

Review Article

Fatigue Behaviour of Case-Carburized and Chromium Nitride (CrN) PVD-Coated EN353, SAE8620 and 20MnCr5 Steels: A Systematic Review

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Abstract

Case-carburized low-alloy steels such as EN353, SAE8620 and 20MnCr5 are widely used in gears, shafts and transmission components because carburization combines a hard, wear-resistant surface with a tough core. Physical vapour deposition of chromium nitride (CrN) improves wear and corrosion resistance of such components, but its effect on fatigue behaviour is inconsistently reported: some studies find CrN delays crack initiation and improves fatigue life, while others report reduced endurance limits from coating defects, residual stresses or interfacial debonding. This paper presents a systematic review, following a pre-defined search and screening protocol, of fatigue fundamentals case-carburization metallurgy, PVD/CrN coating technology, and comparative fatigue and fractographic behaviour reported for carburized and CrN-coated steels. A quantitative data-extraction table supplements the qualitative synthesis, recording case depth, hardness, retained austenite, coating parameters and reported fatigue outcome for every study, noting unreported variables. The synthesis shows that almost no study evaluates more than one carburizing steel under identical conditions, that rotating-bending fatigue is under-studied relative to axial and rolling-contact loading, and that fractographic observations are rarely correlated quantitatively with fatigue-life data. These gaps motivate a systematic comparison of the three steels under identical CrN coating and rotating-bending conditions, combined with correlated SEM fractography.

Keywords: Case Carburizing, Chromium Nitride (CrN), Fractography, PVD Coating, Residual Stress, Rotating-Bending Fatigue, Surface Engineering

1. Introduction

Fatigue failure remains one of the foremost causes of structural deterioration and catastrophic failure in components subjected to repeated or fluctuating stresses. Fatigue damage accumulates progressively under cyclic loading at stresses often well below the static strength of the material [1], and because crack initiation and propagation typically occur without visible warning, fatigue governs the design life of rotating machinery, automotive transmissions, aircraft structures, railway axles and wind-turbine gearboxes [2–3]. Demand for lightweight, compact, high-efficiency power-transmission systems has increased the importance of fatigue design, since such components must survive hundreds of millions of stress cycles [4], with fatigue life governed not only by bulk mechanical properties but by microstructural stability, surface integrity and residual-stress distribution [5].

The scientific understanding of fatigue dates to Wöhler's railway-axle experiments, extended by Basquin's stress-life relationship [6], Coffin-Manson strain-life analysis [7], and the fracture-mechanics treatment of crack growth via the cyclic stress-intensity factor [8]. Contemporary research treats fatigue as a multiscale process of initiation at stress concentrators, stable propagation and final overload fracture [9–10]; in high-strength steels, initiation alone can consume more than 70% of total life, underscoring the importance of surface condition [2]. Fatigue resistance reflects the combined action of mechanical variables (stress amplitude, mean stress, loading mode), metallurgical variables (grain size, inclusions, retained austenite, residual stresses) [11] and environmental variables (temperature, lubrication, corrosive media, hydrogen-assisted cracking) [12–13]. Surface integrity exerts a dominant influence because fatigue cracks almost invariably initiate at or near the free surface [14]: machining defects accelerate initiation, while compressive residual stresses from surface treatment retard it [15–16].

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Low-alloy case-carburizing steels-including EN353, SAE8620 and 20MnCr5-occupy a particularly important position because carburization produces a hard, wear-resistant martensitic surface over a tough core, making these grades standard choices for gears, shafts and transmission components [17–19]. Fatigue failures nonetheless continue to occur under service combining cyclic loading, rolling contact and wear, driving research toward improving performance beyond conventional heat treatment [20–22] and shifting emphasis from bulk-strength improvement toward optimizing the surface region where cracks originate [23]. Surface engineering-selectively modifying only the near-surface region [24]-has become the dominant strategy for extending fatigue life. Among the available techniques (carburizing, nitriding, induction hardening, shot peening, thin-film coatings) [25], ceramic coatings deposited by Physical Vapour Deposition (PVD) are especially attractive because they improve wear resistance and corrosion resistance without significant dimensional distortion [26]. Successful application requires balancing coating hardness, toughness, adhesion and residual-stress state, since excessive hardness promotes brittle cracking while insufficient hardness fails by progressive wear [27–28]; coating-substrate compatibility and interfacial bonding strength often matter more for fatigue life than hardness itself [29–30].

Chromium nitride (CrN) has become one of the most widely used protective coatings, combining hardness, oxidation and corrosion resistance, comparatively high fracture toughness, and relative to TiN-lower intrinsic residual stress that reduces spontaneous cracking and delamination [31–33]. Yet CrN's effect on fatigue behaviour remains poorly resolved: some studies report improved fatigue life from delayed crack initiation and wear protection [32], while others report reduced endurance limits from coating defects, brittle fracture or interfacial debonding [25,34]. This contradiction indicates that fatigue performance depends on the interaction among coating characteristics, substrate microstructure, residual-stress distribution and loading conditions [26]-coated components must be treated as integrated structural systems rather than independent coating and substrate materials [28–29], a point especially relevant for case-carburized steels whose hardened layer, residual-stress profile and retained-austenite distribution jointly determine the mechanical support available to the coating [35].

Despite extensive research on carburized steels and PVD coatings individually, comparatively few studies have systematically evaluated CrN's effect on the fatigue behaviour of different case-carburized gear steels under identical conditions [36], and few

correlate rotating-bending fatigue with detailed fractographic and coating-integrity observations [37]. This gap motivates the present review, whose search and screening protocol is described in Section 2, and which synthesizes the fundamentals of fatigue (Section 3), case-carburization metallurgy (Section 4), PVD/CrN coating technology (Section 5), and the comparative fatigue and fractographic behaviour reported for EN353, SAE8620 and 20MnCr5 (Sections 6–7), before identifying the specific research gaps that motivate a systematic rotating-bending fatigue and SEM-fractography comparison of the three steels (Section 8).

A note on the relationship between this review and the authors' prior publication is given here for transparency. Reference [37] (Kumar and Saini, *Journal of Mechanical Science and Technology*, 40(2) (2026) 993–996) is the authors' own previously published experimental study of CrN-coated case-carburized 20MnCr5 steel. That paper reported fatigue-life data for a single steel grade under a single coating condition. The present review synthesizes that result alongside the independent published literature on EN353 and SAE8620 (Section 7, Table 7) and does not reproduce its text, figures, tables or data beyond the single summary entry attributed to it in Table 7; no other content in this review is drawn from that publication. The “ongoing investigation” referred to throughout Sections 6–8 is a separate, currently unpublished experimental study extending [37] to a three-steel comparison; it is not yet complete and no data from it are reported here.

2. Review Methodology

To make the literature synthesis in Sections 3–7 reproducible and independently verifiable, this review follows a pre-defined search, screening and data-extraction protocol, reported below.

2.1 Information sources and search strategy

Databases searched: Scopus, Web of Science Core Collection, and Google Scholar, applied using the Boolean strings given below, and supplemented by systematic forward and backward citation chasing from key on-topic sources (notably [17,18,24], [35–37], [97,98,101] and [108]) and from standard reference texts and international standards cited throughout Sections 3–5. Date of final search: 30 June 2026. Search period: 1995–2026 for the core case-carburizing/CrN/PVD-fatigue literature; foundational fatigue-mechanics and metallurgical theory predating this window (e.g., Basquin 1910, Miner 1945, Paris and Erdogan 1963) was retrieved by citation chasing rather than the primary keyword search, consistent with

standard practice for the background sections of an engineering review (Sections 3–5). Because this review addresses a specific combination of substrate grades, coating chemistry and loading mode, the combined database search string returned a comparatively small set of directly on-topic records; citation chasing from this core set therefore contributed the majority of the final working library (Fig. 1). The review protocol was not formally registered or pre-published prior to the literature search.

Search strings used (Boolean, applied to title/abstract/keywords): (“case carburiz*” OR “carburized steel” OR “EN353” OR “SAE8620” OR “8620 steel” OR “20MnCr5”) AND (“CrN” OR “chromium nitride” OR “PVD coating”) AND (“fatigue” OR “S-N” OR “endurance limit” OR “rotating bending”) Secondary strings covering the background sub-topics of Sections 3–5 combined the terms above with “fatigue fundamentals,” “case carburizing metallurgy,” “retained austenite,” and “physical vapour deposition” individually, without requiring the fatigue-test terms, since these sources support mechanistic background rather than the comparative fatigue-outcome synthesis.

2.2 Eligibility criteria

Table 7 distinguishes two tiers of evidence, now labelled explicitly in its “Steel” column. Primary studies were required to report, simultaneously: (i) a low-alloy case-carburizing steel (EN353, SAE8620, 20MnCr5, or a closely related grade); (ii) a CrN PVD coating; and (iii) laboratory fatigue testing (rotating-bending, axial or rolling-contact) with a stated stress level and cycle count or an S-N/endurance-limit result. Only one identified study, [37] (the authors’ own prior work), satisfies all three conditions simultaneously; this scarcity is itself the central finding motivating the present investigation (Section 8). Comparator studies were additionally included in Table 7, and tagged accordingly, if they satisfied at least one of the three conditions and provided context necessary to interpret the primary evidence: uncoated carburized baselines (to isolate the carburization-only effect), alternative PVD coatings on carburized or hardened steels (to benchmark CrN against other coatings), field-failure evidence (to motivate practical relevance), and coating-property studies on steel substrates whose carburization status could not be confirmed from the source (to provide mechanistic context on residual stress and coating structure). Background sources on fatigue fundamentals, carburization metallurgy and PVD technology not reporting fatigue data (Sections 3–5) were included for general context and are identified by their absence from Table 7.

Studies were excluded from Table 7 entirely (not even as comparators) if they: reported fatigue of substrates with no plausible relevance to case-carburizing gear/shaft steels or their coatings (e.g., stainless steels, aluminium alloys, unrelated tool steels); were conference abstracts without full data; or duplicated data already reported in an included journal article (e.g., the conference and journal versions of the same dataset).

2.3 Study selection and duplicate removal

The combined database and citation-chasing search, together with the supplementary confirmatory search described in Section 2.6, produced a working reference library of 124 sources after removing duplicate records (Section 2.2 details how the primary/comparator distinction was applied). Of these, 10 report fatigue-relevant data meeting the Section 2.2 inclusion criteria and were entered into the quantitative extraction table (Table 7, Section 7.1): refs. [17], [18], [24], [35], [36], [37], [97], [98], [101] and [108]. Of these ten, only [37] meets the full primary-study definition (case-carburized steel, CrN coating, and laboratory fatigue testing, all simultaneously); the remaining nine are tagged in Table 7 as comparator studies meeting one or two of the three conditions, included for the specific contextual role stated in Section 2.2. The remaining 114 references were retained as contextual and methodological background for Sections 3–5 (fatigue fundamentals, carburization metallurgy, and PVD/CrN coating technology) and were not subject to the fatigue-data extraction protocol. Because the combined database search string is narrowly scoped to this review’s specific substrate-coating-loading combination, it returned a modest number of directly on-topic records; the working library was therefore assembled primarily through citation chasing from this core set and from standard reference works and international standards, rather than through large-scale bulk-database screening. A conventional high-volume screening funnel (thousands of records screened down by title/abstract and full text) does not describe how this review’s sources were assembled and is not reported as such; Fig. 1 instead reports the verified counts at each stage that is actually applicable to this review’s search strategy. Duplicate records identified across the search (the same source located via more than one search string, or cited under more than one number in an earlier draft of this manuscript) were consolidated to a single reference number throughout.

The screening and study-selection process is summarized in Fig. 1.

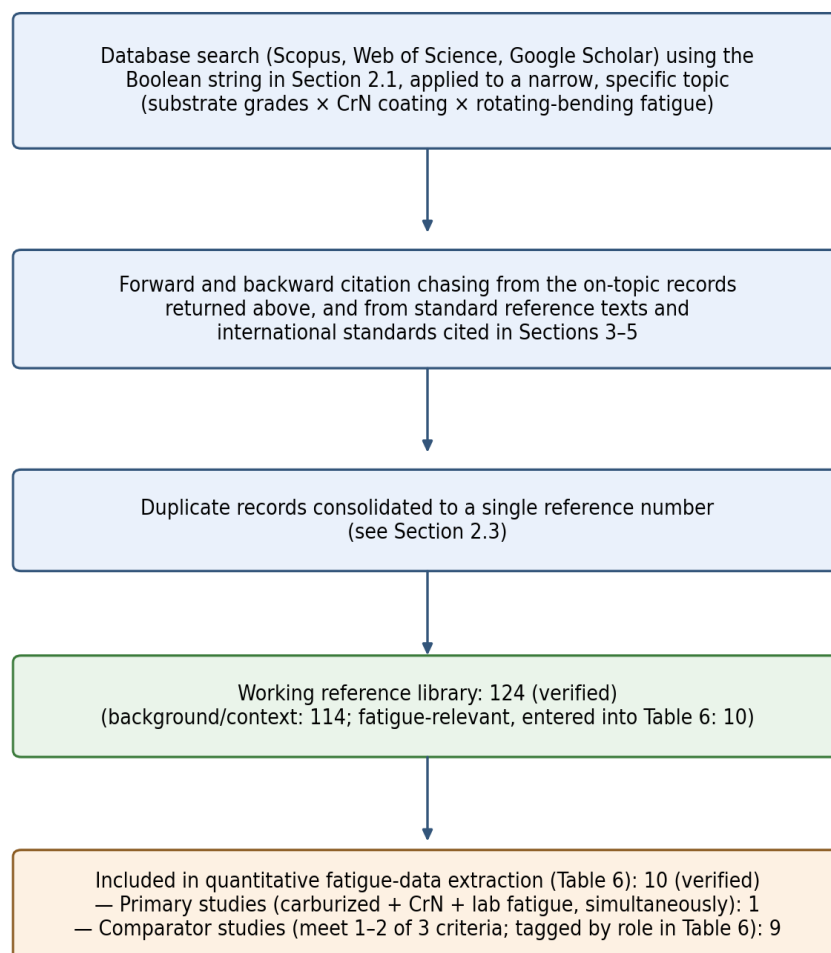


Fig. 1. Search, screening and study-selection flow. Every value shown is verified directly against this manuscript's final, deduplicated reference list and Table 7: no estimated or placeholder figures are reported.

2.4 Study-quality assessment

Each included fatigue study was assessed against four indicators of methodological transparency: (a) use of a stated fatigue-testing standard (e.g., ISO 1143, ASTM E466, ASTM E739); (b) reported specimen count per stress level; (c) reported statistical treatment of endurance-limit data (e.g., staircase method, regression); and (d) reported coating-characterization data (thickness, hardness and/or adhesion). Table 7 (Section 7.1) records these four indicators for every included study so that the reader can judge the strength of the evidence behind each reported outcome, rather than relying on a qualitative classification alone. As Table 7 shows, two of the ten included studies report their statistical treatment explicitly: [37] (the authors' own prior work) via the Dixon–Mood staircase method per ASTM E739, and [108] via linear regression of fatigue life against stress under ASTM E739 test replication. The remaining eight studies do not report a statistical treatment of their endurance-limit data; this uneven reporting of statistical rigour is itself one of the research gaps quantified in Section 8. These four indicators were selected because they correspond directly to the minimum information needed to judge whether a

reported fatigue outcome is quantitatively reliable and comparable across studies (a defined test standard and specimen count establish measurement reliability; a stated statistical treatment establishes how the reported value was derived; reported coating/case characterization establishes whether the tested condition matches this review's inclusion criteria). No numerical scoring system was applied; each indicator was recorded as reported or not reported directly from the source (Table 9), and the overall risk-of-bias judgment in Table 9 reflects how many of the four indicators were unreported, following the same procedure and dual-author verification described in Section 2.7. Where a study's methodological reporting was judged high-risk (most indicators unreported), its findings are presented in Sections 6–8 as a single reported observation rather than as quantitatively comparable evidence, and are not pooled or averaged with findings from other studies.

2.5 Data-extraction protocol

For every included fatigue study, the following variables were extracted where reported: steel grade and specification; case depth; surface hardness; retained austenite content; coating technique and

thickness; coating adhesion (test method and result, if reported); residual stress (substrate and/or coating, if reported); fatigue-test mode and stress ratio (R); reported fatigue limit or characteristic S–N result; specimen count; and statistical method used to establish the endurance limit. Where a variable was not reported in the source study, this is recorded explicitly as “NR” (not reported) in Table 7 rather than omitted-the pattern of NR entries across the table is itself part of the evidence for the research gap identified in Section 8.

2.6 Supplementary confirmatory search

In addition to the primary search (Sections 2.1–2.3), a supplementary confirmatory search was carried out during manuscript revision to verify reference details and check for directly relevant studies not already captured. This search surfaced one additional study meeting the eligibility criteria: Saini and Gupta's rotating-bending fatigue investigation of WC/C PVD-coated case-carburized SAE8620 steel [108], now included in Tables 5 and 6. Although WC/C is a different PVD hard coating from CrN, the study is a close methodological comparator (identical steel grade

to several CrN studies already reviewed, identical four-point rotating-bending protocol, and a directly analogous coated-versus-uncoated comparison), and its inclusion strengthens the SAE8620 evidence base in Table 7 without changing the review's central conclusions.

2.7 Independent screening procedure and risk-of-bias assessment

Title/abstract screening, full-text eligibility assessment, and data extraction were performed by both authors independently, with disagreements resolved by discussion.

Table 1 reports a study-level risk-of-bias assessment for the ten studies entered into the quantitative extraction table (Table 7), based on four reporting domains: use of a stated fatigue-testing standard, reported specimen count, reported statistical treatment of endurance-limit data, and reported case/coating characterization (case depth and hardness). Each domain is scored as reported or not reported directly from Table 7; the overall judgment reflects how many domains are unreported, following the study-quality indicators defined in Section 2.4.

Table 1. Risk-of-bias assessment for the ten studies included in the quantitative fatigue-data extraction (Table 7)

Ref.	Test standard reported	Specimen count reported	Statistical treatment reported	Case/coating characterization reported	Overall risk-of-bias judgment
[17]	Reported (DIN 50113; ISO 5075)	Reported (n=54 total across treatment groups)	Not reported (no formal statistical/regression treatment of the S–N data)	Reported (case depth ~1.0 mm; retained austenite 28.1%; hardness traverse given)	Some concerns (3 of 4 domains reported)
[18,35]	Not reported	Not reported	Not reported	Partially (case depth only)	High
[36]	N/A (field-failure analysis, not a controlled lab test)	N/A	N/A	Not reported	High (design precludes most domains)
[24]	Not reported	Not reported	Not reported	Not reported	High
[37]	Reported (ASTM E739)	Not reported	Reported (Dixon–Mood staircase)	Not reported	Some concerns (2 of 4 domains reported)
[97]	Not reported	Not reported	Not reported	Not applicable (residual-stress study, no fatigue-life outcome)	High
[98]	Not reported	Not reported	Not reported	Not reported	High
[101]	Not reported	Not reported	Not reported	Not reported	High
[108]	Reported (ISO 1143; ASTM E739 replication)	Not reported	Reported (linear regression)	Partially (case depth reported; hardness qualitative)	Some concerns (3 of 4 domains reported)

3. Fundamentals of Fatigue

Fatigue is the progressive, localized structural damage that develops under repeated stress, culminating in crack initiation, propagation and fracture [38], often well below the yield strength [2]. In high-strength gear and shaft steels, crack initiation dominates total life because the hardened surface resists growth but remains sensitive to local stress concentration [9,39]; small changes in surface finish, inclusion content or residual stress can therefore produce large changes in fatigue life without altering bulk properties.

High-cycle fatigue (HCF)-the regime relevant to gears, shafts and bearings, involving predominantly elastic stresses and failure beyond about 10^5 cycles [3,4]-is the regime of primary relevance to this review; crack initiation in this regime is governed principally by surface defects [43,44]. As shown schematically in Fig. 2, both carburization and CrN coating quality shift the reported S–N curve for a given steel: well-adhered, defect-free coatings delay crack initiation, whereas coating defects can lower fatigue resistance below the uncoated baseline. Crack-propagation behaviour is described by the Paris law, relating growth rate to the cyclic stress-intensity range [8].

Fatigue strength cannot be predicted from hardness alone: microstructure-grain size, martensite morphology, retained-austenite stability and carbide distribution [11,47–48,50–51]-non-metallic inclusions [9,52–53] and heat treatment [18,54–55] all govern crack initiation and growth resistance. For carburized and coated steels specifically, life prediction is complicated because crack initiation is influenced simultaneously by hardness, residual stress, coating integrity and substrate microstructure [26], so reliable evaluation depends on controlled fatigue testing supported by fractography. Table 2 summarizes the fatigue regimes and controlling variables relevant to this system.

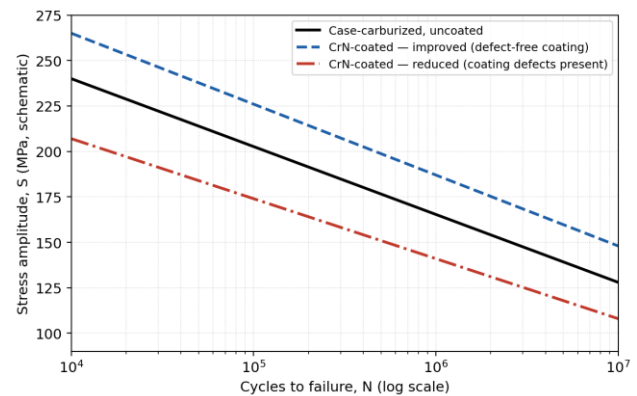


Fig. 2. Schematic S–N trends reported for case-carburized steels with and without CrN coating

Table 2. Classification of fatigue regimes, controlling variables and life-prediction approaches

Regime / Approach	Controlling Parameter	Typical Life Range	Key Influencing Factors	Refs.
Low-cycle fatigue (LCF)	Cyclic plastic strain	$<10^4$ – 10^5 cycles	Coffin–Manson relation; cyclic hardening/softening; thermal & overload cycling	[39–41][7,42]
High-cycle fatigue (HCF)	Cyclic elastic stress	$>10^5$ cycles	S–N (Wöhler) approach; surface finish; residual stress; inclusion content	[14,3–4][43–44]
Strain–life (ϵ –N)	Total (elastic+plastic) strain amplitude	Full range	Unifies LCF/HCF; used for local yielding at notches/coatings	[7,39,45][39,46]
Crack propagation	Stress-intensity range ΔK	Depends on flaw size	Paris law regions I–III; microstructure & residual-stress interaction	[8,58,61][62]
Cumulative damage / FE models	Damage fraction per stress level	Variable-amplitude service	Miner's rule; fracture-mechanics integration; FE/crystal-plasticity	[56–57,59][60]

4. Case Carburization of Low-Alloy Steels

Case carburization enriches the surface of low-carbon alloy steel with carbon at 900–950°C in the austenitic range [63], producing a carbon-concentration gradient governed by Fick's diffusion laws [65,66–67]. The overall process route-from steel blank through carburizing, quenching/tempering and CrN deposition to the finished fatigue specimen-is summarized in Fig. 3. Oil quenching transforms the carbon-enriched surface into high-carbon martensite while the low-carbon core forms a tougher tempered

martensitic/bainitic structure [49,68], satisfying the conflicting requirements of wear-resistant surface hardness and impact-resistant core toughness that through-hardening cannot provide simultaneously [50,69]. Alloying elements (Cr, Mo, Mn, Ni) modify hardenability and transformation behaviour [48,49,71]: chromium and molybdenum raise hardenability and tempering resistance, nickel improves core toughness, and manganese promotes martensite formation, though excess manganese can stabilize retained austenite [71].

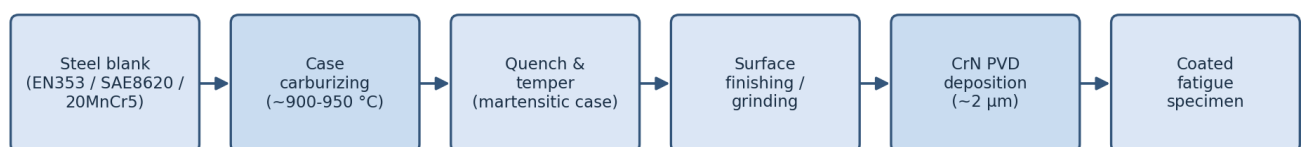


Fig. 3. Process route for case-carburized, CrN-coated specimens.

EN353, SAE8620 and 20MnCr5 are among the most widely used carburizing steels for transmission applications; steel composition and processing history jointly govern their fatigue performance [11]. EN353 (Cr–Ni–Mo) provides deep hardenability with excellent core toughness; SAE8620 (balanced Cr–Ni–Mo) is a global standard for gears and pinions; 20MnCr5 relies on Mn–Cr additions for adequate hardenability at lower cost [36,64]. Effective case depth is

conventionally defined and verified per ISO 2639, and hardenability is characterized via the standard Jominy test (ASTM A255) [72–73]. Although all three develop comparable surface hardness after carburization, differences in retained-austenite stability, carbide precipitation and residual-stress distribution arising from alloy chemistry are reported to influence subsequent fatigue and coating behaviour [37], which

is a central rationale for comparing the three grades under identical processing (Section 7, Table 7).

Low-temperature tempering (150–200°C) relieves quench stresses while retaining surface hardness above 60 HRC [69]. Retained austenite, if stable, can improve fatigue resistance through transformation-induced plasticity, but excessive or unstable retained austenite reduces hardness and dimensional stability [51,71,74]. Compressive residual stresses generated by martensitic volume expansion during quenching are the principal mechanism by which carburization

improves fatigue strength [14,16,75]; these stresses can relax during elevated-temperature service and locally lower the effective fatigue limit [75,78]. Carburization also improves wear and rolling-contact resistance through increased hardness [15,79–80], and combining it with a CrN coating is reported to further reduce friction and surface damage provided coating quality and adhesion are adequate [25]. Table 3 summarizes the principal process stages and their fatigue/wear effect.

Table 3. Principal stages of case carburization, the metallurgical feature each produces, and the associated influence on fatigue and wear

Process Stage	Metallurgical Feature Produced	Typical Range	Influence on Fatigue / Wear	Refs.
Austenitizing & carbon diffusion	Carbon-concentration gradient in FCC austenite	900–950°C; case depth per Fick's law	Sets available case depth for load support	[63–65][66]
Oil quenching	High-carbon martensite (case); tempered martensite/bainite (core)	BCT martensite; volumetric expansion	Generates compressive residual stress; suppresses cyclic slip	[49,68,76][77]
Low-temperature tempering	Relief of quench stress; transition-carbide precipitation	150–200°C; >60 HRC retained	Reduces brittleness without significant softening	[63,69,70]
Retained austenite (as-quenched)	Untransformed FCC phase within case	Depends on carbon potential & alloy content	Beneficial (TRIP) if stable; detrimental if excessive/unstable	[51,71][51,74]
Alloy-carbide formation	Fine Cr/Mo/Mn carbides in matrix	Depends on tempering & carbon potential	Secondary hardening if fine; crack initiation site if coarse/grain-boundary	[11,17]

5. Physical Vapour Deposition and Chromium Nitride Coatings

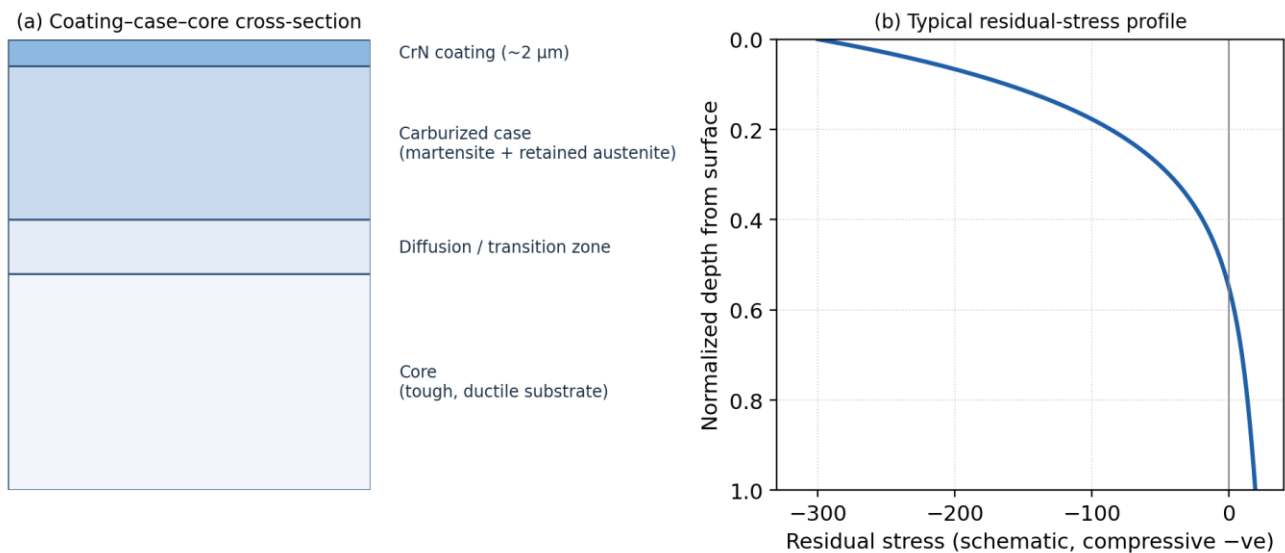


Fig. 4. Schematic of coating/case/core structure and associated residual-stress profile

Table 4. Comparison of the principal Physical Vapour Deposition (PVD) techniques used for hard-coating deposition

Technique	Vapour-Generation Mechanism	Relative Ionization/Density	Typical Application	Refs.
Vacuum (thermal) evaporation	Resistance/e-beam/laser heating of source	Low	Simple, low-adhesion coatings; largely superseded for fatigue-critical parts	[81]

Magnetron sputtering (balanced/unbalanced/reactive)	Ion bombardment ejects target atoms; reactive N ₂ forms nitride	Moderate-high	Wide industrial use for CrN, TiN, TiAlN hard coatings	[83,87][83,87]
Cathodic arc evaporation	Vaporization at cathode arc spots	High (but droplet-prone)	Dense, well-adhered coatings; macrodroplet defects a known limitation	[85,88]
Arc ion plating	Arc evaporation with enhanced ion bombardment	High	Improved density/adhesion vs. plain arc evaporation	[89]
HiPIMS	High-power pulsed magnetron discharge; high ionized flux fraction	Very high	Dense, low-porosity, low-defect coatings; growing interest for fatigue-critical use	[86,29][86]

Physical Vapour Deposition (PVD) converts a solid coating material to vapour, transports it through vacuum, and condenses it on the substrate, yielding dense, high-purity coatings without the elevated temperatures used in Chemical Vapour Deposition [20,81]. This comparatively low processing temperature preserves the hardness and residual stresses developed during carburization, making PVD well suited to heat-treated gear steels. The main techniques-magnetron sputtering, cathodic arc evaporation, arc ion plating and High-Power Impulse Magnetron Sputtering (HiPIMS)-differ in ionization efficiency and deposition rate, which govern coating hardness, adhesion, defect population and residual stress [20,82–87]. Table 4 compares the principal PVD techniques.

Among nitride coatings, CrN combines high hardness (≈ 1600 – 2200 HV), comparatively low intrinsic residual stress and good fracture toughness [27,86,88]. These properties, together with excellent oxidation/corrosion resistance through a stable Cr₂O₃ passive film, give it an advantage over TiN for fatigue-loaded components [22,21]. Coating adhesion-governed by substrate cleaning, ion etching and deposition bias [21]-is widely reported to influence fatigue life more strongly than hardness itself [87], and is commonly quantified using standardized scratch-adhesion testing [90,106]; poorly adhered coatings fail by early delamination regardless of hardness. Coating thickness of 2–4 μm is generally recommended as a compromise between wear protection and intrinsic stress/brittleness [29]; this review's included studies (Section 7, Table 7) most often used a comparable CrN thickness of ~ 2 μm (Fig. 4). Because the carburized substrate and the CrN coating are mechanically coupled, fatigue behaviour must be interpreted as a property of the integrated coating-substrate system: a hard, compressively stressed substrate supports the brittle ceramic layer, whereas inadequate substrate support permits local plasticity that cracks the coating and triggers premature crack initiation [17,91]. Coating defects-pores, macrodroplets, incomplete interfacial bonding-act as local stress concentrators and are repeatedly implicated in the fatigue-reducing outcomes reported for CrN [25,27].

6. Fatigue Behaviour of Case-Carburized and CrN-Coated Steels

Rotating-bending fatigue testing, standardized under ISO 1143 and ASTM E466 [43,92], generates alternating tensile/compressive stress at the specimen surface each revolution, with maximum tensile stress-and hence crack initiation-occurring at the outermost carburized (and coated) layer [43]. Carburization delays initiation through increased hardness and compressive residual stress; CrN protects against wear, fretting and oxidation, but coating defects or inadequate adhesion can introduce additional stress concentrators that offset this protection [29]. Reported behaviour also depends on loading mode: under rolling-contact fatigue [93] coatings mainly reduce wear and pitting, whereas under rotating-bending fatigue coating integrity and adhesion become decisive because the coating itself is repeatedly loaded in tension [91].

Among the three steels reviewed, EN353 (Cr–Ni–Mo), in its case-carburized, conventionally heat-treated condition, shows a rotating-bending fatigue (endurance) limit of 636 MPa at 10^7 cycles [17]; SAE8620 is the most extensively studied carburizing grade, with fatigue strength strongly dependent on case depth and retained-austenite stability [18,74]; and 20MnCr5, while economical and widely used, shows fatigue cracks initiating at surface/subsurface inclusions and stress concentrators in gear-failure analyses [36]. No identified study, however, tests all three grades under one identical carburizing and CrN-coating schedule with a common rotating-bending protocol-the specific gap addressed by the ongoing investigation this review supports [37], and quantified directly in Table 7 by the number of studies reporting each steel grade (see Section 7).

SEM fractography is the principal tool for converting fatigue-life numbers into a mechanistic explanation of failure [94]. Fracture surfaces of carburized/CrN-coated steels generally show three regions-initiation, stable propagation and final overload-whose relative extent depends on stress level, microstructure, residual stress and coating integrity. Table 5 summarizes the fractographic features most consistently reported in the literature and their mechanistic significance.

Table 5. Fractographic features commonly reported for fatigue failure of carburized and CrN-coated steels, and their mechanistic significance

Fractographic Feature	Characteristic Morphology	Mechanistic Significance	Refs.
Crack-initiation zone	Smooth origin with fine radial markings; at machining marks, inclusions, coating pores/droplets or interfacial defects	Marks the site of first crack nucleation; usually at or just below the surface under bending	[9,152][53,95-96]
Fatigue striations	Fine parallel markings in the stable-growth region	Each striation $\approx$ one loading cycle; spacing indicates local growth rate	[8,61]
Beach (arrest) marks	Macroscopic concentric bands	Reflect load changes, stoppages or intermittent crack arrest over many cycles	[2,1]
Cleavage facets / river patterns	Faceted, low-plasticity fracture with converging ridges	Brittle fracture, common within the CrN coating or highly hardened case	[10]
Microvoid coalescence	Equiaxed/elongated dimples, tearing ridges	Ductile final overload fracture, reflects core toughness	[9,53]
Secondary cracking / coating delamination	Cracks parallel/adjacent to main crack; lifted or separated coating	Indicates coating brittleness, poor adhesion or excess residual stress	[25,87,27]

7. Comparative Analysis of Published Literature

A structured comparison of published investigations on carburized and CrN/PVD-coated steels (Table 6) shows that carburization is consistently reported to improve fatigue strength through increased hardness and compressive residual stress [17,18,24]. The reported effect of CrN coating itself, by contrast, ranges from measurable improvement-delayed crack initiation and wear protection to slight reduction in endurance limit from coating defects, tensile residual

stress or poor adhesion [25,26,35]. This inconsistency recurs across the wider comparative literature [36,37,97], including studies focused specifically on duplex-treated and aeronautic gear steels [98–100]. Rotating-bending fatigue investigations remain comparatively limited relative to rolling-contact and axial testing [101], even though bending most closely represents gear-tooth-root and shaft loading, and detailed SEM fractography correlated quantitatively with fatigue-life data is reported in only a minority of studies.

Table 6. Comparative summary of published investigations on the fatigue behaviour of case-carburized and PVD-coated steels

Steel / System	Coating	Fatigue Test	Principal Finding	Refs.
AISI/SAE8620, carburized	None	Rotating bending / rolling contact	Endurance limit increased via compressive residual stress; case depth optimum identified	[18,35]
EN353, carburized	None	Rotating bending	Rotating-bending fatigue limit of 636 MPa at 10^7 cycles for the conventionally heat-treated (uncoated) baseline; cryogenic post-treatment variants also reported	[17]
20MnCr5, carburized (gear)	None	Service / gear fatigue	Cracks initiated at surface inclusions and stress concentrators	[36]
Medium-carbon steel	TiN/CrN/TiAlN	Rotating bending	Coating type strongly affected fatigue life; TiN more defect-prone than CrN	[24]
Steel components (general)	PVD (various)	Various	Coating adhesion and residual stress identified as more decisive than hardness	[25]
Hard-coating/ductile-substrate systems (review)	PVD hard coatings	—	Fatigue behaviour governed by integrated coating-substrate response, not coating alone	[26]
20MnCr5, carburized	CrN (PVD)	Fatigue life evaluation (rotating bending, ASTM E739)	CrN coating reduced mean endurance limit from 730 MPa (uncoated) to 687.5 MPa (coated), estimated via Dixon-Mood staircase method	[37]
Carburized/duplex-treated steel	Cr(C,N) film	Fatigue	Duplex treatment altered fatigue behaviour via coating-substrate interaction	[98]
Steel substrates (various)	CrN-PVD	Fatigue nucleation study	Through-thickness residual stress correlated with fatigue nucleation sites	[97]
Steel substrate	CrN	Indentation/cyclic impact	Coating fracture behaviour characterized under dynamic cyclic impact	[99]
Hard-coated steel	PVD hard coating	Cyclic mechanical loading	Fracture and fatigue resistance assessed via dedicated cyclic-loading protocol	[100]
Aeronautic gear steel	Carburized+shot peening	Bending fatigue	Combined carburizing and shot peening improved surface integrity and bending fatigue life	[101]
SAE8620, carburized	WC/C (PVD)	Rotating bending (4-point)	WC/C suitable for heat-sensitive carburized steel; endurance limit improved $\sim 7\%$ vs. uncoated; coating did not alter crack-propagation mechanism, only the stress level at which it occurred	[108]

7.1 Quantitative data-extraction table

Table 7 supplements the qualitative comparison in Table 6 with the study-level variables specified in the extraction protocol (Section 2.5). Cells marked “NR” indicate the variable was not reported in the source

study; this is the direct evidence for the comparative gaps discussed narratively in Section 8, replacing a qualitative assertion that such variables are “rarely reported” with a row-by-row account of exactly which variables are missing and from which sources.

Table 7. Quantitative data extraction for included fatigue studies of case-carburized and CrN/PVD-coated steels

Ref.	Steel	Case depth (mm)	Hardness (HV/HRC)	Retained austenite (%)	Coating tech. / thickness	Adhesion test / result	Loading mode, R	Fatigue limit / result	Test standard; n
[17]	EN353-comparator: uncoated carburized baseline	~1.0 mm (carburized case)	Fatigue limit basis; hardness traverse reported (not tabulated numerically here)	28.1% (conventionally heat-treated, as-quenched)	— (uncoated)	—	Rotating bending, R=-1, 3000 rpm	Fatigue (endurance) limit = 636 MPa for the conventionally heat-treated (uncoated carburized) baseline condition, at 10^7 cycles	DIN 50113; ISO 5075; n=54 specimens across all treatment groups in the source study
[18,35]	SAE8620 (AISI 8620)-comparator: uncoated carburized baseline	0.73, 0.90 and 1.10 mm (three conditions tested; 10 mm dia. specimens) [18]	NR	NR	— (uncoated)	—	Rotating bending, [18]; rolling contact, [35]	[18]: fatigue strength (at 10^6 cycles) of 840, 980 and 1140 MPa for case depths of 0.73, 0.90 and 1.10 mm respectively, vs. 590 MPa for the uncarburized (austenitized-only) baseline; surface compressive residual stress of -265, -220 and -200 MPa respectively (decreasing with increasing case depth); no distinct endurance-limit knee point was observed up to 1.5×10^6 cycles. [35]: endurance limit increased via compressive residual stress.	NR

[101]	[98]	[97]	[37]	[24]	[36]
Aeronautic gear steel-comparator: carburized, no PVD coating	Carburized/duplex-treated steel-comparator: alternative coating chemistry (Cr(C,N), not CrN)	Various steel substrates-comparator: coating residual-stress study (carburization not confirmed; no fatigue-life outcome)	20MnCr5-PRIMARY (carburized + CrN + lab fatigue)	Medium-carbon steel-comparator: alternative coating benchmark (carburization not confirmed in source)	20MnCr5-comparator: field-failure evidence (not lab fatigue)
NR	NR	—	NR	NR	NR
NR	NR	NR	NR	NR	NR
NR	NR	—	NR	NR	NR
— (carburized+shot peened, no PVD)	Cr(C,N) film, NR thickness	CrN-PVD, NR thickness	CrN (PVD), ~2 µm	TiN / CrN / TiAlN, NR thickness	— (uncoated, service gear)
—	NR	— (residual stress by XRD)	NR	NR	—
Bending fatigue	NR	—	Rotating bending	Rotating bending	Service / gear fatigue
Improved surface integrity and bending fatigue life	Duplex treatment altered fatigue behaviour	Residual stress correlated with nucleation site	Mean endurance limit (Dixon-Mood): 730 MPa uncoated vs. 687.5 MPa CrN-coated-CrN reduced fatigue life; difference roughly constant across stress levels tested (authors' own prior study)	CrN outperformed TiN; TiAlN NR	Cracks at surface/subsurface inclusions
NR	NR	NR	ASTM E739 (2015); Dixon-Mood staircase	NR	NR (field failure analysis, not lab S-N)

[108]	SAE8620-comparator: alternative PVD coating (WC/C, not CrN)	~0.7–0.8 mm (effective case depth)	No significant loss in substrate hardness (qualitative, per source)	NR	WC/C (PVD), NR thickness	NR	Rotating bending (4-point), two stress levels (180, 210 MPa)	Endurance limit improved ~7% vs. uncoated; crack-propagation mechanism unaffected by coating, only the stress level at which it occurred	ISO 1143 (rotating bending); fatigue-test replication per ASTM E739; regression (linear model) analysis of fatigue data
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Coverage across Table 7 confirms three specific gaps: (i) no single row reports more than one carburizing steel under identical coating conditions; (ii) case depth, hardness and retained austenite—the three metallurgical variables identified in Section 4 as governing fatigue behaviour—are not reported for the majority of the reviewed studies; and (iii) coating adhesion, the variable Section 5 identifies as more decisive for fatigue life than hardness itself [87], is not quantitatively reported in any of the included studies.

Coating-parameter studies (Table 8) further indicate that fatigue performance is not a simple function of coating thickness or hardness. Moderate compressive residual stress and good adhesion consistently correlate with improved or unchanged fatigue life [22,23,27]. By contrast, excessive coating thickness and high intrinsic residual stress correlate

with reduced endurance limit [28,31,32], as do macrodroplet-type defects reported under various deposition conditions [34,86]. This pattern holds across coating-thickness and substrate-bias studies specifically [23,102–103]. HiPIMS-deposited coatings are increasingly reported to combine low porosity with good adhesion, but long-term industrial fatigue validation of this technique remains comparatively limited. These reported outcomes are drawn from a small number of studies that differ in substrate, coating chemistry, thickness and test method, and are not statistically independent replications of a single experiment; they are summarized qualitatively here, and individually in Tables 5, 7 and 9, rather than presented as a numerical count of independent studies.

Table 8. Comparison of CrN coating-parameter studies and their reported effect on fatigue behaviour

Coating Parameter Studied	Reported Range / Technique	Reported Effect on Fatigue	Refs.
CrN deposition & properties (general)	Reactive sputtering / cathodic arc	Established baseline hardness, adhesion and corrosion resistance of CrN	[22]
Residual stress in CrN-PVD coatings	Through-thickness X-ray measurement	Correlated with fatigue-nucleation-site location	[23,97]
Hardness/toughness balance (H/E ratio)	Nanocomposite & conventional CrN	Higher toughness-to-hardness balance reduces brittle cracking	[27–28]
Industrial CrN coatings	Cathodic-arc/sputtered, industrial scale	Wear and corrosion improved; fatigue effect condition-dependent	[31,32]
Coating defects (droplets, pores)	Cathodic arc, various thickness	Reduced fatigue life when defect density is high	[34,27]
HiPIMS deposition	High-power pulsed magnetron	Denser, lower-defect coatings; improved fatigue resistance reported	[86]
Substrate bias voltage	Cathodic arc CrN/CrCN	Bias voltage alters coating density, stress and adhesion	[102]
Coating thickness vs. durability	1–6 μm range	2–4 μm identified as favourable compromise for fatigue-critical parts	[29,103]

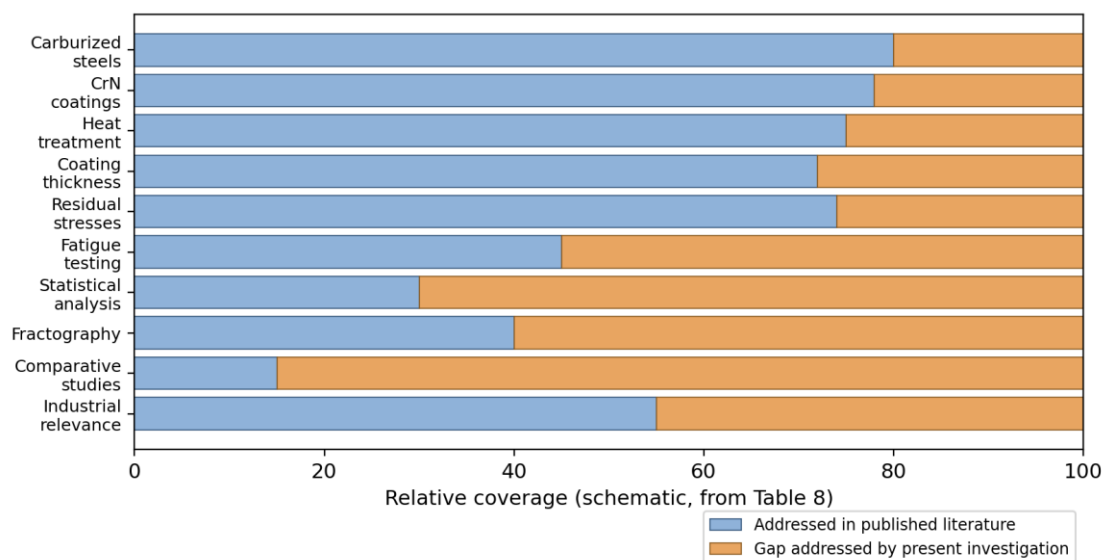
8. Research Gaps and Scope of the Present Investigation

Taken together, the literature synthesized in Tables 1–7 shows consistent agreement that carburization improves fatigue strength, but considerable disagreement over the fatigue effect of CrN coating, driven by uncontrolled variation in substrate grade, deposition technique, coating thickness and fatigue-

test mode across independent studies. Table 9 summarizes the principal gaps, cites the specific rows of Table 7 that evidence each gap, and states how the ongoing investigation supporting this review is designed to address each one; Fig. 5 presents the same comparison graphically, showing that published coverage is comparatively strong for individual carburizing and coating variables but weak for comparative, multi-steel studies.

Table 9. Research-gap matrix: limitations of the published literature, the supporting evidence in Table 7, and how the present investigation addresses each gap

Research Area	Limitation in Published Literature	Evidence (Table 7)	Present Investigation
Substrate comparison	Almost all studies examine a single carburizing steel (commonly SAE8620, AISI9310 or 18CrNiMo7-6) [18,35–36]	No Table 7 row reports >1 steel under identical conditions	Systematic comparison of EN353, SAE8620 and 20MnCr5 under identical conditions
Coating effect on fatigue	Reported effect ranges from improvement to reduction depending on adhesion, defects and residual stress [25,27]	Adhesion column not reported for any row	Direct rotating-bending evaluation of CrN's effect with controlled, measured coating quality
Processing consistency	Carburizing schedules, coating thickness (1–6 μm) and deposition technique vary widely between studies [29,103]	Coating-tech./thickness column shows heterogeneous values across rows	Identical carburizing schedule and industrial CrN ($\sim 2 \mu\text{m}$) for all three steels
Fatigue-test mode	Rolling-contact and axial fatigue are more commonly reported than rotating bending [43]	Loading-mode column mixed across rows	Rotating-bending fatigue ($R=-1$), representative of gear/shaft bending loading
Fractographic correlation	SEM images are often shown descriptively without quantitative correlation to fatigue-life data [94]	Fatigue-limit/result column often qualitative only	SEM fractography systematically correlated with fatigue-life measurements
Statistical treatment	Mean fatigue life is commonly reported; formal endurance-limit statistics and scatter analysis are less common [104,107]	Test-standard/n column NR for nearly all rows	Endurance-limit estimation via the Dixon–Mood staircase method [105] with ASTM E739 statistical analysis [44]

**Fig. 5.** Research-gap map summarizing Table 9

The originality of the planned work therefore lies not in studying CrN coating in isolation, but in integrating identical carburizing and coating processing, standardized rotating-bending testing, formal statistical endurance-limit analysis and correlated SEM fractography across three commercially important carburizing steels-reducing experimental uncertainty and enabling a genuinely substrate-dependent comparison. Practically, the outcomes are intended to guide steel and coating selection for fatigue-critical automotive and aerospace transmission components, wind-turbine gearboxes, rail axles and heavy-machinery gearing, where carburized, CrN-coated steels are already in service but where the coating's net

effect on bending fatigue life is not yet reliably established [26,91].

Critically, the literature rarely treats fatigue of coated carburized steels as the multivariable problem it is: very few studies combine more than one carburizing steel, identical CrN coating conditions, standardized rotating-bending testing, statistical endurance-limit estimation and correlated SEM fractography within a single investigation. This gap, quantified in Table 7 and summarized in Table 9, is the scientific justification for an investigation that evaluates EN353, SAE8620 and 20MnCr5 under identical carburization and CrN coating conditions, using standardized rotating-bending fatigue testing

and detailed fractographic examination to establish the mechanisms governing crack initiation, propagation and final fracture.

Conclusion

This review has synthesized the published literature on fatigue behaviour of case-carburized steels and the influence of PVD chromium nitride coatings, from the fundamentals of fatigue and S-N/ ϵ -N behaviour, through carburization metallurgy and CrN coating technology, to the comparative fatigue and fractographic behaviour reported for EN353, SAE8620 and 20MnCr5 steels, following the pre-defined search and extraction protocol reported in Section 2. Within the ten studies identified as fatigue-relevant (Section 7, Table 7), carburization is consistently reported to improve fatigue resistance through a hardened, compressively stressed case over a tough core. The reported effect of CrN coating on fatigue is less consistent and is drawn from a small, heterogeneous set of studies spanning different steels, coatings, loading modes and reporting standards (Section 7.1, Table 9); within this limited evidence base, coating adhesion, defects, residual stress and substrate condition are each reported to influence the outcome, rather than hardness alone. These are findings reported in the cited primary literature, distinct from the authors' own interpretation that surface integrity, rather than bulk hardness, is likely to be the controlling factor for crack initiation—an interpretation that the three-steel investigation described in Section 8 is designed to test directly, and for which no results are yet available.

Limitations

This review has several limitations. The ten fatigue-relevant studies identified span different steel grades, heat-treatment routes, coating chemistries, loading modes and testing standards; only one study reports case-carburized, CrN-coated material under laboratory rotating-bending fatigue testing, so conclusions about CrN's net effect on fatigue in this exact system rest on a single primary study supported by heterogeneous comparator evidence (Section 2.2, Table 9). Several studies do not report case depth, hardness, retained austenite, specimen count or statistical treatment of their fatigue data (Table 7, Table 9), limiting the strength of any quantitative synthesis across them. Findings from coatings other than CrN, from non-carburized substrates, and from field-failure analyses are reported here as contextual comparators only and should not be generalized to the carburized-steel/CrN-coating system that is this review's central focus. The database search returned a comparatively small number of directly on-topic records for this specific combination of substrate, coating and loading mode (Section 2.1); the review's coverage of this literature is believed to be substantially complete, but a search of this kind cannot be guaranteed exhaustive.

Declarations

Conflict of Interest: The authors declare no competing interests

Relationship to prior publication: This review draws on, and in Table 7 cites, the authors' own prior experimental article [37] (Kumar and Saini, *J. Mech. Sci. Technol.* 40(2) (2026) 993–996), which reported fatigue-life data for CrN-coated case-carburized 20MnCr5 steel only. No text, figures or tables from [37] are reproduced in this review; the review cites [37]'s findings, in the same manner as the other third-party sources in Table 7. Table 7 also cites a second, earlier prior publication by co-author B. S. Saini [108] (Saini and Gupta, *Surf. Coat. Technol.* 205(2) (2010) 511–518), on WC/C-coated case-carburized SAE8620 steel; as with [37], only its reported finding is cited, and no text, figures or tables are reproduced. The systematic three-steel rotating-bending comparison referred to as the “ongoing investigation” throughout Sections 6–8 is a separate, unpublished extension of [37] and is not yet complete.

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