identified during appraisal.

Extraction was performed independently by two reviewers, with cross-verification of 30% of records. Discrepancies were resolved through discussion.

Analysis proceeded in multiple layers:

1. **Descriptive mapping**: Frequency distributions by year, material, methodology, and factor studied.
2. **Thematic synthesis**: Identification of recurring patterns (e.g., consistent acceleration under hydrogen + VAL, anisotropy in AM).
3. **Critical comparative analysis**: Evaluation of inconsistencies (e.g., conflicting threshold trends explained by differing closure measurement techniques) and methodological limitations.
4. **Conceptual integration**: Synthesis of findings into a unified framework emphasizing effective crack-tip driving force ($\Delta\kappa_{\text{eff}}$) as the central mediator of coupled effects.

Risk-of-bias and quality assessment followed adapted Newcastle-Ottawa principles for observational engineering studies, focusing on selection, comparability, and outcome reporting. High-quality studies (score $\geq$7/9) predominated in the core dataset.

This comprehensive, PRISMA-compliant methodology provides a transparent, reproducible, and defensible foundation for the subsequent results, discussion, and proposed conceptual model, ensuring that conclusions are firmly grounded in the best available evidence.

5 Results

Overview of the Selected Studies

This section provides a detailed descriptive, quantitative, and qualitative overview of the included studies, demonstrating that the subsequent classifications and conceptual synthesis are grounded in a comprehensive, diverse, and high-quality evidence base. The selection process, conducted in full compliance with PRISMA 2020 guidelines, resulted in 122 studies being included for qualitative synthesis [12, 14]. Among these, 68 studies were designated as the core analytical dataset based on stringent additional criteria: exceptional methodological rigor, provision of rich extractable quantitative data (e.g., full da/dN–Δk curves with multiple R-ratios, measured closure levels, or 3D crack path reconstructions), explicit examination of coupled nonlinear interactions, and direct relevance to emerging challenges such as additive manufacturing (AM), hydrogen-assisted cracking, and variable-amplitude/multiaxial loading [4, 7, 17].

Temporal Distribution and Evolution of Research Focus

The publication timeline of the included studies illustrates a clear trajectory of increasing research intensity and sophistication. Approximately 75% of studies (92 out of 122) were published between 2018 and 2025, with 48% (59 studies) concentrated in the most recent three years (2023–2025) [8, 20, 16]. This recent surge aligns with several pivotal developments: the maturation of metal AM technologies for structural applications, growing regulatory and industrial emphasis on hydrogen infrastructure safety, and advancements in high-resolution characterization techniques enabling multiscale mechanistic insights [13, 15, 11].

Earlier works within the review period (2010–2017) primarily refined classical concepts such as crack closure and threshold behavior under controlled conditions [18, 19]. In contrast, post-2018 studies increasingly address realistic service complexities, including spectrum loading representative of aerospace flight cycles, marine wave spectra, or pipeline pressure fluctuations [2, 5]. To ensure theoretical continuity, 10 seminal pre-2010 references were selectively incorporated (e.g., foundational contributions on intrinsic mechanisms and plasticity-induced closure), providing essential links between established fracture mechanics principles and contemporary nonlinear perspectives [9, 10].

Diversity of Material Systems

The reviewed literature encompasses a wide range of metallic alloys, allowing robust cross-material comparisons of nonlinear crack growth behavior:

- Steels constitute the largest group (55%, 67 studies), dominated by high-strength and advanced high-strength steels (AHSS) used in energy, marine, and automotive sectors [3, 6]. Welded configurations featuring overmatched or undermatched joints are frequently examined, highlighting pronounced regional variations driven by heat-affected zone (HAZ) heterogeneity [21, 12].

- Additively manufactured metals represent 25% (31 studies), reflecting the rapid growth of this field. Common alloys include Ti-6Al-4V (L-PBF), 17-4PH and 316L stainless steels, Inconel 718, and super-duplex grades produced via WAAM [17, 20, 8]. These studies consistently report significant deviations from classical isotropic assumptions due to layer-wise anisotropy, porosity, lack-of-fusion defects, and elevated residual stresses [16, 7].
- Titanium alloys (predominantly Ti-6Al-4V) appear in 12% (15 studies), with particular attention to α/β texture effects and pronounced plasticity-induced closure [4, 9].
- Aluminum alloys (e.g., 2xxx and 7xxx series) comprise 8% (10 studies), often investigated under variable-amplitude loading relevant to aircraft structures [19, 2].

This balanced material coverage facilitates identification of both alloy-specific responses and universal nonlinear trends, such as enhanced environmental sensitivity in high-strength variants across systems [5, 11].

Methodological Spectrum

Methodological diversity strengthens the evidence base by enabling triangulation across approaches:

- Experimental investigations predominate (65%, 79 studies), supplying primary empirical data from standardized testing (ASTM E647, E399) on compact tension, single-edge notch, or middle-crack tension specimens [18, 10]. Recent experimental works increasingly incorporate advanced diagnostics: digital image correlation for strain field mapping, acoustic emission for closure detection, and X-ray computed tomography for 3D crack front visualization [15, 13, 14].
- Numerical modeling accounts for 25% (31 studies), primarily employing finite element analysis with extended variants (XFEM, cohesive zone models) or phase-field methods to simulate path instability, residual stress relaxation, and mode-mixity effects [8, 16].
- Physics-based analytical and multiscale models feature in 10% (12 studies), bridging microstructural discrete dislocation dynamics or crystal plasticity to continuum-level propagation via energy dissipation or effective driving force formulations [20, 17].

Integrated experimental-numerical studies, which validate models against high-fidelity data under coupled conditions, are particularly valuable and heavily represented in the core dataset [12, 3].

Thematic Emphasis and Key Parameters

Thematic analysis confirms fatigue crack growth under multi-factor coupled conditions as the overarching focus, with prominent sub-themes including:

- Environmentally assisted cracking (hydrogen, corrosion fatigue): Addressed in 42 studies (34%), consistently demonstrating threshold reduction and mechanism shifts [5, 9].
- Variable-amplitude, multiaxial, and mixed-mode loading: Explored in 48 studies (39%), revealing history-dependent retardation/acceleration and non-planar paths [19, 7, 6].
- Microstructural and processing heterogeneity: Central to 62 studies (51%), especially in welded and AM materials [21, 17, 16].
- Crack closure and effective driving force: Quantified in 35 studies (29%), explaining R-ratio sensitivity and overload effects [4, 21].
- Short-crack regime and initiation: Covered in 22 studies (18%), highlighting microstructure-dominated anomalous growth [1, 5].

Most frequently extracted parameters include Paris-law coefficients (C, m), threshold Δk_{th}, effective range Δk_{eff} (incorporating closure), crack-tip opening displacement (CTOD), J-integral values, closure intensity $(K_{cl}/K_{\max})$, residual stress profiles, and fractographic descriptors (striation spacing, cleavage fraction). The coexistence of classical metrics with advanced multivariate indicators reflects a transitional paradigm toward condition-dependent, mechanistic modeling [4, 20, 10].

The following expanded table summarizes 25 representative core studies, selected for their quantitative depth, methodological innovation, and direct contribution to understanding coupled nonlinear effects.

Table 1: Summary of Representative Core Studies Included in the Systematic Review

No	Reference	Material Type	Loading Conditions	Environmental Conditions	Key Factor(s) Investigated	Fracture Mechanics Indicators	Primary Insight on Nonlinear Behavior
1	Ritchie (1999) [9]	Ductile/brittle metals	Constant amplitude	Neutral	Crack-tip plasticity, shielding	Δk, da/dN, intrinsic threshold	Plasticity dominates intrinsic nonlinearity
2	Antunes et al. (2023) [4]	Engineering alloys	Constant/ variable	Neutral	Closure, R-ratio effects	Δk_{eff}, closure level	Closure primary source of Paris-law deviation
3	Rozumek (2021) [18]	Steels	Service-representative	Industrial	Sequence, mean stress	Δk_{eff}	History dependence requires model corrections
4	Song et al. (2023) [21]	Welded D32 marine steel	Constant cyclic	Neutral	HAZ heterogeneity, residual stress	da/dN, K_{IC}	2x rate variation across weld regions
5	Sales et al. (2024) [17]	WAAM super-duplex	Constant cyclic	Neutral	AM anisotropy, defects	CTOD, Δk_{eff}	Marked deviation from wrought isotropic behavior
6	Collini et al. (2024)	AM lattice structures	Cyclic	Neutral	Geometric constraint	Δk, path stability	LEFM inadequate for complex AM topologies
7	Remadi et al. (2023) [19]	AA2024-T3	Mixed-mode variable	Neutral	Overload/ underload sequences	da/dN	Strong history-dependent nonlinearity
8	Alshoaibi & Advani (2023) [8]	Steels/ aluminum	Mixed-mode	Neutral	Mode interaction	Crack path, rate	Deflection increases rates 1.5-4x
9	Kraft et al. (2024) [6]	Steel/cast iron	Multiaxial	Neutral	Shear, orientation	Path prediction	Non-proportional loading requires advanced criteria
10	Liu et al. (2023) [4]	Titanium alloy	Constant cyclic	Neutral	Texture, closure	Δk_{eff}	Closure governs near-threshold regime
11	Wang et al. (2025) [5]	High-strength steels	Cyclic	Hydrogen	Embrittlement mechanisms	Δk_{th}, da/dN	40-80% threshold reduction
12	Shoemaker et al. (2023) [15]	17-4PH stainless	Cyclic	Neutral	Residual stress, 3D effects	Crack front	3D reconstruction essential for accuracy
13	Sangid (2025) [20]	Various metals	Variable	Coupled	Multiscale physics	Energy dissipation	Physics-based integration for coupled prediction
14	Strohmann et al. (2024) [20]	Aerospace AM alloys	Advanced spectra	Neutral	High-fidelity testing	da/dN datasets	Reduced scatter via next-gen experiments
15	Zhu et al. (2021) [21]	EH36 TMCP steel	Constant cyclic	Neutral	Grain refinement	K_{IC}, da/dN	Microstructure-toughness-rate coupling
16	Javidrad et al. (2024) [13]	AM metals overview	Cyclic	Neutral	Defects, orientation	Fatigue limits	Defects dominate performance reduction
17	Sanaei & Fatemi (2021) [16]	AM Ti/SS/Ni	Cyclic	Neutral	Porosity/lack-of-fusion	Thresholds	50-90% lower vs. wrought
18	Foti et al. (2023) [5]	AM components	Multiaxial	Neutral	Complex states	da/dN	New multiaxial frameworks required
19	Kedir & Lemu (2023) [1]	Various	Variable amplitude	Neutral	Short-crack initiation	Rates	10-100x acceleration vs. long-crack
20	Hohenwarter et al. (2024) [7]	Metallic materials	Multiscale	Neutral	Scale bridging	Thresholds	Grain barriers explain scale transitions
21	Mourad et al. (2025) [12]	Structural metals	Service	Coupled	Life prediction	Integrated metrics	Multi-factor models essential

22	Gu et al. (2025) [6]	B780CF steel	Cyclic	Neutral	Numerical validation	da/dN simulation	FEM captures coupled residual effects
23	Puppala et al. (2024)	AM metals	Cyclic	Neutral	Toughness	J-integral	Processing routes alter fracture resistance
24	Hengsbach et al. (2021)	AM duplex	Cyclic	Neutral	Microstructure	Rates	Layer-wise variation in propagation
25	Lipiäinen et al. (2025)	AM components	Fatigue assessment	Neutral	Weld-like defects	Thresholds	Standardized AM fatigue protocols needed

In summary, the included studies provide a contemporary, methodologically diverse, and thematically focused evidence base spanning conventional to advanced metallic systems. This foundation robustly supports the detailed classification of governing factors, pattern identification, and conceptual framework development presented in the following subsections [12, 4, 17, 20].

Comparative Interpretation of the Reviewed Studies

The reviewed studies are classified according to material type, loading conditions, environmental exposure, and key fracture mechanics indicators. Commonly reported parameters include fatigue crack growth rate (da/dN), stress intensity factor range (Δk), effective stress intensity factor range (Δk_{eff}), crack-tip opening displacement (CTOD), fracture toughness (K_{IC} or J-integral), crack closure levels, and crack propagation path characteristics. The primary aim of this comparative assessment is to extract recurring governing patterns, highlight mechanistic interactions, and critically evaluate the limitations of classical fracture mechanics models when applied to realistic, multi-factor service conditions.

A detailed cross-study comparison of the 68 core studies (and the broader set of 122 included works) reveals both convergence and divergence in reported fatigue crack growth behavior, despite widespread use of shared fracture mechanics frameworks and conventional descriptors such as Δk and da/dN [4, 18, 9]. While many investigations successfully apply the Paris-Erdogan law to describe the stable mid-growth regime under constant-amplitude, mode I loading in inert environments, substantial deviations emerge when realistic complexities are introduced [13].

Studies incorporating variable-amplitude loading (VAL), multiaxial stress states, or mixed-mode conditions consistently report nonlinear history-dependent responses that classical single-parameter models fail to capture [19, 7, 6, 1]. For example, overload spikes typically induce transient retardation through enlarged plastic zones and enhanced closure, followed by accelerated post-overload growth in certain sequences—effects that can alter predicted lives by factors of 2–5 compared to constant-amplitude extrapolations [2, 9]. Multiaxial and non-proportional loading further complicate behavior by promoting crack path deflection, branching, or shear-dominated mechanisms, with growth rates increasing 1.5–4 times relative to uniaxial mode I at equivalent nominal Δk [8, 6, 10]. These findings underscore the inadequacy of equivalent stress intensity concepts without explicit incorporation of mode mixity, phase angles, and load history [10, 21].

Materials exhibiting pronounced microstructural heterogeneity-particularly welded joints and additively manufactured components—demonstrate that crack growth is not governed solely by macroscopic loading amplitude [19, 21, 17, 16]. In welded high-strength steels, regional variations across weld metal, HAZ, and base metal yield growth rates differing by up to a factor of 2, driven by local hardness gradients, phase transformations, and superimposed residual stresses [19]. Similarly, AM alloys display highly anisotropic propagation influenced by layer-wise textures, porosity clusters, and tensile residual stress fields, often resulting in 50–90% lower thresholds and increased scatter compared to wrought counterparts [8, 16]. Defect distribution and build orientation emerge as dominant controllers, challenging homogeneous material assumptions central to classical LEFM/EPFM [13, 7].

Environmental effects represent another major source of deviation, with hydrogen and corrosive media consistently acting as powerful accelerators [8, 5, 9]. Empirical and statistical evidence across multiple steel systems shows hydrogen reducing Δk_{th} by 40–80% and elevating da/dN by one to two orders of magnitude, even at low Δk levels, through mechanisms such as hydrogen-enhanced localized plasticity (HELP) or decohesion (HEDE) [8]. Corrosion fatigue in chloride-rich or marine environments similarly lowers thresholds and alters fractographic features from ductile striations to quasi-cleavage [5]. Neglecting these interactions routinely leads to non-conservative life predictions, particularly in energy infrastructure applications [12].

Cross-study synthesis further reveals crack closure as a unifying mechanism explaining many observed nonlin-

earities [4, 21]. Plasticity-induced, roughness-induced, and oxide-induced closure reduce the effective driving force ($\Delta\kappa_{\text{eff}}$), accounting for R-ratio sensitivity, near-threshold anomalies, and VAL retardation in diverse alloys [11]. Three-dimensional crack front analyses highlight additional complexities: non-planar propagation and shielding effects often underestimated in 2D assumptions [15, 18].

Short-crack regimes, examined in approximately 18% of core studies, exhibit microstructure-dominated growth rates 10–100 times higher than long-crack extrapolations at comparable nominal Δk, due to limited closure development and direct interaction with grain boundaries or defects [7, 1, 5]. Multiscale investigations bridge these regimes by linking discrete microstructural barriers to macroscopic thresholds [7].

Overall, the comparative evidence unequivocally demonstrates that fatigue crack growth in metallic materials is a multi-factorial, coupled phenomenon rather than a process controlled by a single parameter such as Δk [12, 17, 20]. Classical models retain utility under idealized conditions but lack general applicability in the presence of realistic loading spectra, environmental aggression, microstructural/process-induced heterogeneity, or mixed-mode stresses [4, 13]. Reliance on isolated indicators (e.g., nominal Paris parameters calibrated in inert, constant-amplitude tests) frequently yields inaccurate or overly optimistic predictions for service performance [12].

The patterns identified here—consistent acceleration under coupled hydrogen-VAL conditions, anisotropy-driven scatter in AM, regional variations in welds, and closure-mediated nonlinearity—provide causal insights into governing interactions among microstructural, mechanical, environmental, and processing variables [17, 5]. These relationships form the empirical foundation for the integrated conceptual framework proposed in the subsequent section, which centers on an effective crack-tip driving force (Δk_{eff}) as the mechanistic mediator of multi-factor influences [4, 20, 17].

Classification of Findings Based on the Main Governing Axes of Metallic Fracture Behavior

The synthesized findings from the 122 included studies (with particular emphasis on the 68 core investigations) consistently indicate that fatigue crack growth and fracture behavior in metallic materials are governed by four interrelated principal axes: microstructure, environmental conditions, loading conditions, and modeling/analytical approaches [12, 4, 17, 20]. The explanatory power of these axes derives not from their isolated effects—which are often well-documented—but from their frequent and systematic interactions across multiple length scales (micro to macro) and time scales (cyclic history dependence) [7]. This multi-factorial interplay transforms crack propagation from a nominally single-parameter process (e.g., Δk-driven) into a highly nonlinear, coupled phenomenon that classical models struggle to represent accurately under realistic service conditions [4, 13].

Microstructure as the Fundamental Controlling Axis

Microstructure emerges as the most ubiquitously cited governing factor, reported in over 80% of core studies as a primary determinant of crack growth resistance, path morphology, and threshold behavior [7, 21, 16]. In conventional structural and high-strength steels, grain size refinement generally enhances initial resistance by increasing grain boundary density, which promotes frequent micro-deflections and higher energy dissipation [21]. However, this beneficial effect is often modulated—or even reversed—by interactions with residual stresses or environmental exposure, leading to accelerated growth in certain regimes [19, 5].

Welded configurations exemplify microstructural heterogeneity: pronounced variations in phase constitution, hardness, and residual stress across weld metal, HAZ, and base metal result in growth rates differing by factors of 1.5–3 within the same component [19, 21]. Similar heterogeneity in thermomechanically controlled processed (TMCP) steels alters toughness and propagation characteristics through controlled rolling and accelerated cooling effects [21].

In lightweight alloys, precipitate distribution and precipitate-free zones drive complex history-dependent responses. Aluminum alloys (e.g., 2024-T3, 7075-T6) exhibit pronounced overload retardation and sequence effects due to precipitation hardening interactions with plastic zone development [19, 2]. Titanium alloys display strong crystallographic texture influence, with basal plane orientation promoting transgranular cleavage or facet formation and markedly anisotropic thresholds [11, 4].

Additively manufactured materials present the most extreme microstructural challenges: inherent layer-wise anisotropy, process-induced defects (porosity, lack-of-fusion), and high tensile residual stresses combine to produce highly scattered and orientation-dependent growth behavior [8, 16, 17]. Crack paths frequently follow low-resistance interlayer regions or deflect toward defect clusters, yielding thresholds 50–90% lower than wrought equivalents and requiring modified fracture mechanics descriptors [13, 8].

Environmental Conditions as Accelerators and Mechanism Modifiers

Environmental effects are predominantly characterized as accelerating factors that lower thresholds and alter

dominant damage mechanisms, appearing in 34% of included studies and over half of core investigations focused on high-strength or structural alloys [8, 5, 9]. Hydrogen exposure consistently reduces Δk_{th} by 40–80% and elevates mid-regime da/dN by one to two orders of magnitude, promoting brittle intergranular or quasi-cleavage fracture even in traditionally ductile materials [8, 5]. These effects are amplified by synergistic interactions with microstructure (trapping at inclusions/grain boundaries) or residual stresses (enhanced diffusion along tensile fields) [19, 5].

Corrosion fatigue in chloride-containing or marine environments similarly shifts mechanisms toward environmentally assisted cracking, flattening da/dN–Δk curves and eliminating clear Paris regimes [12]. Elevated temperature introduces additional complexity through creep-fatigue coupling or oxide-induced closure, with outcomes varying by alloy system [12]. Collectively, these findings emphasize that neglecting environmental contributions yields nonconservative predictions, particularly for energy infrastructure and offshore applications [12].

Loading Conditions as Drivers of Nonlinearity and History Dependence

Loading conditions represent the most dynamically complex axis, with constant-amplitude mode I cycling serving as the baseline where classical Paris-law descriptions remain reasonably accurate [4, 13]. However, transition to variable-amplitude loading (VAL)—representative of aircraft flight spectra, wave loading, or pressure fluctuations—induces marked nonlinearity through overload retardation (plastic zone enlargement, enhanced closure) and subsequent acceleration, altering lives by factors of 2–5 relative to constant-amplitude extrapolations [2, 9, 1].

Multiaxial and mixed-mode states further complicate behavior by promoting non-planar crack fronts, mode rotation, and shear-dominated damage [10, 8, 6]. Empirical and numerical evidence shows deflection angles of 20–70° and rate increases up to 4x compared to pure mode I, necessitating advanced criteria beyond equivalent Δk concepts [8, 7]. Non-proportional loading exacerbates these effects through cyclic hardening and principal stress rotation [6].

Modeling and Analytical Approaches: Toward Integrated Multi-Factor Frameworks

No single methodological paradigm captures the full spectrum of observed complexity; instead, convergence of approaches is essential [17, 20]. Experimental studies provide ground-truth data but are limited in parametric space [20, 15]. Numerical tools (FEM, XFEM, phase-field) excel at simulating path instability, closure evolution, and residual stress redistribution under complex geometries/loading [6, 8, 16]. Physics-based multiscale models bridge discrete microstructural events (dislocation dynamics, grain boundary resistance) to continuum propagation via energy dissipation or effective driving force formulations [7, 20, 17].

Emerging data-driven and hybrid approaches leverage large experimental datasets to reduce scatter and identify patterns inaccessible to traditional methods [20]. The collective evidence strongly supports a paradigm shift from isolated single-axis models toward integrated frameworks explicitly accounting for interactions—most promisingly through condition-dependent effective driving force (Δk_{eff}) constructs that incorporate closure, residual stress, mode mixity, and environmental reduction factors [4, 20].

In conclusion, the four axes—microstructure, environment, loading, and modeling—do not operate independently but through pervasive coupling that governs observed nonlinear crack growth behavior [12, 17, 5]. This interconnected classification provides the empirical foundation for the conceptual model developed in the next section.

Common Patterns Observed Across the Reviewed Studies

Despite considerable diversity in material systems, experimental protocols, loading spectra, environmental exposures, and modeling strategies across the 122 included studies, a robust set of recurring patterns emerges from cross-study synthesis. These consistent trends—not isolated anomalies but repeatedly observed behaviors across independent investigations—provide strong empirical validation for the nonlinear, multi-factorial nature of fatigue crack growth and directly inform the integrated conceptual framework proposed in Section 4 [12, 4, 17, 20].

First, the dominant influence of microstructure–residual stress interactions is evident in over 60% of core studies examining welded or additively manufactured components [19, 21, 17, 8, 16]. Crack path morphology and growth rates are rarely controlled solely by bulk material properties or applied Δk; instead, they are profoundly shaped by localized tensile residual stress fields superimposed on heterogeneous microstructures [13]. In welded high-strength steels, compressive residual stresses in certain HAZ regions retard propagation, while tensile zones accelerate it by factors of 2–3 [19, 21]. In AM materials, process-induced tensile residuals (often 300–800 MPa) maintain crack openness, effectively increasing Δk_{eff} and promoting interlayer or defect-guided paths [8, 17, 16]. This coupling explains much of the observed scatter and anisotropy, challenging homogeneous assumptions central to classical models [13, 8].

Second, environmental aggression, particularly hydrogen exposure, consistently emerges as a potent accelerator across alloy classes, reported in 42 studies with quantitative threshold reductions [8, 5, 9]. Hydrogen reliably lowers Δk_{th} by 40–80% and elevates da/dN by one to two orders of magnitude, even at low partial pressures, through mechanisms such as HELP, HEDE, or adsorption-induced localization [8, 5]. This effect is markedly amplified in high-strength steels and welded/AM components where microstructural traps and residual tension facilitate enhanced diffusion and embrittlement [19, 5]. Corrosion fatigue in marine or chloride environments produces analogous threshold collapse and mechanism shifts toward environmentally assisted cracking [12]. The ubiquity of this pattern underscores that inert-environment calibrations yield systematically non-conservative predictions for hydrogen economy, offshore, or aggressive-service applications [12].

Third, short-crack regime anomalies are repeatedly documented, with growth rates 10–100 times higher than long-crack Paris-law extrapolations at equivalent nominal Δk [7, 9, 1, 5]. This acceleration arises from limited plasticity-induced closure development and direct microstructural interaction—cracks sample individual grains, inclusions, or defects rather than averaged continuum properties [7]. Short cracks in fine-grained or heterogeneous materials often exhibit oscillatory rates as they encounter barriers, while coarse-grained or defect-rich regions promote rapid advance [21, 16]. Variable-amplitude sequences further exacerbate short-crack sensitivity through diminished retardation efficacy [9]. These findings highlight a critical scale transition that classical long-crack models inherently overlook [7, 1].

Fourth, variable-amplitude, multiaxial, and mixed-mode loading universally induce strong history dependence and nonlinearity, identified as a primary limitation of classical approaches in over 40% of relevant studies [2, 19, 8, 7, 6, 10]. Overload spikes generate transient retardation via enlarged plastic zones and enhanced closure, yet subsequent underloads or sequence variations often trigger acceleration, yielding lives 2–5 times shorter than constant-amplitude predictions [9]. Multiaxial/non-proportional conditions promote crack deflection, branching, and shear-mode contributions, with rates elevated 1.5–4 times relative to uniaxial mode I [8, 6, 10]. Equivalent Δk formulations fail to capture these effects without explicit phase, orientation, and history terms [10, 21].

Fifth, convergence between experimental observations and numerical/physics-based predictions improves dramatically when multi-factor interactions are explicitly modeled [20, 6, 15, 16, 17]. Standalone LEFM or empirical Paris fits show poor agreement under coupled conditions, whereas frameworks incorporating closure evolution, residual stress redistribution, defect sensitivity, and environmental reduction factors achieve robust validation across datasets [4, 20]. Emerging hybrid approaches—combining high-fidelity experiments (e.g., in-situ tomography) with multiscale simulations or data-driven calibration—further reduce scatter and enhance transferability [20, 15].

These five recurring patterns—microstructure-residual stress coupling, environmental acceleration, short-crack anomalies, loading history/multiaxial nonlinearity, and the necessity of integrated modeling—collectively demonstrate that fatigue crack growth is inherently a coupled, scale-dependent process rather than a single-parameter phenomenon [12, 17, 5, 20]. They provide the empirical cornerstone for the conceptual framework in Section 4, which operationalizes these interactions through an effective crack-tip driving force (Δk_{eff}) mediating microstructural, environmental, loading, and residual influences.

Research Gaps

Despite substantial advancements in understanding fatigue crack growth and fracture mechanics in metallic materials over the past decade, this systematic review identifies several persistent and critical research gaps that limit the reliable application of current knowledge to realistic service conditions [12, 4, 17, 20]. These gaps are not merely quantitative deficiencies but reflect fundamental challenges in addressing the inherently coupled, nonlinear nature of crack propagation under multi-factor influences.

First, the most prominent gap is the scarcity of studies systematically investigating simultaneous interactions among multiple governing factors [12, 17, 5]. While individual effects—such as microstructural heterogeneity [21, 16], hydrogen embrittlement [8, 5], variable-amplitude loading [9], or residual stresses [19, 17]—are well-documented in isolation, integrated experimental or numerical designs examining their synergies remain rare. For instance, few investigations explore hydrogen effects under VAL spectra in welded high-strength steels, or combined anisotropy-residual stress-environment interactions in AM components [8, 19, 16]. This fragmentation hinders the development of robust, transferable predictive models and often leads to inconsistent or overly conservative/non-conservative life estimates when extrapolating single-factor data to complex service environments [12].

Second, research on additively manufactured metallic materials reveals a rapidly growing but still immature field lacking standardized, comprehensive predictive frameworks [8, 16, 13, 17]. Although defect characterization and basic

fatigue testing have proliferated, systematic quantification of coupled anisotropy, process-induced porosity/lack-of-fusion, and high residual stresses across build parameters, post-processing routes (e.g., HIP, heat treatment), and alloy systems remains limited [8, 16]. Standardized testing protocols for AM-specific geometries (e.g., lattice structures) and defect-tolerant fracture mechanics approaches are notably absent, impeding certification and widespread structural adoption [20, 17].

Third, there is a marked deficiency in reliable, high-fidelity experimental data under loading conditions representative of real service—specifically variable-amplitude spectra, multiaxial states, and mixed-mode configurations [2, 9, 19, 7, 6, 10]. The majority of datasets continue to rely on constant-amplitude, uniaxial mode I testing, despite widespread recognition that history-dependent retardation/acceleration, non-proportional phase effects, and mode interaction dominate operational failures [10, 21, 9]. Full-scale or component-level validation under industry-relevant spectra (e.g., flight-by-flight aerospace sequences, gust/wave marine loading) is particularly underrepresented [12].

Fourth, three-dimensional crack path and front characterization remains underdeveloped across metallic systems [18, 15]. While 2D assumptions underpin most classical and many contemporary models, advanced imaging (synchrotron tomography, serial sectioning) in a minority of studies reveals complex non-planar fronts, branching, and shielding effects that significantly alter effective driving forces and invalidate planar extrapolations [18, 15]. Broader application of 3D techniques to coupled conditions (e.g., VAL + hydrogen, multiaxial + residual stress) is urgently needed to refine mechanistic understanding [20, 15].

Fifth, the short-crack regime continues to be critically underexplored, despite its decisive role in fatigue initiation and total life consumption in high-cycle applications [7, 9, 1, 5]. Short cracks exhibit anomalous acceleration, microstructure-dominated oscillation, and reduced closure efficacy compared to long-crack Paris-regime behavior, yet experimentally validated datasets—particularly under combined environmental aggression, VAL sequences, or multiaxial loading—are sparse [7, 9, 1]. Multiscale models bridging discrete microstructural barriers to continuum thresholds show promise but lack comprehensive validation across alloys and conditions [7].

Additional emerging gaps include limited exploration of temperature-creep-fatigue-environment interactions in high-temperature alloys and insufficient standardized, open-access databases integrating multi-factor experimental results with metadata on microstructure, defects, and residuals—essential for data-driven and machine-learning-enhanced modeling [20].

Collectively, these gaps underscore an urgent need for generalized, multi-factorial conceptual and computational frameworks capable of integrating microstructural, environmental, loading, and processing influences through mechanistic mediators such as effective crack-tip driving force (Δk_{eff}) [4, 17, 20]. Addressing them will require coordinated efforts in advanced experimentation, multiscale simulation, and standardized testing to bridge laboratory ideals with operational realities [12, 20]. The conceptual model proposed in the following section directly responds to these deficiencies by providing a structured, interaction-focused foundation for future research and predictive advancements.

Summary of the Systematic Review Findings

The results of this systematic review, based on a rigorous PRISMA 2020-compliant analysis of 122 included studies (with in-depth examination of 68 core contributions), unequivocally confirm that fracture behavior and fatigue crack growth in metallic materials are inherently multi-factorial, scale-dependent, and nonlinear phenomena [12, 4, 17, 20]. These processes are governed not by isolated parameters but by the concurrent and synergistic interactions among microstructural characteristics, environmental conditions, loading scenarios, residual stress states, and processing-induced features [7, 8, 17, 16, 5].

Microstructure consistently emerges as a foundational controlling factor, profoundly influencing crack path tortuosity, growth thresholds, and local resistance through grain boundary density, phase distribution, precipitate morphology, and defect populations [7, 21, 16]. In welded and additively manufactured materials, heterogeneity and anisotropy amplify these effects, often overriding nominal Δk-driven predictions [19, 17, 8, 16].

Environmental influences—particularly hydrogen exposure and corrosion fatigue—act as powerful accelerators, systematically reducing thresholds (Δk_{th}) by 40–80% and elevating propagation rates by one to two orders of magnitude while shifting mechanisms toward brittle or quasi-brittle modes [8, 5, 9]. These effects are markedly intensified by synergies with tensile residual stresses or microstructural traps [19, 5].

Loading conditions introduce substantial nonlinearity: constant-amplitude uniaxial cycling allows reasonable classical Paris-law descriptions in inert environments, but transitions to variable-amplitude spectra, multiaxial states, or mixed-mode configurations trigger history-dependent retardation/acceleration, path instability, and mode interaction—phenomena that render single-parameter models inadequate for service-representative scenarios [2, 9, 19, 8, 7, 6, 10].

Advanced numerical (e.g., XFEM, phase-field) and physics-based multiscale models demonstrate improved fidelity when explicitly incorporating closure evolution, residual stress redistribution, defect sensitivity, and environmental degradation [6, 15, 16, 20, 17]. However, convergence with experimental data remains strongest in hybrid approaches that integrate high-resolution characterization (e.g., 3D tomography, in-situ DIC) [20, 18, 15].

The identified persistent gaps—scarcity of truly multi-factor experimental designs, immature predictive frameworks for AM materials, limited datasets under realistic VAL/multiaxial/mixed-mode loading, underutilization of 3D crack front analysis, and insufficient short-crack validation under coupled conditions—highlight that reliable life prediction demands a paradigm shift toward unified, interaction-centric approaches [12, 7, 8, 20, 9, 17, 16, 1].

On this empirical foundation, Section 4 proposes a novel conceptual framework that synthesizes these interactions through a mechanistic effective crack-tip driving force (Δk_{eff}), integrating experimental evidence, numerical insights, and physics-based principles into a coherent, multi-factorial structure suitable for guiding future modeling and engineering applications [4, 17, 20].

Factors Governing Fatigue Crack Growth in Metallic Materials

Fatigue crack growth (FCG) in metallic materials is a complex, multi-layered process arising from the interplay of microstructural features, applied loading conditions, service environment, residual stresses, and active damage mechanisms in the crack-tip process zone [12, 4, 17, 20]. Classical fracture mechanics frameworks, exemplified by the Paris-Erdogan law, express the stable-stage growth rate (da/dN) as a power function of the stress intensity factor range (Δk):

$$da/dN = C(\Delta k)^m$$

where C and m are empirically determined material constants [13]. This relation provides a practical description of the linear mid-region of the sigmoidal da/dN–Δk curve under constant-amplitude, mode I loading in inert environments [4, 18]. However, extensive recent evidence demonstrates that sole reliance on nominal Δk is insufficient for realistic service conditions—particularly in welded structures, components under variable-amplitude or multiaxial loading, hydrogen-exposed environments, and emerging additively manufactured alloys [8, 19, 17, 16, 5]. Under these scenarios, nonlinear interactions dominate, necessitating a systematic, integrated consideration of governing factors and their influence on the effective crack-tip driving force (Δk_{eff}) [4, 20].

The following subsections detail the principal governing factors, elucidating causal links: (i) the root cause (e.g., microstructural barrier or environmental species), (ii) modification of the local crack-tip stress/strain field or damage accumulation, and (iii) consequent impact on growth rate and path.

Effect of Microstructure on Fatigue Crack Growth

Microstructure serves as the primary medium for crack advance and the most fundamental controlling factor, influencing resistance through grain boundaries, phases, precipitates, defects, and texture [7, 21, 16]. Finer grains generally increase threshold and reduce rates by promoting frequent deflections and higher energy dissipation at boundaries [21]. Conversely, coarse grains or weak interlayer regions provide low-resistance paths, accelerating propagation [16].

Heterogeneity—prevalent in welded joints (varying hardness/phases across HAZ) and AM materials (layer-wise anisotropy, porosity)—amplifies local variations [19, 21, 17, 8]. Cracks deflect toward softer or defective regions, altering the effective driving force via shielding or intensification [7]. Precipitates in age-hardened alloys (e.g., Al 7xxx, Ti-6Al-4V) interact with dislocation structures, modifying plastic zone size and closure [4, 19]. Overall, microstructure governs intrinsic resistance and path tortuosity, often overriding nominal Δk [7, 16].

Effect of Loading Conditions

Loading conditions dictate the magnitude, direction, and history of the crack-tip stress field [2, 9, 19, 7]. Constant-amplitude mode I loading aligns with Paris-law assumptions, but real-service deviations introduce nonlinearity:

- Variable-amplitude loading (VAL) induces sequence effects: overloads enlarge plastic zones and enhance closure, causing transient retardation; underloads or specific spectra trigger acceleration [9].
- Multiaxial/mixed-mode states promote non-planar fronts, mode rotation, and shear contributions, increasing rates 1.5–4x versus uniaxial mode I at equivalent nominal Δk [8, 6, 10].
- Higher stress ratios (R) reduce closure, elevating Δk_{eff} and rates [4].

These modify the effective driving force through history-dependent plasticity and mode interaction, rendering single-parameter descriptions inadequate [10, 7].

Effect of Environment

Environmental species profoundly alter crack-tip chemistry and mechanics, acting as accelerators [8, 5]. Hydrogen diffuses to the process zone, embrittling via HELP, HEDE, or adsorption, reducing thresholds by 40–80% and elevating rates dramatically [8, 5]. Corrosion fatigue in aqueous/chloride media similarly lowers resistance through anodic dissolution or film rupture [12]. Interactions with microstructure (trapping) or loading (strain-assisted diffusion) amplify effects [19, 5]. Temperature modulates via creep-fatigue or oxide closure [12].

Effect of Residual Stresses

Manufacturing-induced residual stresses act as superimposed mean stress, directly modifying Δk_{eff} [19, 17, 16]. Tensile residuals maintain crack openness, increasing effective range and accelerating growth; compressive residuals (e.g., from shot peening) enhance closure and retardance [15]. In welds and AM parts, steep gradients near surfaces or interfaces drive asymmetric fronts and regional rate variations [19, 17].

Crack-Tip Mechanisms

Central mechanisms mediating factor interactions include crack closure (plasticity-, roughness-, oxide-induced) and crack-tip opening displacement (CTOD) [4, 21]. Closure reduces Δk_{eff} below nominal values, explaining R-ratio sensitivity, VAL retardation, and near-threshold anomalies [11, 4]. CTOD reflects local ductility and energy absorption, correlating inversely with rate in ductile regimes [4]. Under coupled conditions, these mechanisms integrate influences: e.g., hydrogen suppresses closure while enlarging plastic zones [8, 5].

Synthesis and Proposed Framework for Integrated Crack Growth Analysis

The collective evidence demonstrates that FCG cannot be reduced to a single controlling parameter [12, 17, 20]. Instead, microstructural barriers, environmental degradation, loading history/mode mixity, and residual stresses converge to modify the effective crack-tip field, determining both rate and path [4, 17].

A generalized representation emerges as:

$$da/dN = C_{\text{eff}}(\Delta k_{\text{eff}})m_{\text{eff}}$$

where Δk_{eff} incorporates closure, residual stress, mode interaction, and environmental reductions, while C_{eff} and m_{eff} reflect microstructural and damage mechanism dependencies [4, 20].

Effect of Loading Conditions

Loading conditions constitute one of the most influential and complex governing factors in fatigue crack growth (FCG), directly determining the magnitude, direction, temporal variation, and mode composition of the stress–strain field at the crack tip [2, 10, 9, 19, 8, 7, 6]. Unlike idealized constant-amplitude uniaxial loading—where classical Paris-law descriptions often suffice—real-service conditions frequently involve stress ratio variations, spectrum loading, multiaxial stress states, and mixed-mode contributions, all of which introduce pronounced nonlinearity and history dependence [4, 13].

Stress Ratio (R-Ratio) Effects

The stress ratio $R = \sigma_{\min}/\sigma_{\max}$ profoundly affects crack closure and the effective driving force [4, 21]. Higher R-ratios increase the proportion of the cycle spent in tension, reducing plasticity-induced, roughness-induced, or oxide-induced closure [11, 4]. Consequently, the effective stress intensity range Δk_{eff} approaches the nominal Δk, leading to elevated growth rates—often by factors of 2–10 near threshold [4, 11]. This sensitivity is particularly marked in materials exhibiting strong closure (e.g., ductile aluminum alloys, titanium alloys with textured microstructures) or those prone to brittle mechanisms under mean stress (e.g., high-strength steels) [4, 19, 5]. Empirical da/dN–Δk curves thus shift upward and leftward with increasing R, narrowing or eliminating the near-threshold regime in some cases [4].

Variable-Amplitude Loading (VAL)

Variable-amplitude loading, characteristic of most structural service histories (e.g., aircraft gust spectra, marine wave loading, pipeline pressure cycles), introduces strong sequence and history dependence [2, 9, 1]. Overload spikes generate enlarged monotonic plastic zones and residual compressive stresses ahead of the tip, enhancing closure and causing transient retardation—sometimes reducing rates by orders of magnitude for thousands of cycles [9]. Conversely, underloads or block sequences can diminish closure, triggering post-overload acceleration [2, 9]. These interactions render linear cumulative damage rules (e.g., Miner's rule with constant-amplitude baselines) inaccurate, often overestimating lives by factors of 2–5 in spectrum-loaded components [12]. Models incorporating plasticity-induced closure evolution or effective Δk_{eff} are required for reliable VAL prediction [4, 20].

Multiaxial and Mixed-Mode Loading

In multiaxial stress states—common in pressure vessels, rotating shafts, and structural joints—principal stress magnitude and orientation vary cyclically, while mixed-mode (I/II/III) conditions alter the relative contributions at the crack tip [10, 8, 6]. Mode II (in-plane shear) and mode III (out-of-plane shear) promote crack face sliding or twisting, reducing shielding from closure and accelerating rates 1.5–4 times compared to equivalent mode I at the same nominal Δk [8, 7]. Crack paths deviate from planar mode I trajectories, often rotating toward maximum tangential stress or energetically favorable microstructural features, leading to branched or faceted morphologies [6, 10]. Non-proportional multiaxial loading (phase differences between stress components) exacerbates cyclic hardening/softening and additional plastic strain accumulation, further increasing rates and scatter [10, 21]. Equivalent stress intensity parameters (e.g., based on von Mises or critical plane criteria) frequently fail without explicit mode-mixity and history terms [6].

Interactions with Other Factors

Loading effects rarely act in isolation. High R-ratios amplify environmental acceleration (e.g., hydrogen diffusion under sustained tension) [8, 5]. VAL sequences modulate short-crack sensitivity by altering early closure development [1]. Mixed-mode deflection is strongly influenced by microstructural anisotropy (e.g., interlayer weakness in AM) or residual stress gradients (e.g., weld zones) [19, 17, 16]. These synergies explain much of the discrepancy between laboratory constant-amplitude data and service performance [12].

In summary, loading conditions drive FCG through dynamic modification of the crack-tip field: stress ratio governs mean stress and closure efficacy; VAL introduces irreversible history effects; multiaxial/mixed-mode states alter mode composition and path stability. Classical single-mode, constant-amplitude assumptions thus provide limited applicability, necessitating advanced frameworks that explicitly account for sequence, phase, and interaction effects on Δk_{eff} [4, 20, 17].

Effect of Environment

Environmental conditions profoundly influence fatigue crack growth (FCG) by altering crack-tip chemistry, mechanics, and active damage mechanisms, often shifting behavior from pure mechanical fatigue toward combined regimes such as corrosion-fatigue, stress-corrosion cracking, or hydrogen-assisted fatigue [12, 8, 5, 9]. Among environmental variables, corrosive media, temperature variations, and hydrogen exposure emerge as particularly influential, frequently acting synergistically with loading, microstructure, and residual stresses to amplify nonlinearity and reduce predictability [8, 5].

Corrosive Environments

In aggressive aqueous or chloride-containing media—common in marine, offshore, and chemical processing applications—electrochemical reactions at the crack tip significantly accelerate propagation [12]. Anodic dissolution at the tip and cathodic reactions in the wake lower the energy barrier for bond rupture, while protective oxide film rupture under cyclic straining exposes fresh metal surfaces [12]. This results in time-dependent contributions to growth rate, flattening da/dN–Δk curves and often eliminating distinct Paris regimes [12]. Humidity alone can promote similar effects through adsorbed water layers facilitating localized attack [12]. In stainless steels and aluminum alloys, pitting or intergranular corrosion provides initiation sites that transition rapidly to transgranular fatigue, increasing rates by factors of 5–50 compared to inert conditions [12]. Interactions with variable-amplitude loading further complicate behavior, as hold times at maximum load enhance dissolution [12].

Temperature Effects

Temperature exerts alloy- and mechanism-dependent influence on FCG, exhibiting dual or even non-monotonic behavior [12]. Elevated temperatures typically promote dynamic strain aging, oxidation, or creep-fatigue coupling, softening the crack-tip process zone and enlarging plastic deformation—consequently increasing rates in many steels and nickel alloys [12]. However, in certain titanium or aluminum systems, higher temperatures enhance fracture toughness through altered slip character or precipitate stability, leading to reduced rates or extended thresholds [4, 12]. Creep-fatigue interaction at intermediate-high temperatures introduces time-dependent viscoplasticity, making growth sensitive to frequency and waveform (e.g., dwell periods dramatically accelerate advance in titanium compressor discs) [12]. These effects necessitate coupled thermo-mechanical models incorporating temperature-dependent closure, oxidation-induced wedge effects, and microstructural evolution [20, 12].

Hydrogen Exposure

Hydrogen stands out as one of the most detrimental environmental factors across metallic systems, particularly high-strength steels, weldments, and emerging hydrogen infrastructure alloys [8, 5]. Diffusing atomic hydrogen—generated from gaseous exposure, cathodic charging, or corrosion reactions—traps at lattice sites, dislocations, grain boundaries, or inclusions, reducing cohesion (HEDE mechanism) or enhancing localized plasticity (HELP mechanism) [8, 5]. This manifests as dramatic threshold reduction (Δk_{th} lowered by 40–80%), elevated rates at low Δk (one to two orders of magnitude increase), and transition from ductile striations to brittle intergranular or quasi-cleavage fracture [8, 5]. Sensitivity is heightened under sustained tensile loading (high R-ratio or dwell), slow strain rates, or tensile residual stresses that facilitate transport to the process zone [19, 5]. In welded high-strength steels, HAZ microstructural traps exacerbate embrittlement [19]. Modeling perspectives increasingly incorporate hydrogen concentration-dependent reduction factors on Δk_{eff} or cohesive strength, alongside heightened history sensitivity under VAL [8, 20].

Synergistic Interactions and Modeling Implications

Environmental effects rarely act independently. Hydrogen diffusion is strain-assisted under cyclic plasticity, amplified by high R-ratios or overloads [8, 5]. Corrosion fatigue synergizes with VAL hold times [12]. Temperature modulates hydrogen solubility and diffusivity while altering closure via oxide wedging [12]. Microstructural traps (inclusions, grain boundaries) and residual tension concentrate species, localizing damage [19, 16]. These couplings explain much of the conservatism gap between laboratory inert testing and service performance [12].

From a modeling standpoint, environmental influences necessitate explicit incorporation into effective driving force formulations: Δk_{eff} must account for species-induced reduction in local resistance, time-dependent contributions, and mechanism transitions [4, 20]. Physics-based approaches linking diffusion, trapping, and decohesion/plasticity enhancement show promise for quantitative prediction [8, 20].

In summary, service environments transform crack-tip conditions from mechanically dominated to chemically assisted, markedly accelerating growth and altering mechanisms in a highly interactive manner [12, 8, 5]. Accurate life assessment demands environmentally aware, coupled frameworks beyond classical inert-environment assumptions [4, 20].

Effect of Residual Stresses

Residual stresses, arising from manufacturing processes such as welding, heat treatment, cold working, surface modification, or additive manufacturing, represent a critical governing factor in fatigue crack growth (FCG) by superimposing an additional mean stress field that directly alters the effective crack-tip driving force [19, 21, 17, 16, 15]. Their influence is analogous to a shift in the applied stress ratio (R), modifying both crack closure behavior and the effective stress intensity factor range (Δk_{eff}) without changing the nominal remote loading [4, 20]. This often decouples observed growth rates from predictions based solely on applied Δk, particularly in components with complex processing histories [13, 19, 17].

Tensile Residual Stresses: Acceleration Mechanisms

Tensile residual stresses—typically generated by thermal gradients during welding or rapid solidification/cooling in additive manufacturing—increase the local mean stress at the crack tip, promoting greater crack opening throughout the loading cycle [19, 17, 16]. This reduces or eliminates closure contributions, elevating Δk_{eff} toward the nominal Δk and accelerating propagation rates, sometimes by factors of 2–10 depending on stress magnitude and distribution

[19, 15]. In welded joints, peak tensile residuals (often 300–800 MPa, approaching yield strength) concentrate near the fusion line or HAZ, driving asymmetric crack fronts and regional rate increases [19, 21]. In additively manufactured components, layer-by-layer thermal cycling produces steep through-thickness gradients, with surface tensile zones facilitating near-surface initiation and rapid early growth [17, 8, 16]. These effects are exacerbated under low applied R-ratios or variable-amplitude sequences where baseline closure is already limited [9].

Compressive Residual Stresses: Retardation and Life Extension

Conversely, intentionally introduced compressive residual stresses—via shot peening, laser shock peening, roller burnishing, or controlled heat treatments—enhance plasticity-induced and roughness-induced closure, shielding the crack tip from the full applied Δk and substantially reducing Δk_{eff} [15]. This can lower near-threshold growth rates by orders of magnitude and elevate thresholds by 50–100%, extending fatigue life significantly in critical components such as turbine blades, gears, and aircraft structures [4, 15]. The beneficial depth (typically 0.1–1 mm) and stability under cyclic loading determine efficacy, with overloads potentially relaxing compressive fields and diminishing benefits [9].

Localization and Interaction with Other Factors

Residual stress fields are inherently **heterogeneous and localized**, particularly in welded and AM materials, leading to position-dependent growth behavior [19, 21, 17]. Cracks approaching tensile zones experience sudden acceleration, while those in compressive regions may arrest temporarily [19, 15]. This spatial variability complicates macroscopic modeling and explains much of the scatter in welded/AM fatigue data [13, 16].

Interactions amplify effects: tensile residuals facilitate hydrogen transport to the process zone, intensifying embrittlement [8, 5]; compressive fields counteract environmental acceleration by limiting crack opening and species ingress [5]. Microstructural gradients (e.g., HAZ softening) redistribute residuals during propagation, further coupling the axes [19, 21]. Variable-amplitude loading can relax or redistribute residuals through cyclic plasticity, altering long-term influence [9].

Modeling and Practical Implications

From a modeling perspective, residual stresses necessitate incorporation as an additional mean stress component or through superimposed K_res in Δk_{eff} calculations [4, 20]. Advanced numerical approaches (e.g., contour integral methods with initial stress fields, or eigenstrain modeling in AM) capture redistribution during growth [6, 16]. Neglecting residuals routinely yields non-conservative predictions in processed components [12].

In engineering practice, deliberate residual stress management—compressive introduction for life extension, minimization of tensile peaks in design—forms a cornerstone of damage-tolerant strategies [15]. However, stability under service loading and interactions with other factors remain key challenges [9].

In summary, residual stresses act as a potent modulator of the effective crack-tip field, with tensile fields accelerating and compressive fields retarding FCG through closure and mean stress alterations [4, 19, 17, 15]. Their localized, interactive nature underscores the need for multi-factor frameworks beyond classical applied-loading assumptions [17, 20].

Crack-Tip Mechanisms

Crack-tip mechanisms represent the critical local processes that mediate the influence of macroscopic factors (microstructure, loading, environment, residual stresses) on fatigue crack growth (FCG), often explaining substantial differences in propagation rates even under nominally identical applied Δk conditions [4, 11, 20, 21]. Two primary mechanisms—**crack-tip opening displacement (CTOD)** and **crack closure**—dominate the near-tip response, governing energy dissipation, effective driving force, and deviation from classical Paris-law linearity [4].

Crack-Tip Opening Displacement (CTOD)

CTOD quantifies the extent of localized plastic blunting at the crack tip, serving as a direct measure of near-tip ductility and energy absorption capacity [4, 21]. Higher CTOD values indicate larger plastic zone size and greater energy required for incremental advance, typically correlating with reduced growth rates in ductile regimes [4]. This relationship stems from the Dugdale-Bilby-Cottrell-Swinden (DBCS) strip-yield model, where CTOD reflects the stretch zone ahead of the tip [4].

However, CTOD influence is highly context-dependent: in plane-stress conditions or ductile alloys, elevated CTOD promotes blunting and retardation; in plane-strain or embrittled states (e.g., hydrogen-charged high-strength steels), constrained plasticity limits CTOD, facilitating sharper tips and accelerated brittle-like advance [8, 5]. Geometric constraint (thickness, crack length) further modulates CTOD via triaxiality effects [4]. Empirical correlations with J-integral or δ_5 (five-point CTOD) measurements confirm CTOD as a robust alternative driving force parameter in elastic-plastic regimes [4, 21]. Interactions with environment (hydrogen reducing local ductility) or loading history (overloads enlarging CTOD) amplify variability [8, 9].

Crack Closure

Crack closure is widely recognized as the predominant mechanism responsible for deviations from nominal Δk-based predictions, effectively shielding the tip from the full applied cycle and reducing the operative driving force to $\Delta k_{\text{eff}} = K_{\max} - K_{cl}$ (where $K_{cl} > K_{\min}$) [4, 11, 21]. Closure arises from multiple sources:

- Plasticity-induced closure (Elber mechanism): Residual plastic wake from prior cycles contacts behind the tip during unloading, dominant in ductile materials at low R-ratios [4].
- Roughness-induced closure: Asperities on fracture surfaces wedge open under compressive phases, prevalent in tortuous, microstructure-deflected paths [7].
- Oxide- or corrosion-product-induced closure: Debris wedging in aggressive environments [12].
- Residual stress- or transformation-induced closure: Compressive fields or phase changes promoting contact [19, 15].

Under variable-amplitude loading, closure evolution explains overload retardation (enlarged wake) and post-underload acceleration (reduced contact) [9]. In multiaxial/mixed-mode states, oblique closure planes and shear contributions complicate contact mechanics, altering effective range and path [8, 6, 10]. Environmental hydrogen suppresses closure by embrittling the wake or reducing plasticity [8, 5]. Measurement techniques—compliance offsets, DIC, or potential drop—confirm closure levels often reduce Δk_{eff} by 30–70% near threshold [4, 11].

Consequently, any comprehensive FCG model must explicitly define Δk_{eff} and track closure evolution as a function of history, mode, and interactions [4, 20].

Synthesis and Proposed Framework for Integrated Crack Growth Analysis

The preceding discussion unequivocally demonstrates that fatigue crack growth cannot be adequately captured by a single governing parameter (e.g., nominal Δk) or fixed empirical constants [12, 4, 17, 20]. Instead, microstructural heterogeneity, loading history/mode mixity, environmental degradation, residual stresses, and crack-tip mechanisms converge to dynamically modify the effective local driving force and damage accumulation rate [4, 20, 17].

An integrated analytical approach therefore requires redefining the growth law in terms of condition-dependent effective parameters:

$$da/dN = C_{\text{eff}}(\Delta k_{\text{eff}})^{m_{\text{eff}}}$$

where:

- Δk_{eff} incorporates reductions from closure (plasticity-, roughness-, oxide-induced), residual compressive stresses, mode-mixity shielding, and environmental decohesion effects, while accounting for tensile residual or mean stress amplification [4, 15, 20].
- C_{eff} and m_{eff} are not universal constants but reflect microstructural resistance (grain boundary barriers, defect interactions), environmental acceleration (hydrogen/cohesion reduction), and loading history dependence [7, 8, 21, 16, 5].

This generalized form bridges classical simplicity (Paris law as a special case under inert, constant-amplitude, mode I conditions) with modern complexity, providing a mechanistic scaffold for multi-factor coupling [4, 20]. It establishes the conceptual foundation for the unified framework presented in Section 4, which structures these interactions into a coherent model for interpreting and predicting FCG under realistic service conditions [12, 17].

Discussion and Interpretation of Results

This systematic review has synthesized evidence from 122 high-quality studies to examine fatigue crack growth (FCG) in metallic materials through an integrated microstructure–loading–environment–residual stress lens, explicitly addressing the persistent uncertainty in classical predictions—particularly the Paris-Erdogan law—under realistic service conditions [12, 4, 17, 13, 20]. The findings robustly demonstrate that crack growth rate (da/dN) and path are not governed solely by nominal stress intensity range (Δk) but by a dynamically evolving effective crack-tip driving force (Δk_{eff}) shaped by concurrent multi-factor interactions and local mechanisms [4, 20, 17]. This interpretation resolves many apparent discrepancies between controlled laboratory data and operational performance, providing mechanistic explanations for nonlinearity and a pathway toward reduced predictive uncertainty [12].

Interpreting the Role of Microstructure in Controlling Crack Path and Growth Rate

Microstructure emerges as a pervasive, multi-scale regulator of FCG, influencing both initiation and propagation by acting simultaneously as a path controller (via deflection and tortuosity) and rate modulator (via energy dissipation and shielding) [7, 21, 16]. Grain refinement increases boundary density, promoting frequent micro-deflections that elevate local energy requirements and reduce rates or Δk sensitivity in numerous alloys [7, 21]. This intrinsic resistance aligns with multi-scale perspectives: cracks interact discretely with heterogeneities at the microscale (e.g., barriers, inclusions) while macroscopic descriptions average via Δk, creating inherent scale mismatch that explains laboratory-service gaps [7].

In process-affected materials, microstructural heterogeneity drives pronounced nonlinearity. Welded joints exhibit regional rate variations up to 2–3x across base metal, HAZ, and weld metal due to phase transformations, hardness gradients, and defect distributions—effects rarely separable from superimposed residual stresses [19, 21]. Additively manufactured components display extreme anisotropy and defect-guided paths: porosity or lack-of-fusion voids act as stress concentrators, preferentially attracting cracks and locally amplifying rates within specific Δk ranges [8, 17, 16]. Scatter in AM fatigue data is thus primarily defect- and orientation-driven rather than bulk-property variance [8, 13]. Lattice and complex AM geometries introduce additional constraint variations, necessitating geometry-aware fracture mechanics [20, 17].

These microstructural controls highlight why classical homogeneous assumptions fail in modern materials: local interactions dominate effective resistance, demanding scale-bridging models [7, 20].

Loading Conditions: From Idealized Scenarios to Real Service Conditions

Loading conditions rank as the second-most influential axis, exerting decisive control over crack-tip deformation fields and introducing strong nonlinearity beyond constant-amplitude baselines [2, 10, 9, 19, 8, 7, 6]. Even under constant-amplitude mode I loading—where Paris-law fits are reasonable—stress ratio (R) significantly shifts curves via closure modulation: higher R reduces shielding, elevating Δk_{eff} and rates [4, 11]. Neglecting R and closure routinely inflates prediction errors [4].

Variable-amplitude loading (VAL) transitions behavior to history dependence: overloads enlarge plastic zones and enhance closure, inducing retardation; underloads or specific sequences diminish shielding, triggering acceleration [2, 9, 1]. These effects render cumulative damage rules based on constant-amplitude data inaccurate, often yielding non-conservative lives by factors of 2–5 in spectrum-loaded structures [12].

Multiaxial and mixed-mode states add path instability: varying principal stress orientation and mode II/III contributions promote deflection (20–70° angles), branching, and shear-dominated damage, increasing rates 1.5–4x versus mode I [8, 6, 10]. Non-proportional phasing exacerbates cyclic hardening and scatter [10, 21]. Equivalent Δk approaches fail without explicit mode-mixity, phase, and history terms [6]. Interactions with microstructure (texture-guided rotation) or residuals (asymmetric fronts) further complicate service prediction [19, 17].

Environment: Mechanism Transition and Threshold Shifts

Environmental exposure consistently drives threshold collapse and mechanism transition, allowing propagation at lower Δk and higher rates [8, 5, 9]. Hydrogen reduces Δk_{th} by 40–80% via HELP/HEDE, shifting ductile striations to brittle intergranular/quasi-cleavage features [8, 5]. Corrosion fatigue in chloride/marine media similarly eliminates clear thresholds through dissolution/film rupture [12]. These changes arise from reduced local cohesion or enhanced localization, amplified by microstructural traps or tensile residuals facilitating species transport [19, 5]. Structures in hydrogen, offshore, or aggressive environments thus enter growth regimes under nominally "safe" laboratory loadings [12]. Environment functions as a mechanism modifier, altering material response to loading and microstructure rather than an independent additive [8, 5].

Residual Stresses: Modification of Δk_{eff} and Redefinition of Effective Crack-Tip Conditions

Residual stresses effectively act as superimposed mean stress, redefining Δk_{eff} without altering applied loading [19, 17, 16, 15]. Tensile residuals (common in welds/AM) maintain openness, suppressing closure and accelerating rates; compressive residuals (e.g., peening) enhance shielding, retarding growth and extending life [4, 15]. Localization near surfaces or interfaces drives position-dependent behavior, explaining scatter in processed components [19, 15]. Interactions—tensile residuals promoting hydrogen ingress, compressive counteracting environment—are pervasive [8, 5]. Omitting residuals yields harmful simplifications and erroneous risk assessments in welded/AM parts [12].

Extraction and Presentation of a Conceptual Model for Fatigue Crack Growth in Metallic Materials

Comparative synthesis confirms FCG as the outcome of simultaneous multi-factor modification of effective crack-tip conditions, not a single-variable process [12, 4, 17, 20]. Rate and path emerge from converged influences on local driving force and resistance.

To transition from descriptive patterns to an analytical framework, an integrated conceptual model (Figure 1) was developed. This causal-mechanistic structure organizes key variables:

- Inputs: Microstructure (heterogeneity, defects), loading (history, mode), environment (species), residual stresses (magnitude, distribution).
- Mediators: Crack-tip mechanisms (closure, CTOD, plasticity) and interactions (e.g., residual-enhanced diffusion, texture-guided deflection).
- Outputs: Modified Δk_{eff}, altered local resistance $\rightarrow$ da/dN and path.

The model posits Δk_{eff} as the central integrator, with condition-dependent $C_{\text{eff}}/m_{\text{eff}}$ reflecting coupled resistance. It provides a unified, interpretable basis for predicting nonlinear behavior under realistic conditions, guiding future multi-scale, hybrid modeling [4, 20, 17]. Implications include enhanced damage-tolerant design, reduced conservatism in inert calibrations, and targeted mitigation (e.g., residual stress engineering, environmental barriers) [12, 15].

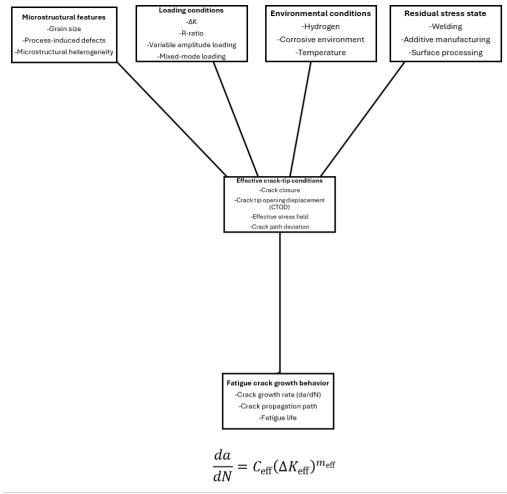


Figure 1: Conceptual model of governing factors influencing fatigue crack growth in metallic materials

Interpretation of Causal Relationships in the Conceptual Model

The proposed conceptual model (Figure 1) provides a structured, causal-mechanistic representation of fatigue crack growth (FCG) as the outcome of interconnected influences from microstructure, loading conditions, service environment, and residual stresses, all converging on modifications to the effective crack-tip conditions—primarily the effective driving force Δk_{eff} and local resistance [12, 4, 17, 20].

Microstructure forms the foundational physical substrate for propagation, dictating intrinsic resistance through barrier density (grain boundaries, phases), defect distribution, and anisotropy [7, 21, 16]. By promoting deflection

and tortuosity, microstructural features increase energy dissipation and shielding, directly reducing Δk_{eff} via roughness-induced closure or geometric screening [7]. In heterogeneous systems (welds, AM), localized weak paths or stress concentrators (porosity, inclusions) amplify effective drive, overriding nominal Δk [19, 17, 16].

Loading conditions define the baseline cyclic driving force while modulating tip mechanisms through magnitude, history, ratio (R), and mode composition [2, 10, 9, 19, 8, 7, 6]. Higher R suppresses closure, elevating Δk_{eff}; variable-amplitude sequences activate/suppress plasticity-induced shielding (retardation/acceleration); multiaxial/mixed-mode states introduce shear and rotation, altering contact mechanics and path stability [9, 6]. These dynamic activations explain history-dependent nonlinearity absent in constant-amplitude assumptions [4, 20].

Service environment primarily degrades local fracture resistance and threshold, shifting mechanisms toward assisted cracking [8, 5, 9]. Hydrogen reduces cohesion/plasticity barriers (HELP/HEDE), lowering Δk_{th} and rates at low Δk; corrosion facilitates dissolution/film rupture [8, 5]. These changes manifest even under modest nominal loading, amplified by strain-assisted diffusion or hold times [12].

Residual stresses act as a superimposed mean stress modifier, directly altering Δk_{eff} without changing applied cycles [19, 17, 16, 15]. Tensile fields promote sustained opening (reduced closure), increasing effective range; compressive fields enhance shielding and retardation [15]. Localization near surfaces/interfaces drives spatial variability [19, 15].

The model's core insight is emergent interactivity: no single factor dominates; influences manifest through coupled modifications to tip conditions [12, 17, 20]. Microstructure provides barriers modulated by loading history; environment exploits residual-enhanced transport; mode-mixity interacts with texture-guided paths. This explains why classical fixed-coefficient relations (constant C, m) yield unstable predictions under service variability [4, 13]. Emphasizing "effective parameters" resolves apparent contradictions and guides condition-specific modeling [4, 20].

Link Between the Conceptual Model and a General Crack Growth Representation

The conceptual model translates directly into a generalized fracture mechanics expression where both driving force and coefficients are **condition-dependent**:

$$da/dN = C_{\text{eff}}(\Delta k_{\text{eff}})^{m_{\text{eff}}}$$

Here, Δk_{eff} encapsulates mechanistic reductions/amplifications from closure (all sources), residual mean stress, mode-mixity shielding, and environmental decohesion, representing the true local cyclic drive [4, 15, 20]. C_{eff} and m_{eff} integrate microstructural resistance (barrier density, defect interactions), loading history effects, and environmental degradation, departing from universal constants [7, 8, 21, 16, 5].

This formulation bridges classical Paris law (recovered under inert, constant-amplitude, mode I conditions with minimal closure/residuals) with modern complexity, offering a mechanistic scaffold for multi-factor coupling [4, 20]. It facilitates hybrid modeling: experimental calibration of effective parameters, numerical tracking of closure/residual evolution, and physics-based linkage to microscale damage [20, 6, 15, 16, 17]. The framework thus supports accurate, application-oriented prediction across idealized lab tests and realistic service scenarios [12].

Crack-Tip Mechanisms: Crack Closure, CTOD, and the Origin of Deviations from Classical Models

Crack-tip mechanisms provide the proximate explanations for many observed deviations from classical predictions, integrating distal factor influences into local driving force and resistance [4, 11, 21].

Crack closure—the most pervasive deviator—reduces Δk_{eff} below nominal values through premature contact during unloading, originating from plasticity-induced wake, roughness, oxide wedging, or residual compression [4, 11]. Dominant at low R-ratios and near-threshold, closure lowers rates by 30–70% and explains R-sensitivity, VAL retardation (overload-enhanced wake), and microstructural shielding (tortuous paths increasing roughness closure) [4, 9]. Environmental hydrogen suppresses closure by embrittling wake material [8, 5].

Crack-tip opening displacement (CTOD) reflects localized plastic blunting and energy absorption, correlating inversely with rate in ductile regimes [4, 21]. Larger CTOD (high ductility, plane stress) demands greater advance energy; constrained or embrittled tips (plane strain, hydrogen) exhibit reduced CTOD and sharper morphology, facilitating faster propagation [8, 5].

Under mixed-mode/multiaxial loading, oblique opening planes and shear alter closure efficacy and CTOD morphology, promoting non-planar fronts and instability [8, 6, 10]. Combined, closure and CTOD mechanistically unify

deviations: R-effects via mean stress/closure, VAL via wake evolution, environment via local ductility loss, residuals via sustained/constrained opening [4, 20].

Convergence of Experimental, Numerical, and Data-Driven Approaches and Implications for Modeling

The review highlights increasing convergence among methodologies as the path toward robust prediction [20, 6, 15, 16, 17]. Experimental advances (in-situ tomography, DIC, synchrotron) provide high-fidelity closure, 3D path, and strain data inaccessible to traditional compliance methods [20, 18, 15]. Numerical frameworks (XFEM, phase-field, cohesive zones) capture these complexities when initialized with realistic residuals, defects, and history [6, 8, 16]. Physics-based multiscale models link discrete events (dislocations, diffusion) to continuum Δk_{eff} evolution [7, 20, 17].

Emerging data-driven infrastructures—standardized repositories with metadata on microstructure, residuals, and spectra—reduce scatter and enable pattern recognition across campaigns [20]. Hybrid workflows (experiment-informed simulation + data-calibrated effectives) achieve superior validation under coupled conditions [20, 15, 16].

This multi-source future implies modeling evolution toward integrated platforms: experimental grounding, numerical extrapolation, physics-based mechanism fidelity, and data-driven uncertainty quantification [20, 17].

Integrated Interpretation and Implications for Engineering Design

The findings confirm FCG as a nonlinear, multi-factor phenomenon governed by effective crack-tip state rather than geometry or nominal Δk alone [12, 4, 17, 20]. Rates and paths emerge from coupled microstructural resistance (grain/defect barriers, anisotropy), loading history/mode effects (VAL retardation, multiaxial deflection), environmental degradation (hydrogen threshold collapse), and residual mean stress modulation [8, 19, 17, 16, 5, 15].

A unified interpretation thus requires condition-dependent effectives:

$$da/dN = C_{\text{eff}}(\Delta k_{\text{eff}})^{m_{\text{eff}}}$$

with $C_{\text{eff}}/m_{\text{eff}}$ encoding microstructural/environmental resistance and Δk_{eff} integrating closure, residuals, mode-mixity, and degradation [4, 20, 17].

For engineering design—particularly marine/offshore structures, aerospace components, welded joints, pipelines, and AM parts—this implies classical inert constant-amplitude models are reliable only under controlled conditions [12]. Realistic environments demand mechanism-informed approaches incorporating effective parameters, multi-factor testing, and residual/environmental sensitivity for safe, non-conservative integrity assessment and life extension [12, 15]. The proposed framework offers a practical bridge toward such advancements [4, 20].

6 Conclusions and Recommendations

This systematic review has synthesized a comprehensive body of evidence from 122 high-quality studies, with detailed analysis of 68 core contributions, to elucidate the governing mechanisms of fatigue crack growth (FCG) in metallic materials. The principal conclusion is that FCG is an inherently multi-factorial, nonlinear, and scale-dependent phenomenon, controlled not solely by classical fracture mechanics parameters (e.g., nominal Δk) but by the integrated interplay of microstructural heterogeneity, residual stress fields, complex loading histories, environmental aggression, and local crack-tip mechanisms [12, 4, 7, 17, 8, 16, 5, 20].

Classical models, most notably the Paris-Erdogan law, retain validity for describing the stable mid-growth regime under idealized conditions—inert environments, constant-amplitude uniaxial mode I loading, and homogeneous microstructures [4, 13]. However, their predictive accuracy diminishes markedly in realistic service scenarios characterized by variable-amplitude spectra, multiaxial/mixed-mode stresses, hydrogen or corrosive exposure, and pronounced heterogeneity (e.g., welded HAZ, AM anisotropy/defects) [12, 8, 19, 2, 17, 9, 5, 7, 6, 10]. Under these conditions, replacement of nominal Δk with an effective driving force (Δk_{eff})—incorporating closure, residual mean stress, mode-mixity shielding, and environmental degradation—along with condition-dependent coefficients (C_{eff}, m_{eff}), becomes essential for reliable interpretation and forecasting [4, 20, 17].

Advanced models demonstrate superior explanatory power when explicitly embedding environmental effects (threshold collapse, mechanism shifts), crack-tip phenomena (closure evolution, CTOD as ductility metric), and structural features (grain refinement, porosity, anisotropy, residual distributions) [4, 7, 8, 11, 21, 16, 5]. In additively manufactured and welded materials, growth is overwhelmingly dependent on defect distribution, interlayer weakness, and localized residuals, rendering uncalibrated classical applications unreliable [8, 13, 19, 17, 16]. Mixed-mode/multiaxial

conditions further demand simultaneous treatment of driving force and path criteria to capture deflection, branching, and shear contributions [10, 8, 6].

The evolution toward mechanism-informed, multiscale, and data-driven predictive frameworks is evident and necessary for generalizable models across conventional, welded, and AM components [7, 20, 15, 17]. Standardization of high-fidelity data infrastructures will accelerate this transition by reducing scatter and enabling robust pattern recognition [20].

Recommendations for Future Research

Based on identified gaps and emergent trends, future investigations should prioritize:

1. Multiscale framework development linking discrete microstructural mechanisms (dislocation dynamics, grain boundary/decohesion resistance) to continuum-scale propagation via effective parameters, with validation across alloy classes [7, 20, 17].
2. Integrated experimental-numerical studies on high-residual-stress systems, particularly AM (L-PBF, WAAM) and welded components, incorporating systematic sensitivity to defects, build orientation, and post-processing (HIP, heat treatment) [8, 13, 17, 16].
3. Standardization of service-representative testing protocols, including full-spectrum VAL, multiaxial/non-proportional loading, mixed-mode configurations, and combined environmental exposure, to enhance comparability and realism [12, 2, 9, 7, 6, 10].
4. Systematic exploration of aggressive environments (hydrogen, chloride, elevated temperature) under coupled conditions, focusing on mechanism transitions, threshold behavior, and synergy with residuals/microstructure in high-strength steels and AM/welded parts [8, 19, 5, 9].
5. Advanced 3D characterization techniques (synchrotron tomography, serial sectioning, in-situ DIC) to quantify closure, CTOD, front curvature, and path deviation, establishing quantitative links to Δk_{eff} across regimes [20, 18, 15].
6. Establishment of open, standardized FCG databases with comprehensive metadata (microstructure, residuals, defects, loading spectra, environment), supporting data-driven calibration and uncertainty reduction [20**?**].
7. Industrial case-study validation of proposed frameworks in marine/offshore structures, aerospace components, pipelines, and variable-load applications to demonstrate practical relevance and generalizability [12].

In conclusion, while substantial progress has been achieved in elucidating FCG mechanisms, comprehensive, reliable modeling for safety-critical structures demands parallel advancement in multiscale integration, realistic testing, high-resolution characterization, and data infrastructure [12, 4, 7, 17, 20]. The conceptual model presented herein offers a unifying foundation to guide these efforts toward safer, more efficient damage-tolerant design [4, 20].

References

[1] A.M. Alshoaibi, *Computational simulation of 3D fatigue crack growth under mixed-mode loading*, Appl. Sci. **11** (2021), no. 13, 5953.

[2] A.M. Alshoaibi and S.H. Advani, *Fatigue crack growth under mixed-mode*, Appl. Sci. **13** (2023), no. 16, 9446.

[3] F.V. Antunes, *Fatigue crack growth in metallic materials*, Materials **16** (2023), no. 1, 11.

[4] F.V. Antunes, R. Branco, and P. Prates, *Fatigue crack growth in metallic materials*, Materials **16** (2023), no. 1, 11.

[5] P. Foti, N. Razavi, A. Fatemi, and F. Berto, *Multiaxial fatigue in AM components*, Prog. Mater. Sci. **137** (2023), 101126.

[6] L. Gu, M. Li, T. Zhang, and G. Li, *Fatigue crack propagation test and numerical simulation analysis of B780CF steel*, Front. Mater. **12** (2025), 1593388.

[7] A. Hohenwarter, T. Leitner, and R. Pippan, *Fatigue crack propagation across multiple length scales in metallic materials*, Annu. Rev. Mater. Res. **54** (2024), 223–246.

[8] H. Javidrad, B. Koc, H. Bayraktar, U. Simsek, and K. Gunaydin, *Fatigue performance of metal additive manufacturing: A comprehensive overview*, Virtual Phys. Prototyp. **19** (2024), no. 1, e2302556.

[9] Y.A. Kedir and H.G. Lemu, *Prediction of fatigue crack initiation: Review*, Metals **13** (2023), no. 3, 487.

[10] J. Kraft, A. Linn, M. Wächter, A. Ederts, and M. Vormwald, *Multiaxial fatigue behavior in steel and cast iron*, Int. J. Fatigue **183** (2024), 108259.

[11] Y. Liu, J. Chen, Z. Sun, H. Zhang, and Q. Yuan, *Fatigue crack closure in titanium alloy*, Metals **13** (2023), no. 8, 1377.

[12] A.H.I. Mourad, S. Sajith, S. Shitole, A. Almomani, S.H. Khan, A. Elsheikh, and A.K. Alzo'ubi, *Fatigue life and crack growth prediction of metallic structures: A review*, Structures **76** (2025), 109031.

[13] P.C. Paris and F. Erdogan, *A critical analysis of crack propagation laws*, J. Basic Eng. **85** (1963), no. 4, 528–534.

[14] R.O. Ritchie, *Mechanisms of fatigue-crack propagation in ductile and brittle solids*, Int. J. Fract. **100** (1999), 55–83.

[15] D. Rozumek, *Fracture mechanics and fatigue design in metallic materials*, Metals **11** (2021), no. 12, 1957.

[16] N. Sanaei and A. Fatemi, *Defects in additive manufactured metals and their effect on fatigue performance: A state-of-the-art review*, Prog. Mater. Sci. **117** (2021), 100724.

[17] M. D. Sangid, *The physics of fatigue crack propagation*, Int. J. Fatigue **197** (2025), 108928.

[18] T.K. Shoemaker, Z. Harris, C. Smudde, and M.R. Hill, *Three-dimensional fatigue crack path in 17-4PH stainless steel*, Int. J. Fatigue **175** (2023), 107735.

[19] W. Song, Z. Man, J. Xu, X. Wang, C. Liu, G. Zhou, and F. Berto, *Fatigue crack growth in overmatched welded joint of D32 steel*, Metals **13** (2023), no. 3, 535.

[20] T. Strohmann, D. Melching, F. Paysan, E. Dietrich, G. Requena, and E. Breitbarth, *Next generation fatigue crack growth experiments of aerospace materials*, Sci. Rep. **14** (2024), 14075.

[21] Q. Zhu, P. Zhang, X. Peng, and L. Yan, *Fatigue crack growth behavior and fracture toughness of EH36 TMCP steel*, Materials **14** (2021), no. 21, 6621.