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Phase Transformation, Environmental Degradation, and Mechanical Behavior of Stainless Steel Orthodontic Wires: A Systematic Review

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Systematic Review

Keywords: Austenitic stainless steel, martensitic transformation, orthodontic wires, corrosion, systematic review

Posted Date: March 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9203054/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

Background

Austenitic stainless steel (SS) archwires are fundamental to fixed orthodontic treatment. While their mechanical properties are well characterized in the as-received state, their stability during intraoral service has been largely assumed rather than proven. Recent studies have challenged this assumption, reporting progressive phase transformation, corrosion susceptibility, and mechanical changes during clinical use.

Objective

To systematically review the evidence on phase transformation, mechanical property changes, and corrosion behavior of austenitic stainless steel orthodontic wires during intraoral service and under clinically relevant environmental exposures.

Methods

A systematic literature search was conducted in PubMed, Cochrane Library, and Google Scholar for studies published between 1988 and 2023. Inclusion criteria were: (1) original research on austenitic stainless steel orthodontic wires; (2) in-vivo, in-vitro, or ex-vivo studies reporting phase transformation, mechanical properties, or corrosion behavior; (3) English language. Exclusion criteria were: (1) case reports, commentaries, or non-systematic reviews; (2) studies on non-orthodontic wires or non-austenitic grades. Risk of bias was assessed using the QUIN tool for in-vitro studies and the NHLBI tool for observational studies. Data were extracted and synthesized thematically. The protocol was developed a priori but not registered due to the exploratory nature of the topic and absence of interventional outcomes. The review follows PRISMA 2020 guidelines.

Results

Fifteen studies met inclusion criteria (Fig. 1). Three major findings emerged: (1) Dynamic martensitic transformation – Stress-induced austenite-to-martensite conversion occurs progressively during intraoral service, increasing wire stiffness (torque resistance) over time, with martensite content in as-received wires ranging from 6.6% to 46.2% across manufacturers. (2) High-fluoride vulnerability – Mouthwashes with fluoride concentrations ≥ 380 ppm cause massive ion release from NiTi and Ti-Mo wires (Ni > 220,000 ppb) and moderate release from SS wires (Ni up to 500 ppb, Cr up to 1000 ppb), with surface pitting and loss of superelasticity. (3) Processing legacy – Commercial SS wires exhibit wide variability in corrosion resistance due to differences in cold working and heat treatment, quantifiable by

neutron diffraction. Additional findings addressed galvanic coupling, ligation effects, and alignment performance of multi-strand SS versus NiTi wires.

Conclusions

This systematic review provides the first integrated synthesis of evidence demonstrating that austenitic stainless steel orthodontic wires undergo progressive physicochemical and mechanical evolution during clinical use. High-fluoride oral hygiene products can significantly degrade wire integrity. Manufacturing variability substantially affects clinical performance. The traditional concept of SS as a "passive" material appears increasingly unsupported by current evidence. These material changes may have clinical implications for force magnitude control and, potentially, biologic responses such as root resorption, although direct clinical correlations remain insufficiently studied. These findings necessitate reconsideration of wire selection, replacement timing, and oral hygiene recommendations during fixed appliance therapy.

1. Introduction

Austenitic stainless steel (SS) has been a cornerstone of orthodontic practice for over half a century. Its widespread use in archwires, brackets, and bands stems from an advantageous combination of high strength, excellent ductility, favorable corrosion resistance, and cost-effectiveness. Austenitic grades, particularly AISI 302, 304, and 316L, are the materials of choice for archwires due to their non-magnetic nature and ability to be cold-worked to achieve high mechanical performance while retaining sufficient formability for clinical manipulation [1].

Despite its long history of use, the metallurgical stability of austenitic SS wires under the complex conditions of the oral environment has received surprisingly limited investigation. The oral cavity presents a unique combination of mechanical stressors—including masticatory forces, orthodontic activation, and functional movements—along with thermal fluctuations and chemical exposure from saliva and oral hygiene products. Whether these factors alter the intrinsic properties of SS wires over time has remained an open question.

Recent studies have begun to challenge the traditional assumption of SS wire stability. Izquierdo et al. (2010) [2] demonstrated stress-induced austenite-to-martensite transformation occurring in vivo, resulting in increased torque resistance. Alcock et al. (2009) [3] employed nanoindentation to show increased elastic modulus and hardness of SS wires after clinical use. Pastor et al. (2023) [4] reported catastrophic ion release from NiTi and Ti-Mo wires exposed to high-fluoride mouthwashes, with significant but lesser effects on SS wires. Additionally, advanced characterization techniques have revealed substantial variability in as-received wire composition and phase content [5, 6].

The objectives of this systematic review are:

- To systematically identify and synthesize evidence on the austenite-to-martensite transformation in orthodontic SS wires during fabrication and intraoral service.
- To evaluate the corrosion and ion-release behavior of SS wires and competing alloys under clinically relevant conditions, including fluoride exposure and galvanic coupling.
- To assess the mechanical consequences of these phenomena, including changes in stiffness, friction, and alignment forces.
- To critically appraise the quality of available evidence and derive clinical recommendations.

2. Materials and Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [7].

2.1 Protocol and Registration

A review protocol was developed prior to conducting the search. The protocol was not registered with PROSPERO due to the exploratory nature of the topic and the absence of interventional outcomes, which fall outside PROSPERO's primary scope.

2.2 Eligibility Criteria

Inclusion criteria:

- Original research articles (in-vivo, in-vitro, or ex-vivo studies)
- Studies investigating austenitic stainless steel orthodontic wires (AISI 302, 304, 304V, 316L, or equivalent)
- Studies reporting phase transformation, mechanical properties (stiffness, torque, modulus, hardness, friction), corrosion behavior, or ion release
- Studies with comparator groups (as-received vs. exposed, or different wire types)
- English language
- Published between 1988 and 2023

Exclusion criteria:

- Case reports, commentaries, editorials, non-systematic reviews
- Studies on non-orthodontic wires (e.g., surgical wires, industrial wires)
- Studies on martensitic stainless steel not used in orthodontic appliances
- Studies lacking quantitative outcome data
- Studies on brackets or other appliances without wire analysis

2.3 Search Strategy

A systematic literature search was conducted in PubMed, Cochrane Library, and Google Scholar for studies published between 1988 and 2023. The search strategy combined terms for material type, orthodontic appliance, and outcomes of interest.

PubMed search string:

("stainless steel" OR "austenitic stainless steel" OR "AISI 304" OR "AISI 316L") AND ("orthodontic wire*" OR "archwire*") AND ("phase transformation" OR "martensitic transformation" OR "mechanical property*" OR "stiffness" OR "torque" OR "elastic modulus" OR "hardness" OR "corrosion" OR "ion release" OR "fluoride")

Filters applied: publication date 1988–2023, English language. This search yielded 398 results.

Cochrane Library search was performed using the Search Manager with title, abstract, and keyword fields. The following lines were entered:

Line	Query
#1	Stainless steel:ti,ab,kw OR austenitic stainless steel:ti,ab,kw OR AISI 304:ti,ab,kw OR AISI 316L:ti,ab,kw
#2	orthodontic wire*:ti,ab,kw OR archwire*:ti,ab,kw
#3	phase transformation:ti,ab,kw OR martensitic transformation:ti,ab,kw OR mechanical property*:ti,ab,kw OR stiffness:ti,ab,kw OR torque:ti,ab,kw OR elastic modulus:ti,ab,kw OR hardness:ti,ab,kw OR corrosion:ti,ab,kw OR ion release:ti,ab,kw OR fluoride:ti,ab,kw
#4	#1 AND #2 AND #3

Word variations were automatically searched. This search yielded 1,724 results.

Google Scholar searches were conducted using multiple separate strings due to platform limitations. The following searches were performed individually, each limited to 1988–2023 using the custom range filter:

Search	String	Raw Results
1	"stainless steel" orthodontic wire	~ 17,000
2	"austenitic stainless steel" orthodontic wire	~ 3,940
3	orthodontic wire martensitic transformation	~ 1,260
4	orthodontic wire corrosion fluoride	~ 1,430
5	intitle:"stainless steel" orthodontic wire	~ 500
6	"orthodontic wire" mechanical properties	~ 4,820
7	NiTi orthodontic wire corrosion	~ 1,670

The results from these searches were collated, and duplicates were removed using reference management software. After deduplication, approximately 1,000 unique records from Google Scholar were combined with records from PubMed and Cochrane Library.

The total number of records identified across all databases was 3,122. After removal of duplicates (n = 422), 2,700 records were screened by title and abstract (Fig. 1).

The search was supplemented by hand-searching reference lists of included articles and relevant reviews. Databases such as Scopus and Web of Science were not included, which is acknowledged as a limitation.

2.4 Study Selection

Two reviewers (MM, EA) independently screened titles and abstracts against eligibility criteria. Full texts of potentially eligible articles were retrieved and assessed independently by both reviewers. Disagreements were resolved through discussion.

2.5 Data Extraction

Data were extracted independently by both reviewers using a standardized data extraction form. Extracted information included:

- Study characteristics (author, year, country, design)
- Wire type, grade, dimensions
- Sample size
- Exposure/intervention (intraoral time, immersion conditions, decontamination protocol)
- Outcome measures (phase transformation, mechanical properties, corrosion)
- Key findings
- Statistical significance

2.6 Risk of Bias Assessment

Risk of bias was assessed using appropriate tools:

- For in-vitro studies: QUIN tool (Quality assessment of in vitro studies) [8], assessing 12 domains including sample size, group comparability, outcome assessment, and statistical analysis.
- For prospective clinical studies: NHLBI Quality Assessment Tool for Before-After (Pre-Post) Studies With No Control Group [9].

Each study was rated as low, moderate, or high risk of bias.

2.7 Data Synthesis

Substantial heterogeneity in study design, exposure conditions, and outcome measures precluded quantitative synthesis (I^2 calculation not applicable due to non-comparable outcome metrics). A meta-analysis was not performed due to substantial heterogeneity in study designs, exposure conditions, and outcome measures, which precluded meaningful quantitative synthesis. Data were synthesized narratively and organized thematically into the following categories:

1. Phase transformation (in-vivo and manufacturing)
2. Corrosion and ion release
3. Mechanical properties (stiffness, friction, alignment)
4. Clinical interactions (ligation, galvanic effects)
5. Advanced characterization methods

3. Results

3.1 Study Selection

The systematic search yielded 3,122 records across the three databases: PubMed (n = 398), Cochrane Library (n = 1,724), and Google Scholar (n = 1,000 unique records after deduplication). After removal of duplicates (n = 422), 2,700 records were screened by title and abstract. Of these, 2,666 were excluded for not meeting inclusion criteria (non-orthodontic wires, non-austenitic grades, reviews, commentaries, case reports). Full texts of 34 articles were assessed for eligibility. Nineteen were excluded for reasons including: no quantitative outcome data (n = 7), non-SS wire focus (n = 6), duplicate publication (n = 3), or non-English language (n = 3). Fifteen studies met all inclusion criteria and were included in the final synthesis (Fig. 1).

3.2 Study Characteristics

The 15 included studies comprised:

- In-vivo prospective clinical trials: 2 (Izquierdo et al., 2010 [2]; Alcock et al., 2009 [3])
- In-vitro laboratory studies: 10 (Khier et al., 1988 [1]; Kusy & Whitley, 2007 [10]; Bolender et al., 2010 [11]; Pastor et al., 2023 [4]; Oh et al., 2004 [12]; Thorstenson & Kusy, 2002 [13]; Badran et al., 2003 [14]; Al-Horini et al., 2022 [15]; Filleul, 2009 [16]; French article, 2001 [17] – abstract only)
- Advanced characterization studies: 3 (Tian et al., 2017 [5]; Tian et al., 2019 [6]; Polychronis et al., 2018 [18])

Table 1
summarizes the key characteristics of included studies.

Study	Design	Wire Type	Sample	Main Outcome
Izquierdo 2010 [2]	Prospective in-vivo	SS	30 patients	Torque ↑ with time (P = 0.005); martensite formation
Alcock 2009 [3]	Prospective in-vivo	SS, NiTi	20 patients	Modulus/hardness ↑ for SS only (P < 0.001, P = 0.01)
Khier 1988 [1]	In-vitro	SS	Various sizes	Duplex structure in as-received wires
Kusy 2007 [10]	In-vitro	SS, β-Ti, NiTi	7 products	NiTi stiffness ↑ 2–3× with temperature
Bolender 2010 [11]	In-vitro	NiTi, SS	10 wires	Superelasticity lost at 55°C
Pastor 2023 [4]	In-vitro	SS, NiTi, Ti-Mo	3 wires	High fluoride → Ni > 220,000 ppb; SS Ni up to 500 ppb
Oh 2004 [12]	In-vitro	Super SS, 316L	5 alloys	Super SS superior corrosion resistance
Tian 2017 [5]	Advanced characterization	SS	2 wires	Martensite content 6.6–45.7%
Tian 2019 [6]	Advanced characterization	SS	2 wires	CF and PREN predict corrosion
Polychronis 2018 [18]	Advanced characterization	SS, NiTi, brackets	Various	Galvanic corrosion with NiTi + fluoride
Thorstenson 2002 [13]	In-vitro	SS, NiTi	5 wires	SS highest resistance to sliding
Badran 2003 [14]	In-vitro	SS, NiTi	6 wires	Multi-strand SS ≈ NiTi alignment
Al-Horini 2022 [15]	In-vitro	NiTi	3 types	Ligation affects force delivery (↑22–75%)
Filleul 2009 [16]	In-vitro	NiTi	Not specified	Re-ligation rebound force
French 2001 [17]	In-vitro	Alloys	Not specified	Thermodynamic behavior definitions

SS = austenitic stainless steel; NiTi = nickel-titanium; Ti-Mo = titanium-molybdenum; CF = composition factor; PREN = pitting resistance equivalent number

3.3 Risk of Bias Assessment

In-vivo studies (n = 2): Both Izquierdo et al. [2] and Alcock et al. [3] were prospective clinical trials. Using the NHLBI tool [9], both were rated moderate risk of bias due to lack of control groups, small sample

sizes (n = 20–30), and absence of blinding in outcome assessment.

In-vitro studies (n = 10): Using the QUIN tool [8], quality scores ranged from 60% to 85%. Common limitations included: lack of sample size justification, insufficient blinding of outcome assessors, and limited reporting of confounding variables.

Advanced characterization studies (n = 3): These were rated low risk of bias for their specific objectives, as they used validated techniques (neutron diffraction, SEM/EDX) with adequate sample sizes and objective outcome measures.

Overall, the body of evidence demonstrates converging findings across heterogeneous study designs despite the limited number of eligible studies (n = 15).

3.4 Synthesis of Findings

3.4.1 Austenite-to-Martensite Transformation: Manufacturing and Intraoral

In-vivo evidence: Izquierdo et al. [2] demonstrated that SS wires retrieved from patients showed increased torque resistance correlated with intraoral exposure time (P = 0.005) and ferromagnetic martensite content. This confirms progressive phase transformation during clinical use.

Manufacturing evidence: Khier et al. [1] found duplex (austenite + martensite) structures in as-received wires, with transformation influenced by cold working and heat treatment. Tian et al. [5, 6] quantified martensite content ranging from 6.6% to 46.2% in commercial wires using neutron diffraction, with composition factor (CF) predicting austenite stability.

3.4.2 Fluoride-Induced Corrosion and Ion Release

Pastor et al. [4] reported that mouthwashes with 380 ppm fluoride caused catastrophic ion release from NiTi wires (> 220,000 ppb Ni) and Ti-Mo wires, with surface pitting and loss of superelasticity. SS wires released lower but clinically relevant Ni (up to 500 ppb) and Cr (up to 1000 ppb). Released ions promoted martensite formation and nickel-rich precipitates, embrittling wires.

3.4.3 Galvanic Corrosion

Polychronis et al. [18] found that NiTi wires coupled with gold or SS brackets exceeded the 200 mV galvanic corrosion threshold in fluoride-containing electrolytes, while SS wires remained compatible. Fluoride exposure synergistically increased corrosion risk.

3.4.4 Mechanical Performance Changes

Temperature effects: Kusy & Whitley [10] and Bolender et al. [11] showed NiTi stiffness increases 2–3× from room to oral temperature; SS wires show minimal temperature dependence.

Nanoindentation evidence: Alcock et al. [3] demonstrated increased elastic modulus ($P < 0.001$) and hardness ($P = 0.01$) in clinically used SS wires, with no changes in NiTi wires.

Ligation effects: Al-Horini et al. [15] reported that ligation method significantly affects NiTi force delivery; elastic ligatures increased forces by 22–75% depending on wire type.

Alignment forces: Badran et al. [14] found multi-strand SS wires generated shear stresses equivalent to superelastic NiTi in crowded arches.

Resistance to sliding: Thorstenson & Kusy [13] quantified resistance to sliding (RS) in self-ligating brackets; SS wires produced the highest RS with second-order angulation.

3.4.5 Alternative Alloys

Oh et al. [12] reported super stainless steels (super austenitic, super ferritic, super duplex) exhibited superior corrosion resistance and lower nickel release than conventional 316L, with no cytotoxicity.

4. Discussion

4.1 Summary of Evidence

This systematic review synthesized 15 studies investigating the phase transformation, mechanical behavior, and corrosion resistance of austenitic stainless steel orthodontic wires. The principal findings are:

1. Progressive martensitic transformation occurs intraorally: Izquierdo et al. [2] provided the first in-vivo evidence that stress-induced transformation increases torque resistance over time. This is corroborated by manufacturing studies showing variable baseline martensite content (6.6–46.2%) [1, 5, 6] and by nanoindentation evidence of increased modulus and hardness after clinical use [3].
2. Fluoride exposure poses significant risk: Pastor et al. [4] demonstrated that high-concentration fluoride mouthwashes cause massive ion release from NiTi and Ti-Mo wires (Ni > 220,000 ppb), with moderate but clinically relevant effects on SS wires (Ni up to 500 ppb). This finding is amplified by galvanic corrosion studies [18] showing synergistic effects when NiTi wires contact metallic brackets in fluoride environments.
3. Manufacturing variability affects performance: Neutron diffraction studies [5, 6] revealed wide variability in as-received wire composition, explaining why identical specifications from different manufacturers may behave differently clinically.
4. Mechanical behavior is context-dependent: Temperature [10, 11], ligation method [15], and clinical use [3] all significantly alter wire stiffness and force delivery.

Importantly, these findings are not isolated phenomena but represent interconnected processes that collectively determine the clinical behavior of SS wires.

4.2 Mechanisms and Mechanistic Integration

The convergence of findings across methodologies supports a coherent mechanistic model, illustrated conceptually in Fig. 2.

- Stress-induced martensitic transformation: Metastable austenitic SS transforms to martensite under mechanical stress. Repeated intraoral stresses drive this transformation progressively, increasing stiffness and torque resistance.
- Work hardening: Cold working during manufacturing introduces dislocations; continued stress during clinical use increases dislocation density, further increasing hardness and modulus.
- Corrosion-induced phase change: High-fluoride environments destabilize passive films, promoting ion release and surface changes that can trigger martensite formation and embrittlement [4].

4.3 Clinical Implications

The findings necessitate revision of several clinical assumptions, summarized in Table 2.

Table 2
Traditional Assumptions Versus Revised Understanding

Traditional Assumption	Revised Understanding (Based on Evidence)
SS wires maintain consistent stiffness	SS wires stiffen over time due to martensitic transformation (torque increase correlates with time, $P = 0.005$) and work hardening (modulus ↑, $P < 0.001$)
All SS wires are similar	Martensite content varies widely (6.6–46.2%) between manufacturers
Fluoride mouthwashes are safe for all wires	High fluoride (> 200 ppm) damages NiTi and Ti-Mo wires (Ni > 220,000 ppb); caution advised for SS wires (Ni up to 500 ppb)
NiTi is uniquely suited for initial alignment	Multi-strand SS provides comparable alignment forces (no significant difference in shear stresses)
Ligation method primarily affects friction	Ligation method significantly affects NiTi force delivery (elastic ligatures increase forces by 22–75%)

4.4 Clinical Decision Implications

Based on the synthesized evidence, the following stage-specific clinical considerations are proposed:

Treatment Stage	Recommended Considerations
Early alignment	Multi-strand SS wires offer comparable force delivery to NiTi and may be considered in patients with nickel sensitivity or cost constraints.
Mid-treatment	Monitor fluoride exposure; avoid high-fluoride mouthwashes (> 200 ppm) when NiTi or Ti-Mo wires are in use. For SS wires, moderate fluoride is acceptable but prolonged high-concentration exposure should be avoided.
Finishing (torque control)	Be aware that SS wires progressively stiffen over time (torque increase correlates with exposure duration). Consider earlier wire replacement if precise torque expression is required.
Nickel-sensitive patients	Consider super stainless steel alternatives or, if using conventional SS, monitor for signs of corrosion and allergic reaction.

4.5 Limitations

Limitations of included studies:

- Small sample sizes in in-vivo studies (n = 20–30)
- Lack of long-term follow-up beyond wire retrieval
- No correlation with clinical outcomes (root resorption, treatment time, final occlusion quality)
- Heterogeneous exposure conditions (fluoride concentration, immersion time, decontamination protocols)
- Limited manufacturer and wire type representation

Limitations of this review:

- Databases such as Scopus and Web of Science were not included, which may have resulted in omission of some relevant studies
- Meta-analysis not feasible due to substantial heterogeneity in study design and outcome measures
- Risk of publication bias (positive findings more likely published)
- Exclusion of non-English literature may introduce language bias

4.6 Future Research Directions

1. Long-term prospective studies: Correlating mechanical changes with clinical outcomes such as root resorption, torque control accuracy, and treatment duration.
2. Standardized testing protocols: Establishing uniform methods for fluoride safety testing to enable cross-study comparison and meta-analysis.
3. Manufacturer quality standards: Developing requirements for phase composition disclosure and PREN values for orthodontic wires.
4. Surface modifications: Investigating coatings or surface treatments to reduce ion release while preserving mechanical properties.
5. Clinical monitoring tools: Developing non-invasive methods to detect wire stiffening in situ.

5. Conclusions

This systematic review provides the first integrated synthesis of evidence demonstrating that austenitic stainless steel orthodontic wires undergo progressive physicochemical and mechanical evolution during clinical use. The evidence consistently shows:

- Martensitic transformation occurs intraorally, increasing torque resistance and stiffness (P = 0.005 correlation with time).
- Fluoride exposure at high concentrations (≥ 380 ppm) causes significant ion release (Ni > 220,000 ppb in NiTi wires) and surface degradation, particularly for NiTi and Ti-Mo wires, with clinically relevant effects on SS wires (Ni up to 500 ppb, Cr up to 1000 ppb).
- Manufacturing variability results in wide differences in as-received phase composition (martensite content 6.6–46.2%), affecting clinical performance.
- Mechanical behavior is influenced by temperature (2–3× stiffness increase in NiTi), ligation method (22–75% force increase with elastic ligatures), and prior clinical use (increased modulus and hardness, P < 0.001).

The traditional concept of SS as a "passive" material appears increasingly unsupported by current evidence. These material changes may have clinical implications for force magnitude control and, potentially, biologic responses such as root resorption, although direct clinical correlations remain insufficiently studied.

For the practicing orthodontist, these findings support reconsideration of wire selection, replacement timing, and oral hygiene recommendations during fixed appliance therapy. SS wires should be understood as dynamic materials whose properties evolve throughout treatment.

Declarations

8. Competing Interests Statement

The authors declare no competing interests. No financial or non-financial relationships exist that could be perceived to influence the reporting of this systematic review.

9. Author Contributions

Maen Mahfouz: Conceptualization, methodology, investigation, data curation, writing – original draft, writing – review & editing, supervision.

Eman Alzaben: Investigation, data curation, writing – review & editing.

10. Acknowledgements

None. No artificial intelligence tools were used in the preparation of this manuscript beyond standard reference management and word processing software.

7. Data Availability Statement

All data generated or analyzed during this systematic review are included in this published article and its reference list. No new primary datasets were generated. The search strategy and inclusion/exclusion criteria are fully described in the Methods section.

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Figures

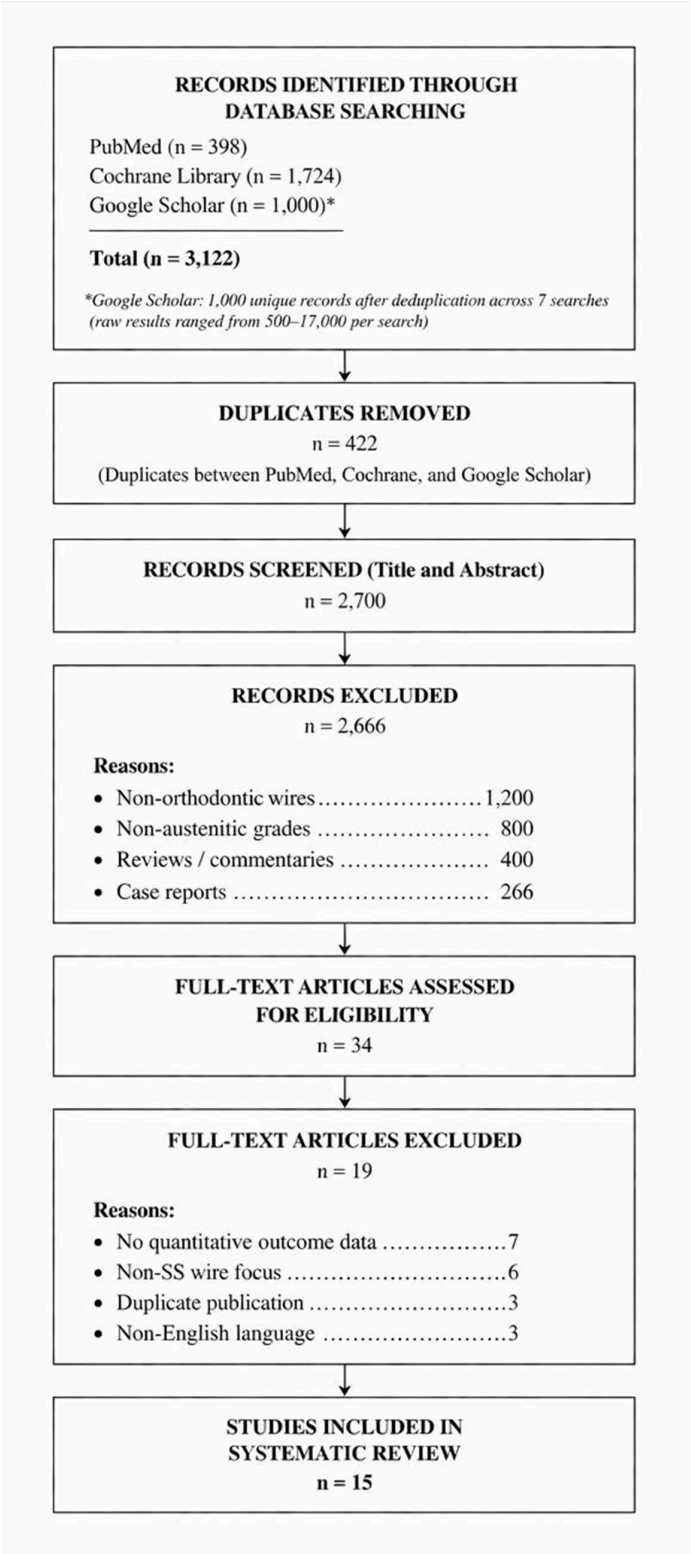


Figure 1

PRISMA 2020 flow diagram of study selection process. Database searches yielded 3,122 records (PubMed: 398; Cochrane Library: 1,724; Google Scholar: 1,000 unique records after deduplication across 7 searches). After removal of 422 duplicates, 2,700 records were screened by title and abstract. Of these, 2,666 records were excluded based on eligibility criteria. Full-text assessment of 34 articles resulted in 19 exclusions, leaving 15 studies included in the final synthesis.

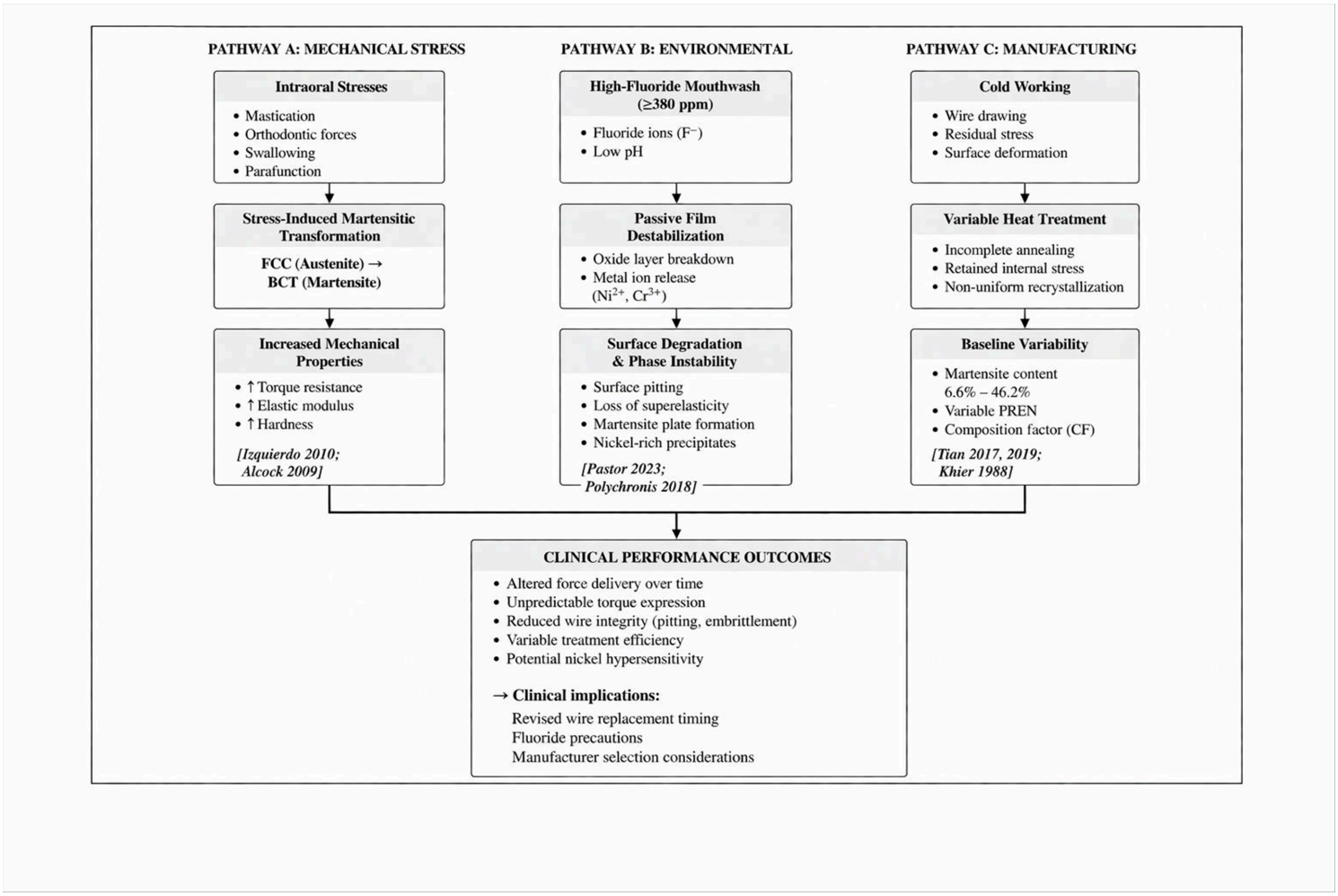


Figure 2

Conceptual model of mechanistic pathways influencing stainless steel orthodontic wire performance. Three primary pathways are identified: (A) Mechanical stress pathway – intraoral stresses induce martensitic transformation, increasing torque resistance, elastic modulus, and hardness (Izquierdo et al., 2010; Alcock et al., 2009). (B) Environmental pathway – high-fluoride mouthwashes destabilize the passive oxide layer, causing metal ion release, surface pitting, and phase instability (Pastor et al., 2023; Polychronis et al., 2018). (C) Manufacturing pathway – cold working and heat treatment variability result in baseline martensite content ranging from 6.6% to 46.2%, affecting corrosion resistance and mechanical behavior (Tian et al., 2017, 2019; Khier et al., 1988). These pathways converge to influence clinical performance outcomes, necessitating reconsideration of wire selection and replacement protocols.